Final Technical Report for:

Boundary Layer Controls on the Shallow-to-Deep Cumulus Transition

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1. Executive Summary

This project advanced our understanding of the processes governing cumulus cloud formation and provides an improved observational basis for validating earth system models. To be specific, the project used laser- and radar-remote sensors to examine the physical properties of updrafts that rise from earth's surface and initiate clouds deeper in the atmosphere. These updrafts comprise "thermals" and "plumes" and occur at small spatial and temporal scales (e.g., 10s of minutes, 100s of meters). These small scales preclude explicit representation in most earth system and climate models, and thus necessitate "sub-grid-scale" parameterization of updraft processes. The innovation of this project was to directly measure the size, shape, strength and water vapor content of these updrafts with Doppler and Raman lidars, respectively, and to link these updraft properties to cloud processes using vertically pointed weather radars. The resulting data sets comprise 100s of thousands of updrafts and thousands of clouds, which far exceeds previous efforts, and thereby provides a robust statistical and physical representation of these processes.

From these large datasets the project produced a sequence of scientific analyses that: (1) Elucidate how variations in the turbulent structure of the convective boundary layer control shallow cumulus convection, (2) Quantify the upward transport of water vapor to cloud base via thermals and plumes, (3) Validate large-eddy simulations of updrafts and shallow convective clouds, (4) Demonstrate a size-to-strength relationship between updraft width and updraft speed, and (5) Demonstrate how updrafts interact with the stability at the top of the convective boundary layer to modulate the depth and vigor of convective clouds. These results have been disseminated via several published journal articles, academic theses, and conference presentations. Collectively these results contribute to the Atmospheric System Research (ASR) program's goal to "improve understanding of the key cloud, aerosol, precipitation, and radiation processes that affect the Earth's radiative balance and hydrological cycle, particularly processes that limit the predictive ability of regional and global earth system models"

2. PROJECT ACTIVITIES:

2.1 Project Goals:

The goals of the project, as listed in the original proposal, were:

G1: to advance our fundamental understanding of the boundary-layer controls on cumulus convection.

G2: to improve the physical basis for testing and refining mass-flux and probability density function (PDF) closures for convective parameterizations.

In pursuit of these goals we used observations from the Atmospheric Radiation Measurement (ARM) program on days with varying convective cloud cover to examine the following science questions:

Q1: How does the turbulent structure of the boundary layer vary across the transition from shallow to deep convection?
Q2: How do sub-cloud circulations affect the vertical and horizontal extent of cumulus clouds?
Q3: What are the relationships between bulk boundary layer statistics and cloud base updrafts?
Q4: Do observations support CIN-based mass flux closures?
Q5: Do observations support the PDF based closures assumed in CLUBB?

These questions and the overarching goals were answered and addressed through a sequence of scientific analysis, a summary of which follows.

2.2 Project outcomes:

The goals of this project were completed via a sequence of presentation and publications, including two MS thesis manuscripts. Each of these documents address a portion of the goals or a subset of the scientific questions delineated above. Below is a description of each of the publications (i.e., the abstract) accompanied by a summary of how it addresses the project goals.

2.2.1. Published Papers:

(1) Lareau, N. P. (2020). Subcloud and Cloud-Base Latent Heat Fluxes during Shallow Cumulus Convection. *Journal of the Atmospheric Sciences*, *77*(3), 1081-1100.

