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How important is the PBL top representation to shallow cumulus simulations?

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ENERGY

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Introduction

- **Observations show a significant variation of mixed layers across five ARM sites.**
- **LASSO results indicate the importance of large-scale conditions near the PBL top and of improving PBL-top processes for shallow cumulus simulations.**
- **Common Community Physics Package (CCPP) single-column model (SCM) simulations informed by observations explore the strengths and limitations of PBL parameterizations in representing PBL variabilities and PBL-top processes.**

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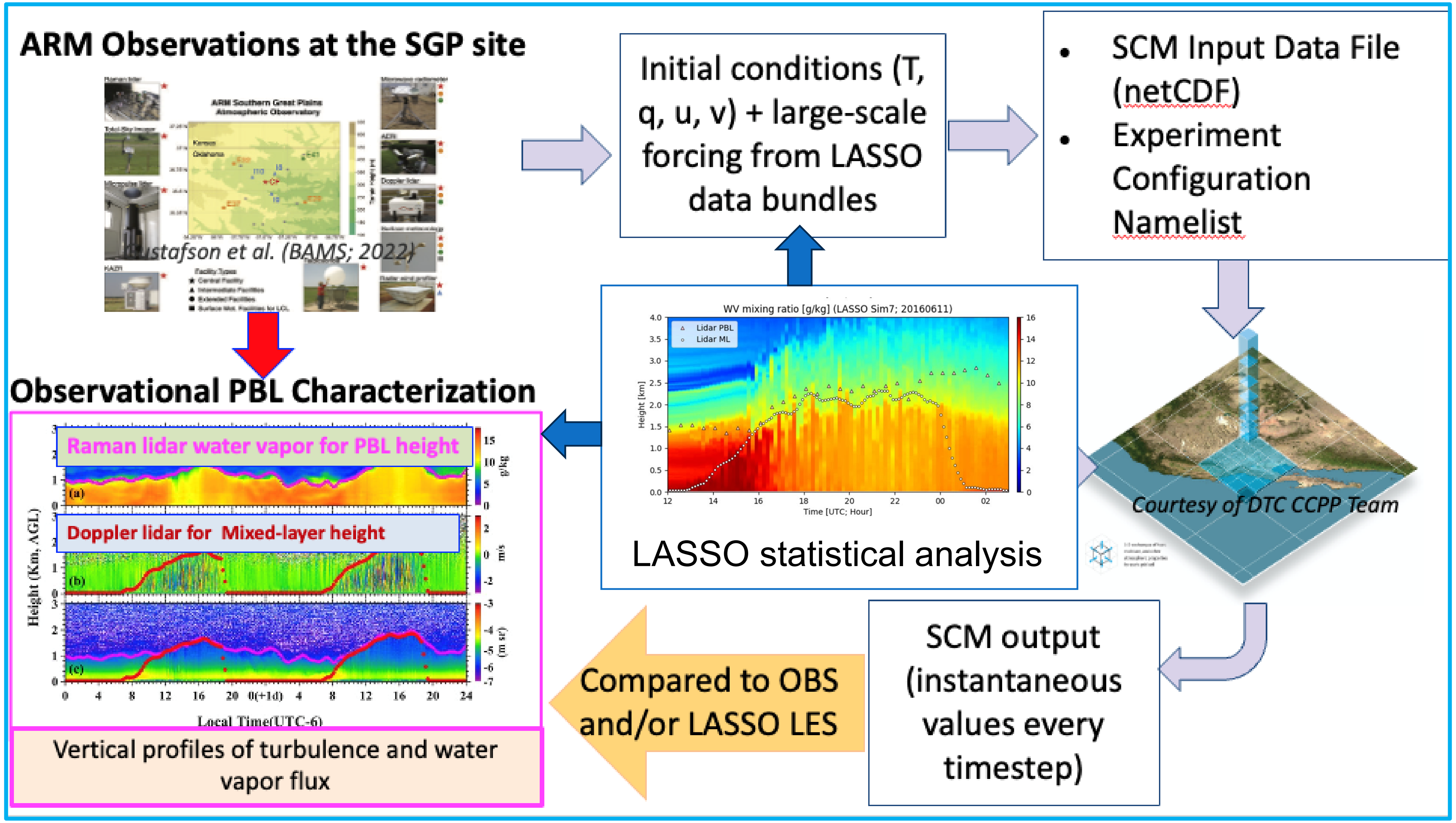
Motivation and Goals

- PBL plays a critical role in the earth system especially in shallow cumulus (ShCu) formation and shallow-to-deep convection transition.
- Observing and modeling PBL processes are still challenging.
- ARM measurements at the SGP supersite and supplemental sites offer great opportunities to study the PBL structure and processes.

