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Supporting Information for

Sub-cloud turbulence explains cloud-base updrafts for shallow cumulus ensembles: First observational evidence

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Text S1: LASSO data

The Large-Eddy Simulation (LES) Atmospheric Radiation Measurements (ARM) Symbiotic Simulation and Observation (LASSO) project was launched in 2015 by the U.S. Department of Energy's ASR program (Gustafson Jr et al., 2020). Routine large-eddy simulations of shallow convection at ARM's SGP observatory were conducted between 2015 and 2019. One of the core concepts of LASSO is to provide a library of ShCu cases for researchers to conduct composite analysis with statistical robustness. This contrasts with previous LES studies that are limited to only a couple of ShCu cases. In this study, we use all the 18 ShCu cases released in the first two phases (2015 and 2016) of the LASSO. The output from two different models are used: Weather Research and Forecasting (WRF) (Skamarock et al., 2008) and System for Atmospheric Modeling (SAM) (Khairoutdinov and Randall, 2003). Both models were run with resolutions of 100 m in the horizontal and 30 m in the vertical within a domain with a size of 14.4 km. The initial state and the forcing data are the same: balloon-based sounding used as the initial state, large-scale-forcing input obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis averaged over the spatial scale of 114 km, and the homogenized surface fluxes obtained from the ARM Variational Analysis (VARANAL) product. The WRF model used in this study adopted LASSO-Morrison cloud microphysical scheme (Gustafson et al., 2017) whereas the SAM uses the two-moment Bulk scheme (Morrison et al., 2005). Here, we offer additional discussions on two aspects of the LASSO data. First, one may suspect if the horizontal resolution of 100 m is fine enough for studying the vertical velocity (Guo et al., 2008; Donner et al., 2016; Endo et al., 2019). Since this study is focused on the ensemble-averaged vertical velocity, this resolution issue is more or less alleviated. Improving the horizontal resolution to 25 m has a discernable, but not significant, influence on the domain-averaged vertical velocity statistics (Endo et al., 2019). Second, the selection of the specific combinations of large-scale and surface forcing data is purely random. There is no conclusive evidence as to which combination of forcing is superior to others.

We determine the cloud-base height (z_b) as the altitude with the largest cloud cover. At the z_b, we selected cloudy pixels with liquid water greater than 0.01 g m^{-3} to compute the cloud-base updrafts. The averaging routines are the same as those described in Section 3 of the main manuscript. The TKE_{ML} is computed as $0.5 * (u'^2 + v'^2 + w'^2)$ averaged below the z_b. The mixed-layer height, *h*, is determined as the altitude with the most negative buoyancy fluxes. The convective time scale, t^*, is computed as $h/(\mathrm{TKE}_{\mathrm{ML}})^{1/2}$.

Text S2: Comparison between the DL- and LAASO-derived results

As shown in Figure 3a and S4c, d and summarized in Table S1, WRF and SAM show ~ 50% steeper slope of the relationships between the $\overline{w_b}$ and $(\mathrm{TKE}^{w}{}_{\mathrm{M}})^{1/2}$ than that from the DL. We think that the larger slope is likely due to the known problem of LES in overestimating the updrafts near cloud bases (Endo et al., 2019). As shown in Endo et al., (2019), compared with DL observations, the LES tends to shift the probability density function (PDF) of cloud-base vertical velocities toward the positive end. This leads to weaker downdrafts and stronger updrafts at cloud bases. This problem is found to be a consequence of model physics underestimating the evaporative and radiative cooling near cloud bases, processes driving downdrafts. It's reasonable to conjecture that such an effect should be less influential for weaker sub-cloud forcing. As a thought experiment, one may imagine the evaporative cooling to approach zero as the convection gradually shuts off, leaving little chance for the underestimated evaporative cooling to modify the $\overline{w_b}$.