Abstract: Doppler and Raman lidar observations of vertical velocity and water vapor mixing ratio are used to probe the physics and statistics of subcloud and cloud-base latent heat fluxes during cumulus convection at the ARM Southern Great Plains (SGP) site in Oklahoma, United States. The statistical results show that latent heat fluxes increase with height from the surface up to ~0.8Zi (where Zi is the convective boundary layer depth) and then decrease to ~0 at Zi. Peak fluxes aloft exceeding 500 W m^{-2} are associated with periods of increased cumulus cloud cover and stronger jumps in the mean humidity profile. These entrainment fluxes are much larger than the surface fluxes, indicating substantial drying over the 0–0.8Zi layer accompanied by moistening aloft as the CBL deepens over the diurnal cycle. We also show that the boundary layer humidity budget is approximately closed by computing the flux divergence across the 0–0.8Zi layer. Composite subcloud velocity and water vapor anomalies show that clouds are linked to coherent updraft and moisture plumes. The moisture anomaly is Gaussian, most pronounced above 0.8Zi and systematically wider than the velocity anomaly, which has a narrow central updraft flanked by downdrafts. This size and shape disparity results in downdrafts characterized by a high water vapor mixing ratio and thus a broad joint probability density function (JPDF) of velocity and mixing ratio in the upper CBL. We also show that cloud-base latent heat fluxes can be both positive and negative and that the instantaneous positive fluxes can be very large (~10 000 W m−2). However, since cloud fraction tends to be small, the net impact of these fluxes remains modest.

Contribution to project goals: This paper uses co-located Doppler and Raman lidars to provide novel quantification of the vertical water vapor transport via boundary layer updrafts. It addresses **G1** by advancing our fundamental understanding of CBL processes impacting cloud processes and

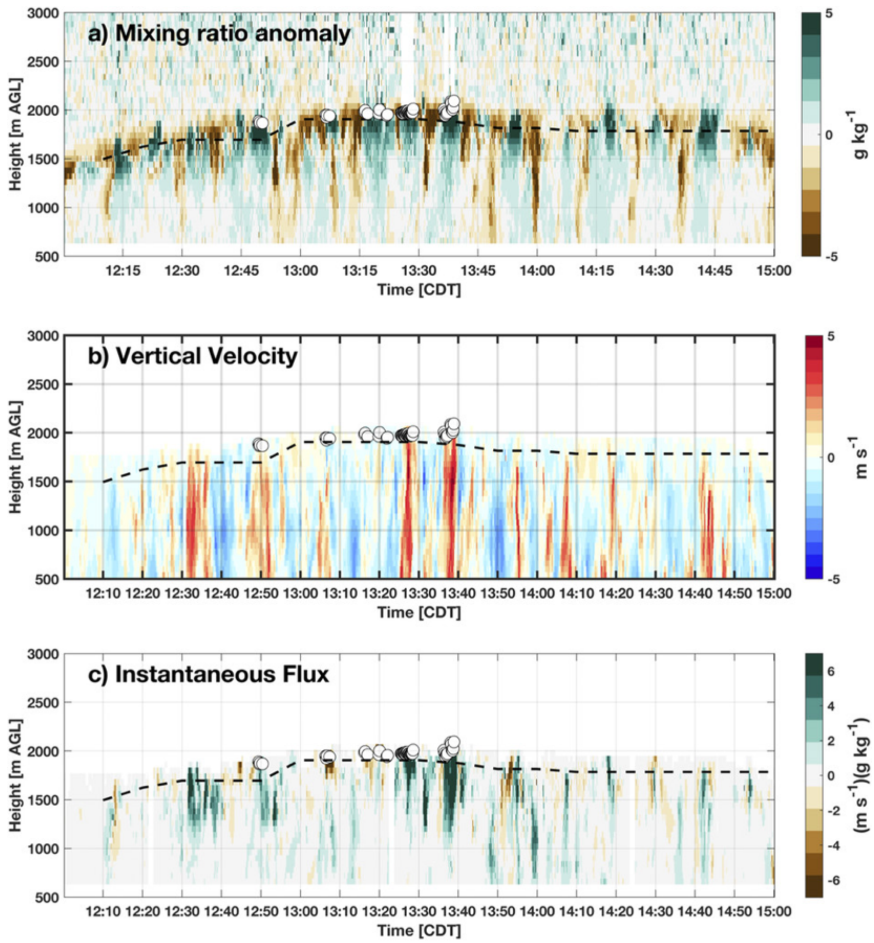

Figure 1 Example of data used in flux computation. (a) The 30-min-mean water vapor mixing ratio anomalies from the adaptively filtered RL data. (b) Vertical velocity anomalies from the Doppler lidar. (c) Instantaneous kinematic water vapor flux. Shown in each panel are the CBL heights (dashed line) and cloud-base detections (filled white circles).