- Combine ARM observations, LASSO ensemble simulations, and CCPP-SCM simulations to
  - Characterize PBL structure and variations.
  - Understand factors controlling PBL variations and ShCu development.
  - Identify issues in PBL parameterizations and improve ShCu simulations.

Approach

Synergizing observation analysis, LASSO analysis, and SCM simulations to better understand warm PBL structure and processes, and improve PBL and shallow cumulus simulations



ARM Observations at the SGP site

ustafson et al. (BAMS; 2022)

Observational PBL Characterization

Raman lidar water vapor for PBL height

Doppler lidar for Mixed-layer height

Vertical profiles of turbulence and water vapor flux

Initial conditions (T, q, u, v) + large-scale forcing from LASSO data bundles

- SCM Input Data File (netCDF)
- Experiment Configuration Namelist

LASSO statistical analysis

Courtesy of DTC CCPP Team

SCM output (instantaneous values every timestep)

Compared to OBS and/or LASSO LES

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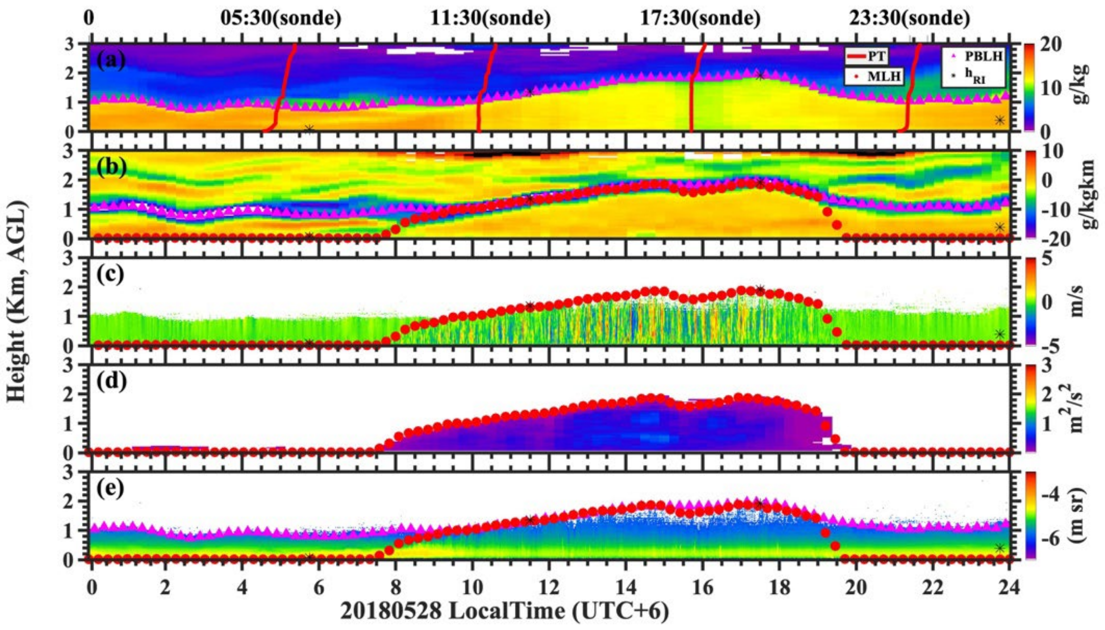
Observation Analysis: SGP Central Site

- Develop a new method using Raman lidar (RL) water vapor mixing ratio (WVMR) for PBL height determinations.
- Develop a new method using Doppler lidar (DL) vertical velocity measurements for mixed layer height (MLH) determinations.