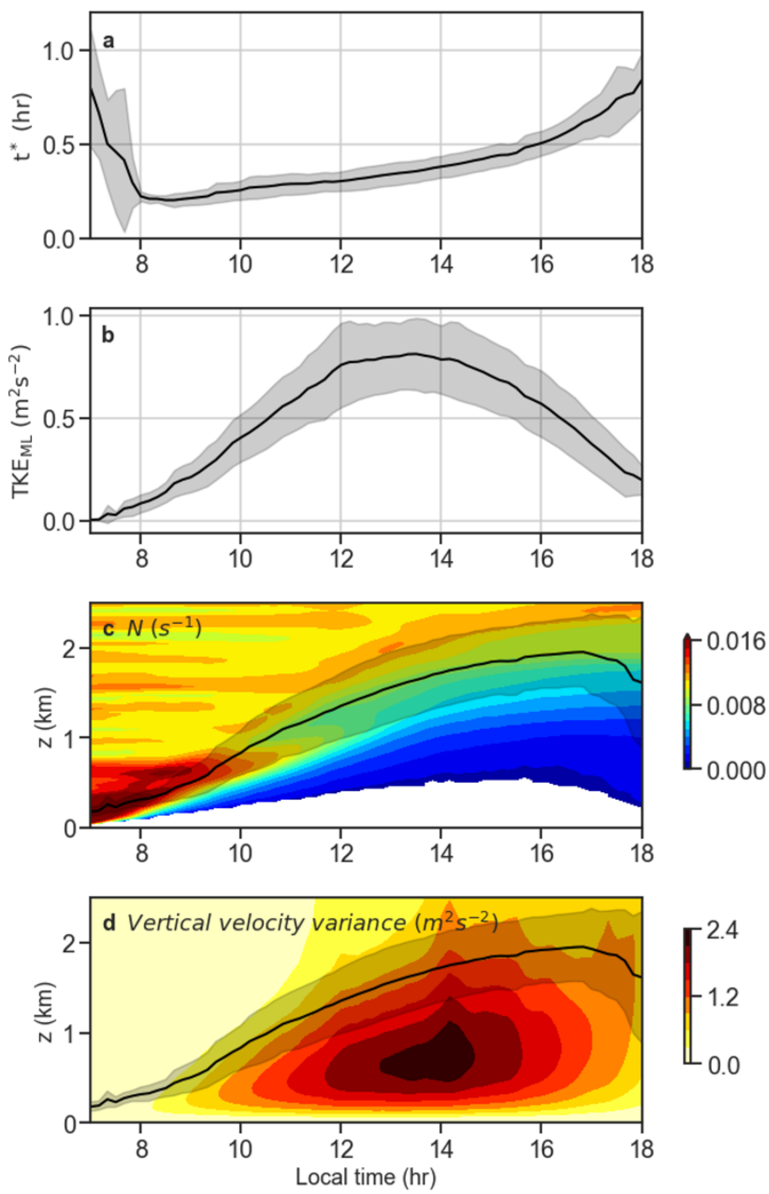

Figure S1: WRF-simulated composite diurnal variations of t^* (a), TKE_{ML} (b), and height-time plots of Brunt-Vaisala frequency (c), and vertical velocity variance (d). In (c) and (d), the black lines mark the diagnosed mixed-layer height (h). All plotted are the composite means of the 18 ShCu cases from the 1st phase of the LAASO project.

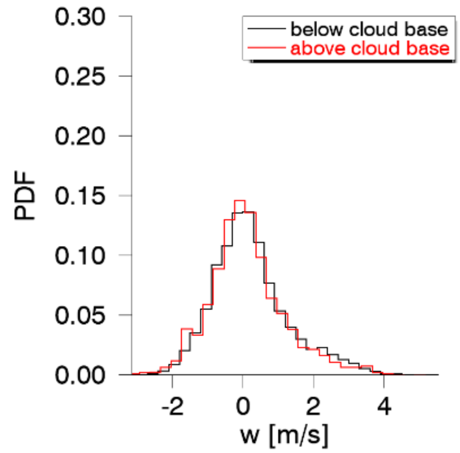

Figure S2: Probability density functions of vertical velocity for pixels at 100 m below (black) and above (red) the cloud bases.