G2 by providing a technique and data set that can be used to compare with model predictions of water vapor flux (see Fig. 1). This paper also addresses **Q2** by linking subcloud circulations (i.e., updrafts and water vapor flux) to cloud cover and **Q5** by examining the joint-probability density function (JPDF) of vertical velocity and water vapor, such as predicted in some subgrid-scale parameterizations (e.g., CLUBB).

(2) Griewank, P. J., Heus, T., Lareau, N. P., & Neggers, R. A. (2020). Size dependence in chord characteristics from simulated and observed continental shallow cumulus. *Atmospheric Chemistry and Physics*, *20*(17), 10211-10230.

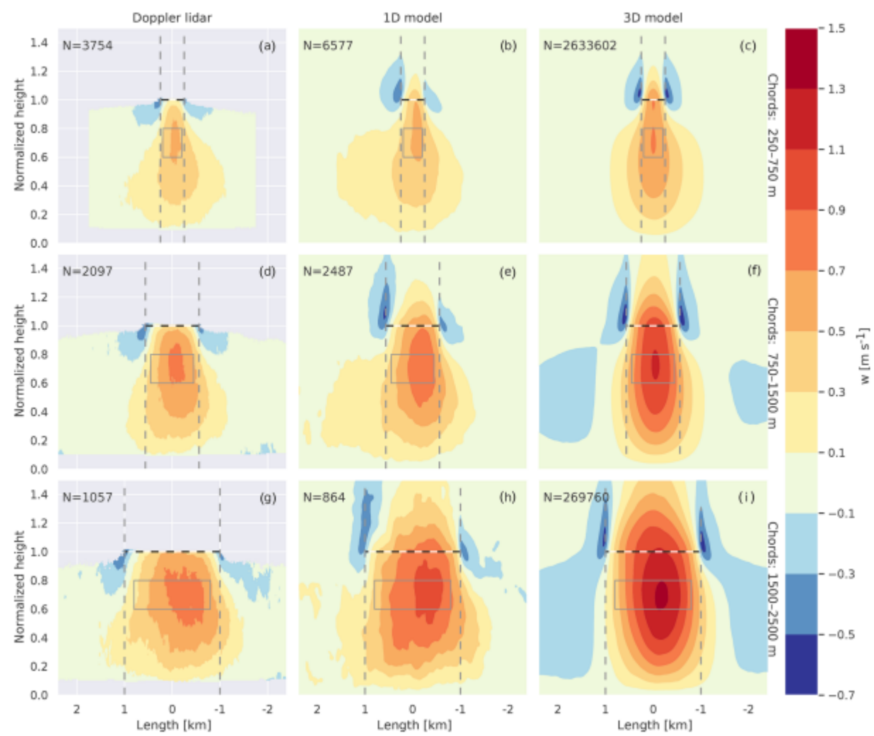

Figure 2. Normalized vertical velocity scenes from Doppler lidar observations (a, d, g), 1D column output (b, e, h), and 3D snapshots (c, f, i). The scenes are composites of the normalized scenes binned by chord lengths of 250–750 m (a, b, c), 750–1500 m (d, e, f), and 1500–2500 m (g, h, i). After merging the scenes the normalized length is rescaled to match the mean length of the bin (e.g., 500 m for 250–750 m). The black dashed and white horizontal line marks the chord base, the dashed grey lines the chord beginning and end, and the grey box the area.