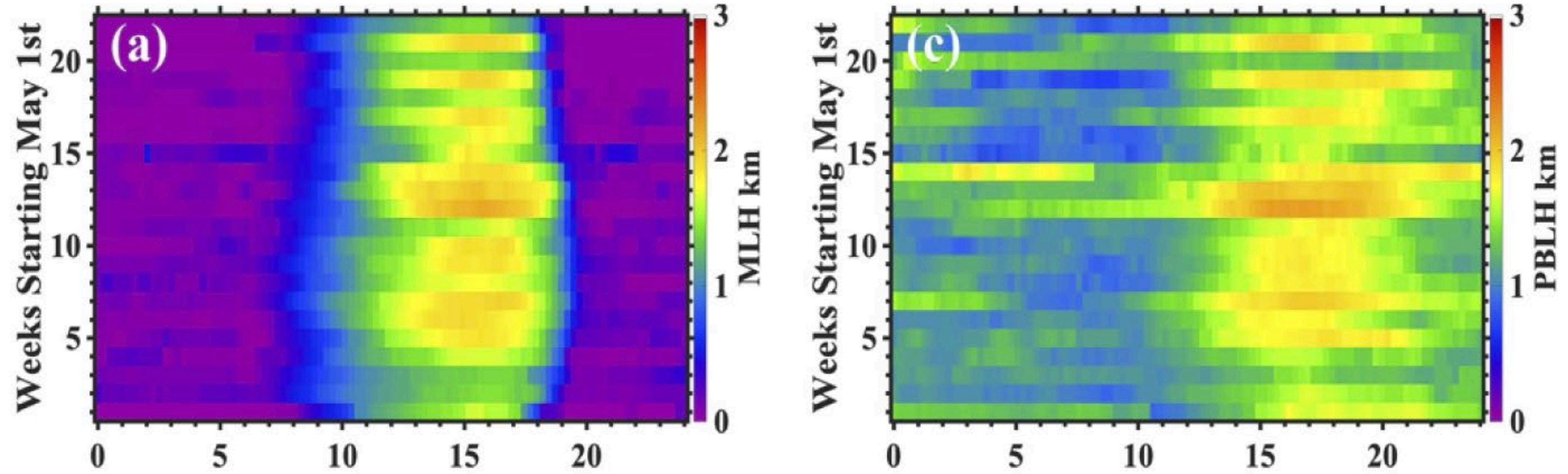
PBL and mixed layer heights (MLH) on May 28, 2018 derived from the developed new approaches. (a) RL WVMR; (b) WVMR vertical gradients; (c) DL vertical velocity; (d) wavelet derived high frequency wave energy; (e) DL aerosol profiles. PBL height and MLH are shown with purple triangles and red dots.



- At the SGP central site, the seasonal and diurnal variations of warm PBL including convective mixed layer can be effectively documented with Raman lidar and Doppler lidar.
- **Noticeable day-to-week variations indicate the control of synoptic weather.**

October 1st

Weekly mean warm PBL under fair conditions



May 1st

Local time (UTC-6)