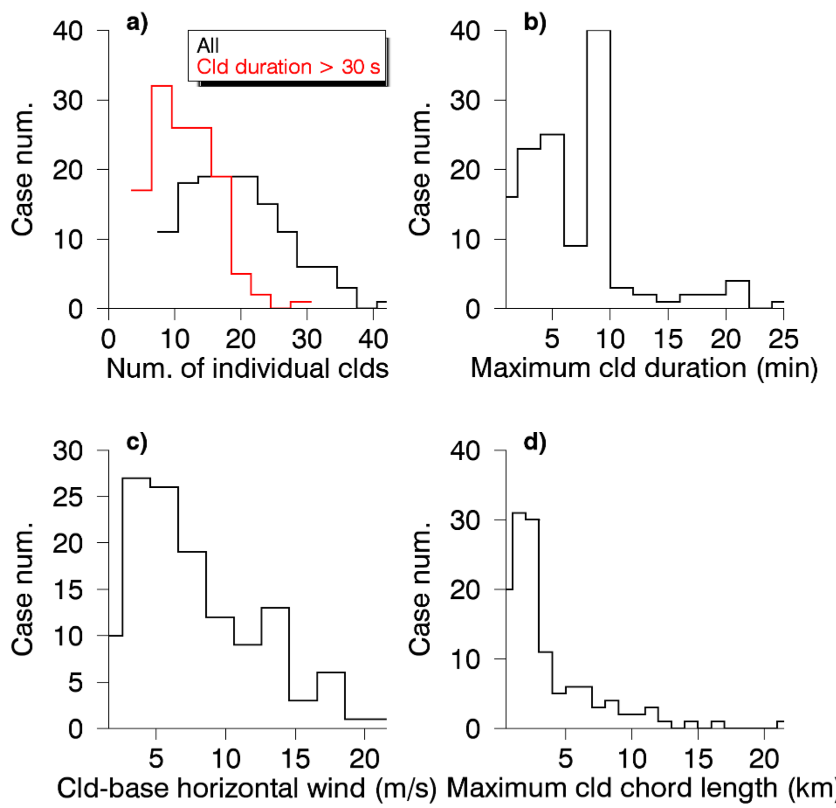

Figure S3: Statistical distribution of key quantities for the 128 ShCu cases including (a) the number of individual cumuli (the red marks those that last longer than 30 secs), (b) maximum cloud duration, (c) horizontal wind speed near cloud base, and (d) maximum cloud chord length.