Abstract: In this study we compare long-term Doppler and Raman lidar observations against a full month of large eddy simulations of continental shallow cumulus clouds. The goal is to evaluate if the simulations can reproduce the mean observed vertical velocity and moisture structure of cumulus clouds and their associated subcloud circulations, as well as to establish if these properties depend on the size of the cloud. We propose methods to compare continuous chords of cloud detected from Doppler and Raman lidars with equivalent chords derived from 1D and 3D model output. While the individual chords are highly variable, composites of thousands of observed and millions of simulated chords contain a clear signal. We find that the simulations underestimate cloud size and fraction but successfully reproduce the observed structure of vertical velocity and moisture perturbations. There is a clear scaling of vertical velocity and moisture anomalies below the chords with chord size, but the moisture anomalies are only 1 %–2 % higher than the horizontal mean values. The differences

between the observations and simulations are smaller than the difference in sampling the modeled chords in time or space. The shape of the vertical velocity and moisture anomalies from cloud chords sampled spatially from 3D model snapshots is almost perfectly symmetric. In contrast, the chords sampled temporally from the lidar observations and 1D model output have a marked asymmetry, with stronger updrafts and higher moisture anomalies occurring earlier on.

Contribution to project goals: This study combines observations and high resolution simulations (i.e., large-eddy simulations) drawing on a collaboration with other ASR-funded scientists (e.g., R. A. Neggers). The paper advances our understanding of the size-to-strength relationship in boundary layer updrafts, thereby addressing **G1**, and compares model statistics with observations, thereby addressing our goal of providing a physical basis for evaluating model performance (**G2, see Fig. 2**). The paper also contributes to answering **Q2** and **Q3** by examining and comparing both modeled and observed boundary layer updraft and convective boundary layer processes linked to shallow cumulus clouds. More broadly these results inform the size-to-strength relationships employed in some parameterizations for turbulent and cloud processes, such as the Eddy Diffusivity Mass-Flux (EMDF) approach.

(3) Lareau, N. P., Zhang, Y., & Klein, S. A. (2018). Observed boundary layer controls on shallow cumulus at the ARM Southern Great Plains site. *Journal of the Atmospheric Sciences*, *75*(7), 2235-2255.

Abstract: The boundary layer controls on shallow cumulus (ShCu) convection are examined using a suite of remote and in situ sensors at ARM Southern Great Plains (SGP). A key instrument in the study is a Doppler lidar that measures vertical velocity in the CBL and along cloud base. Using a sample of 138 ShCu days, the composite structure of the ShCu CBL is examined, revealing increased vertical velocity (VV) variance during periods of medium cloud cover and higher VV skewness on ShCu days than on clear-sky days. The subcloud circulations of 1791 individual cumuli are also examined. From these data, we show that cloud-base updrafts, normalized by convective velocity, vary as a function of updraft width normalized by CBL depth. It is also found that 63%of clouds have positive cloud-base mass flux and are linked to coherent updrafts extending over the depth of the CBL. In contrast, negative mass flux clouds lack coherent subcloud updrafts. Both sets of clouds possess narrow downdrafts extending from the cloud edges into the subcloud layer. These downdrafts are also present adjacent to cloud-free updrafts, suggesting they are mechanical in origin. The cloud-base updraft data ares ubsequently combined with observations of convective inhibition to form dimensionless ‘‘cloud inhibition’’(CI) parameters. Updraft fraction and liquid water path are shown to vary inversely with CI, a finding consistent with CIN-based closures used in convective parameterizations. However, we also demonstrate a

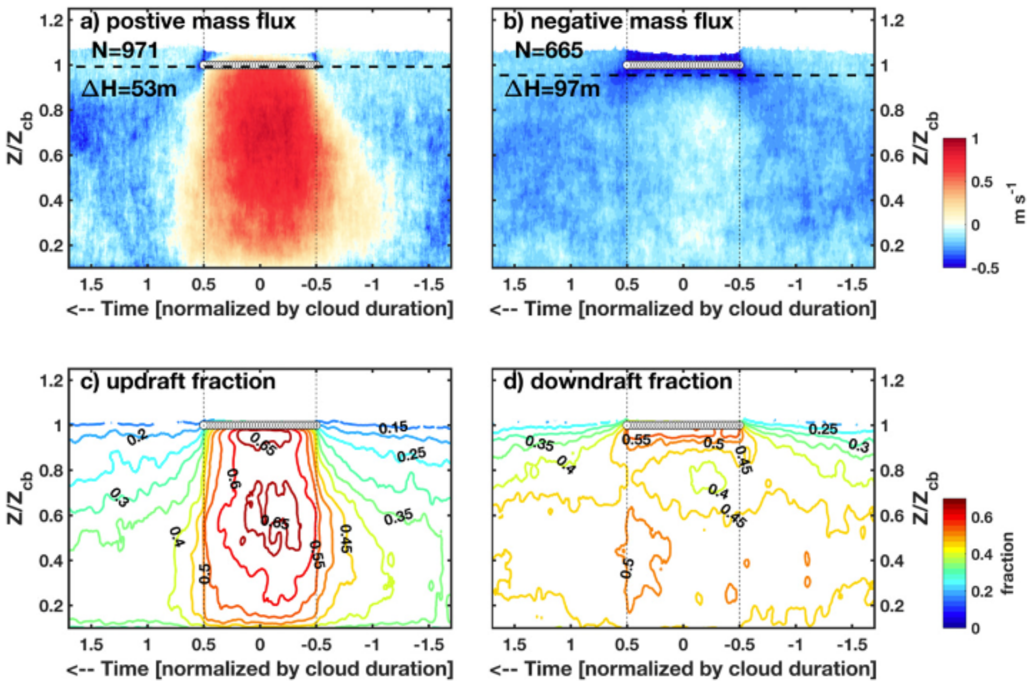

Figure 3. Composite subcloud vertical velocity analysis for (a) positive mass flux clouds and (b) negative mass flux clouds. The height is normalized by cloud-base height (Zcb), and the time is normalized by cloud duration such that all clouds occur between20.5 and 0.5(vertical dashed lines). Time increases to the left. The mean cloud base is indicated in white circles. The mean distance between the cloud-base height and the CBL top (DH) is indicated, and the CBL top is shown as a dashed black line. The number of clouds in each sample (N)is indicated. (c) Updraft and (d) downdraft fraction for positive mass flux and negative mass flux clouds, respectively.

limited link between CBL vertical velocity variance and cloud-base updrafts, suggesting that additional factors, including updraft width, are necessary predictors for cloud-base updrafts

Contribution to project goals: This paper answers, in part, questions **Q1-4**, and contributes to both **G1** and **G2**. For example, the study examines how *CIN*-based closures assumptions help explain the variation in shallow cloud depth. This is accomplished with lidar and radiometer observations that characterize updraft strength and stratification, respectively. The paper also establishes that updraft strength varies with updraft width. The analytic approaches used to create composite updrafts in this paper (e.g., Fig. 3) have since contributed to a number of related publications.

2.2.2. Papers In Review:

(1) Keene, C., and N. P. Lareau (2021): The observed variation of coherent updraft objects with height in the convective boundary layer. *Journal of Applied Meteorology and Climatology* (in revision, initial decision "major revisions")*