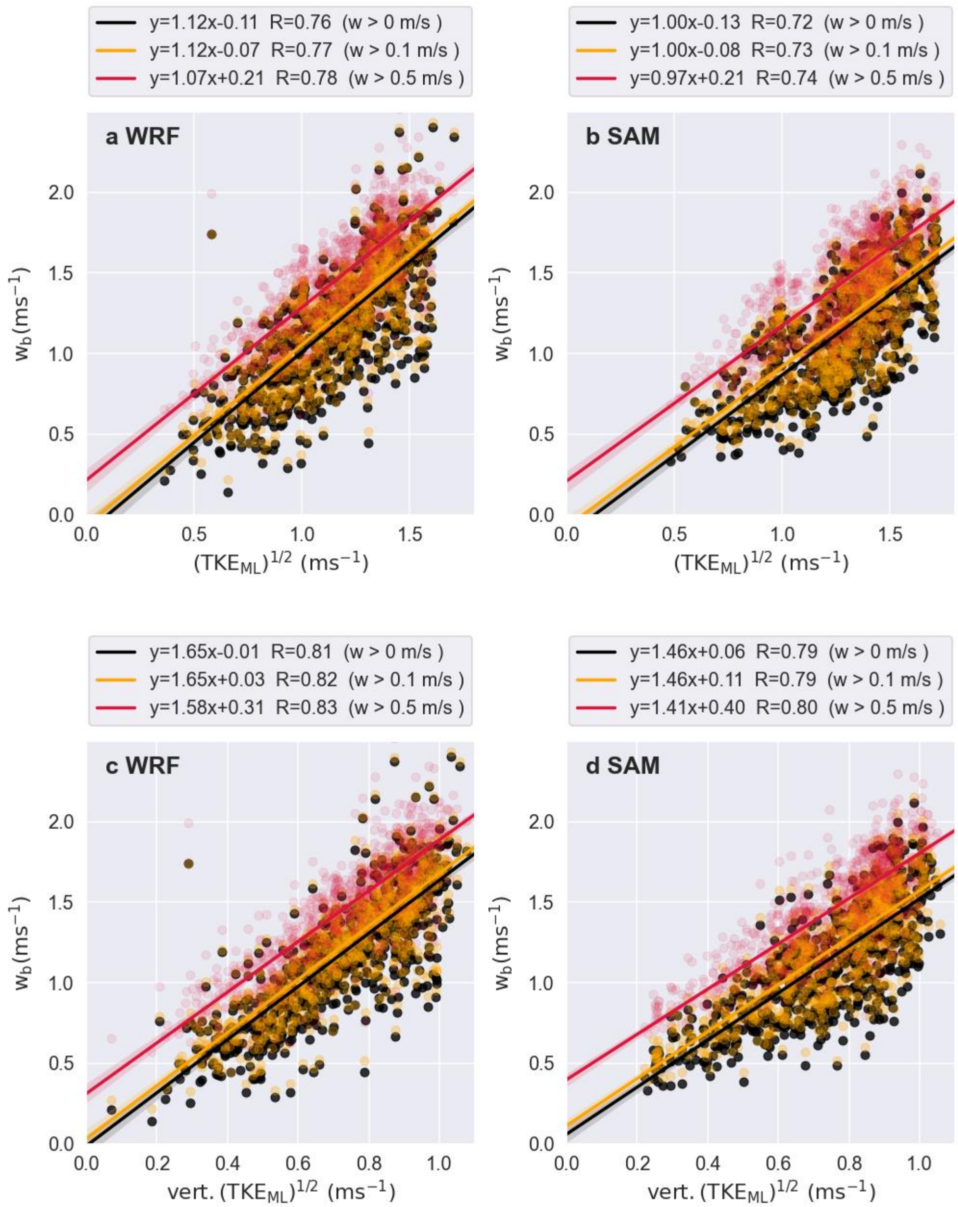

Figure S4: Scatter plots of simulated $\overline{w_b}$ versus $(\mathrm{TKE_{ML}})^{1/2}$ (upper) and $(\mathrm{TKE^{w}_{ML}})^{1/2}$ (bottom), simulated by WRF (left) and SAM (right).

	Slope	Intercept (m/s)	Slope (forced through origin)	Corr.
DL $\overline{w_b}$ (w > 0 m/s)	1.04 ± 0.09	0.11 ± 0.06	1.20	0.73
DL $\overline{w_b}$ (w > 0.1 m/s)	1.04 ± 0.09	0.20 ± 0.06	N/A	0.73
DL $\overline{w_b}$ (w > 0.5 m/s)	0.98 ± 0.10	0.61 ± 0.07	N/A	0.68
DL $\overline{w_b^{vol}}$ (w > 0 m/s)	1.81 ± 0.15	0.22 ± 0.10	2.11	0.74
DL $\overline{w_b^{vol}}$ (w > 0.1 m/s)	1.80 ± 0.15	0.24 ± 0.10	N/A	0.74
DL $\overline{w_b^{vol}}$ (w > 0.5 m/s)	1.64 ± 0.14	0.50 ± 0.10	N/A	0.71
WRF $\overline{w_b}$ (w > 0 m/s)	1.65 ± 0.04	-0.04 ± 0.03	1.63	0.81
WRF $\overline{w_b}$ (w > 0.1 m/s)	1.65 ± 0.04	0.03 ± 0.03	N/A	0.82
WRF $\overline{w_b}$ (w > 0.5 m/s)	1.58 ± 0.04	0.31 ± 0.03	N/A	0.83
SAM $\overline{w_b}$ (w > 0 m/s)	1.46 ± 0.04	0.06 ± 0.03	1.54	0.79
SAM $\overline{w_b}$ (w > 0.1 m/s)	1.46 ± 0.04	0.11 ± 0.03	N/A	0.79
SAM $\overline{w_b}$ (w > 0.5 m/s)	1.41 ± 0.04	0.40 ± 0.03	N/A	0.80

Table S1: Statistics of the relationships between the ensemble-mean cloud-base updrafts and $(TKE^{w}_{ML})^{1/2}$ derived from DL, WRF, and SAM data.

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