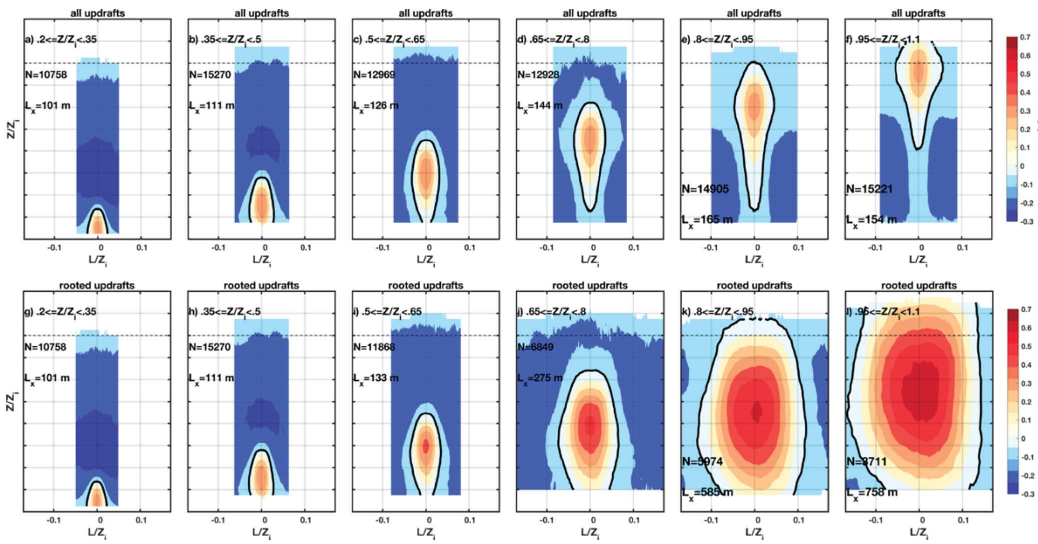

Figure 4. Composite updraft objects for the sample of "all" updrafts (a-f) and the sub-sample of "rooted" updrafts (g-l). In each panel the normalized height bin (Z/Z_i) is shown, as are the sample size (N) and the bin-median chord length (L_x). The shading shows the bin-median vertical velocity (blue is negative, red positive) and the approximate updraft contour (black line).

***note:** this manuscript is derivative of an M. S. Thesis, listed below in impacts on education

***Abstract*:** Buoyant plumes and thermals rising through the convective boundary layer (CBL) modulate the flux of heat, moisture, momentum, and aerosols from the surface to aloft. These fluxes also determine the lower boundary conditions for cumulus development provided that thermals and plumes rise to their condensation level. In coarse resolution climate and weather models these plume fluxes can be represented using "eddy-diffusivity mass-flux" (EDMF) parameterizations, wherein the "mass flux" is accomplished by a spectrum of buoyant plumes. In this study, we analyze the properties of ~100,000 coherent CBL updrafts recorded with a network of five Doppler lidars in Oklahoma, USA on days with clear and cumulus topped CBLs. We present the composite evolution of these updraft objects as a function of height, which reveals a quasi-linear broadening of updrafts as they ascend and the increasing skewness of the updraft strength with height. Interestingly, updrafts that are vertically continuous through the CBL tend to be both stronger and wider than their isolated counterparts. These data also show a strength-to-width relationship in updrafts: wider and taller updrafts are stronger than narrow or shallow updrafts. We also examine updraft sensitivity to the convective velocity scale (w*) and horizontal wind speed (U), finding that periods with large w* and low U yield the strongest updrafts. Finally, we examine the diurnal variation and environmental controls on the updraft fraction, finding that large w* yields large updraft fractions and upward mass flux. These results will help inform the representation of updrafts parameterizations of CBL and cloud layer processes.

Contribution to project goals: This paper establishes the statistical distribution (i.e., probability density functions (PDFs)) of updrafts in the subcloud layer using >100,000 Doppler lidar updraft observations. From these data we are able to examine how updrafts properties vary with height (e.g., Fig. 4), how updraft width and strength are related, and how updrafts vary with environmental conditions, including surface heat fluxes and wind speed. These results directly address goal **G1**, and questions **Q2,3** and contribute to **Q5**. These results also contribute to **G2** by providing robust statistics which can be used to validate and refine convective parameterizations.

(2) Daub, B. , and N. P. Lareau (submitted 2021): Boundary Layer Controls on Continental Cumulus Clouds. *Journal of Applied Meteorology and Climatology* (in review, submitted November 2021). *

***note:** this manuscript is derivative of an M. S. Thesis, listed below in impacts on education

Abstract:
In this study we examine the boundary-layer controls on the shallow to deep cumulus transition by differentiating boundary layer properties on the basis of convective outcomes, ranging from shallow to deep, as observed at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site in Oklahoma, USA. Doppler lidar, radar, and radiosonde data are combined to determine statistical differences in boundary layer and cloud layer properties using a large sample (236) of days with a range of convective outcomes: shallow, congestus, and deep convection. In these analyses, the radar characterizes diurnal cloud depth, the lidar quantifies updraft and downdraft properties in the subcloud layer, and daily radiosonde data provides the convective inhibition (CIN). Combined, these data are used to test the hypothesis that deep convection occurs when the strength of the boundary layer turbulence (i.e., TKE) exceeds the strength of the energy barrier (i.e., CIN) at the top of the CBL. Results show that days with deep convective clouds have significantly lower vertical velocity variance and weaker updrafts within the subcloud layer. However, CIN values are also found to be significantly lower on deep convective days, allowing for these weaker updrafts to penetrate the energy barrier and reach the level of free convection (LFC). In contrast, shallow convective outcomes occur when the updrafts are strong in an absolute sense, but are weak when compared to the strength of the energy barrier. These findings

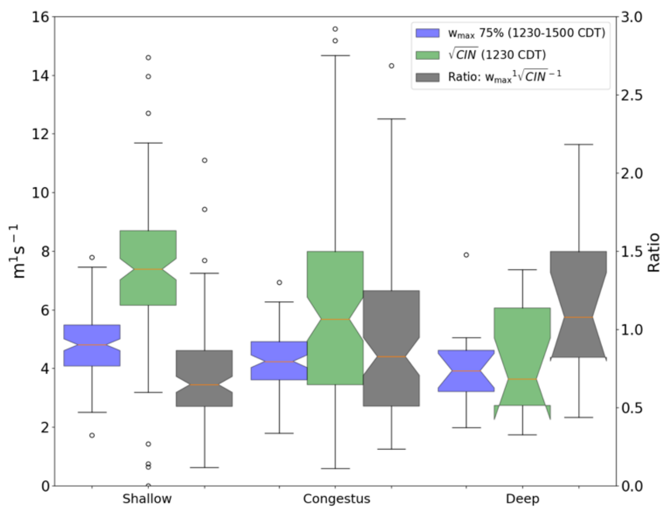

Figure 5. Comparing 75% of maximum updrafts between 1230-1500 CDT (blue boxplot) and $\sqrt{CIN}$ (green boxplot) from 1230 CDT radiosondes between different cloud depth categories. The 2nd y-axis and black boxplots display the ratio between the two datasets. Boxplot notches are used to help determine the significance of difference between the medians of the same variable between different cloud depth categories. Boxplot notches that do not overlap provide a statistically significant difference between the medians. $\sqrt{CIN}$ for deep convective days displays a boxplot that has a wider notch than lower interquartile range.

support the use of the CIN/TKE framework in parameterizing convection in coarse resolution models.

Contribution of project goals*:* This paper examines the variations in boundary layer processes as they are linked to different convective outcomes, ranging from shallow non-precipitating clouds to deep, heavily-precipitating clouds. It directly answers **Q1** and **Q4**. We answer **Q4** by by comparing lidar-derived updrafts, radiosonde stratification data (i.e., *CIN*), and radar-based convective outcomes. These results show that deeper clouds occur when updrafts become strong *relative* to the *CIN*, but that updrafts linked to deep clouds tend to be weaker than those driving shallow clouds (See Fig. 5). **Q1** is answered by comparing bulk statistics for the turbulent structure of the CBL spanning days with different convective outcomes. These data show that the CBL is less turbulent on deep convective days, which is a somewhat counterintuitive finding.

2.2.3 Conference and Workshop Presentations:

Lareau, N. P. and C. Keene (2020): How do updrafts vary with height in the subcloud layer? Department of Energy, Atmospheric Systems Research, Joint User Facility and PI Meeting (virtual)

Lareau, N. P. and C. Keene (2019): Subcloud and cloud base vertical velocity and water vapor anomalies during shallow cumulus convection Department of Energy, Atmospheric Systems Research, Joint User Facility and PI Meeting, Rockville, MD

Keene, C., & Lareau, N. (2019, December). The observed variation of updrafts with height in the cumulus topped boundary layer. In AGU Fall Meeting Abstracts (Vol. 2019, pp. A41L-2745).

Daub, B., & Lareau, N. (2019, December). Observations of the shallow-to-deep cumulus transitions at ARM-SGP. In AGU Fall Meeting Abstracts (Vol. 2019, pp. A41L-2744).

Griewank, P. J., Neggers, R., Heus, T., & Lareau, N. (2018, December). Confronting a multi-plume scheme with observations of continental shallow convection. In AGU Fall Meeting Abstracts (Vol. 2018, pp. A21K-2854).

Keene, C. A., & Lareau, N. (2018, December). Lidar Observations of Cold Pool Updrafts and Convective Initiation. In AGU Fall Meeting Abstracts (Vol. 2018, pp. A23L-3048).

Lareau, N. (2018, December). Observations of Updrafts and Water Vapor Anomalies at ARM SGP on Days with Cumulus Convection. In *AGU Fall Meeting Abstracts* (Vol. 2018, pp. A41D-02).

Lareau, N.P., S. Klein*, and Y. Zhang (2018, February): Using Doppler lidar observations of vertical velocity to infer boundary layer controls on shallow cumulus at the ARM

Southern Great Plains Site. The 2nd global atmospheric system studies (GASS) conference, Victoria, Australia. **presenting author*

Lareau, N.P. (2018, March): Boundary layer and cloud layer observations across a network of 5 Doppler Lidars. Department of Energy, Atmospheric Systems Research, Joint User Facility and PI Meeting. Tysons, VA.

2.2.4 Impact on education:

This grant supported two Master of Science (MS) graduate students in the Department of Physics, Atmospheric Sciences Program at the University of Nevada, Reno. Both students successfully completed their degrees in May 2021, including drafting and publicly defending MS theses. Each thesis is now in review with scientific journals. Support for each student included tuition, computing resources, conference travel, and PI mentoring time. Each student developed strong Python coding skills, familiarity with ARM instrumentation and data streams, experience with conference presentations, and manuscript preparation. Following degree completion both students have moved on to Atmospheric Science's research and operations jobs.

The two student MS thesis manuscripts are as follows:

(1) Keene, C. (2021). The observed variation of coherent updraft objects with height in the convective boundary layer (Order No. 28497407). Available from Dissertations & Theses @ University of Nevada Reno; ProQuest Dissertations & Theses Global. (2561875119).

Permanent link: http://hdl.handle.net/11714/7851

(2) Daub, B. J. (2021). Boundary layer controls on cumulus clouds at the ARM southern great plains site (Order No. 28496795). Available from Dissertations & Theses @ University of Nevada Reno; ProQuest Dissertations & Theses Global. (2561926056).

Permanent Link: http://hdl.handle.net/11714/7842

2.2.5 Collaboration with other ASR researchers:

This grant contributed to collaboration amongst ASR researchers. To be specific, the paper

Griewank, P. J., Heus, T., Lareau, N. P., & Neggers, R. A. (2020). Size dependence in chord characteristics from simulated and observed continental shallow cumulus. Atmospheric Chemistry and Physics, 20(17), 10211-10230.

reflects a collaboration amongst a modeling group (Neggers, Heus, and Griewank) and an observational group (Lareau). This collaboration emerged from the annual ASR PI Meeting and reflects the goals of the ASR program to use observations to improve the representation of processes that contribute to uncertainty in earth system models. In this case the collaboration examined the fidelity of model representation of updrafts. As part of this collaboration Dr.

Lareau hosted the lead author and post-doctoral researcher, P. Griewank, for an extended visit at the University of Nevada, Reno.

Additional collaborations include ongoing work with Lawrence Livermore National Laboratories (LLNL), especially using the latent heat flux data described in:

Lareau, N. P. (2020). Subcloud and Cloud-Base Latent Heat Fluxes during Shallow Cumulus Convection. Journal of the Atmospheric Sciences, 77(3), 1081-1100

3. FUNDING ACKNOWLEDGEMENT

The work described in this documented was supported by DE-SC0019124 and via the University of Nevada, Reno.