CHU ET AL. 2022, OPTICS EXPRESS, HTTPS://DOI.ORG/10.1364/OE.45172

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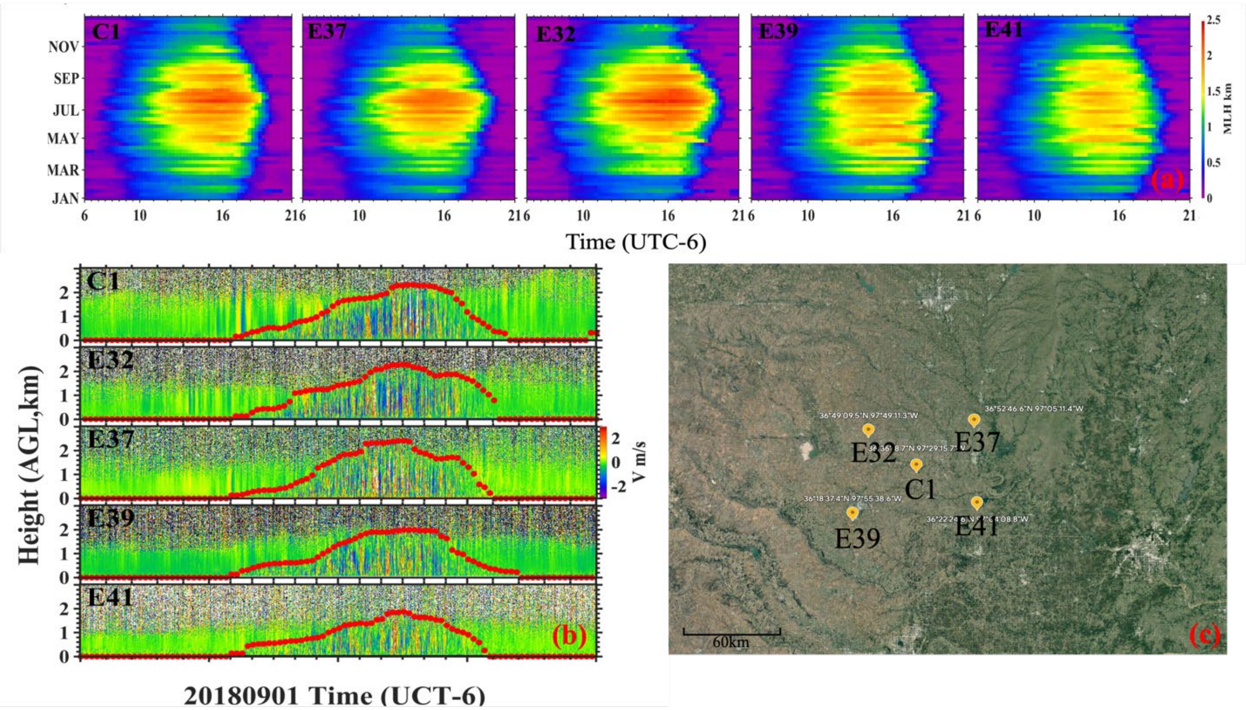
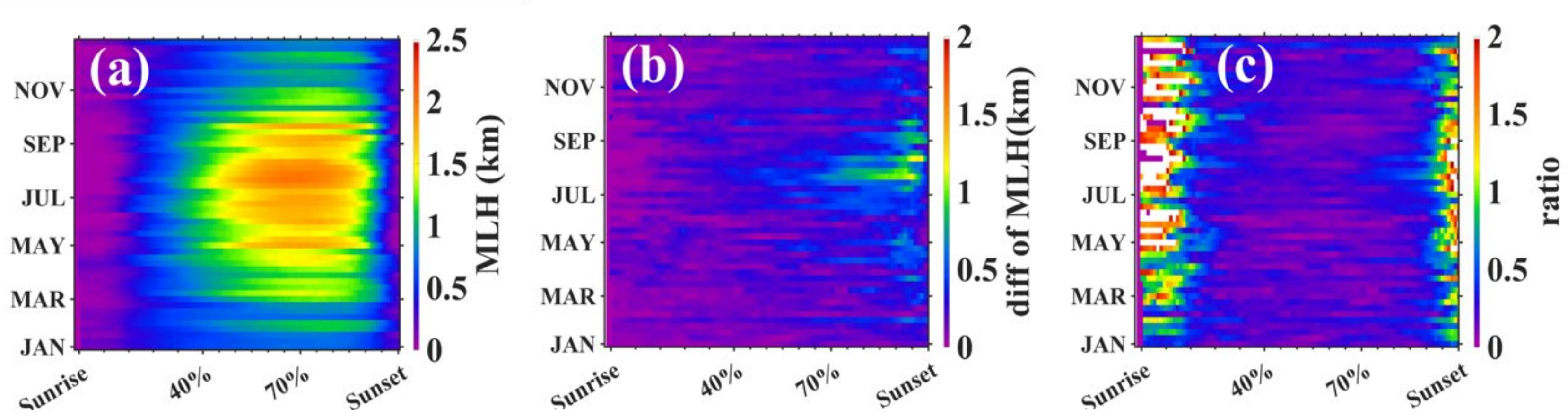
Observation Analysis: Multiple Sites

- MLHs show strong spatial and temporal variabilities.
- The mean MLHs of the northern and central sites are higher than the southern sites.
- Differences in MLHs over the five sites range from 0 to 2 km with a median value over 500 m.
- **Summer season and afternoon have larger intra-site variations.**



(a) Weekly averaged MLH from January to December from 6 to 21 (UTC-6) for each site. (b) The daily MLH was obtained from vertical wind farm data for five sites on the same day. (c) The locations of ARM SGP sites.



(a) The Seasonal-diurnal five sites' mean ML height; (b) Seasonal-diurnal five sites' MLH difference (highest MLH minus lowest MLH); (c) Seasonal-diurnal five sites' MLH difference ratio (highest MLH minus lowest MLH)/mean MLH)

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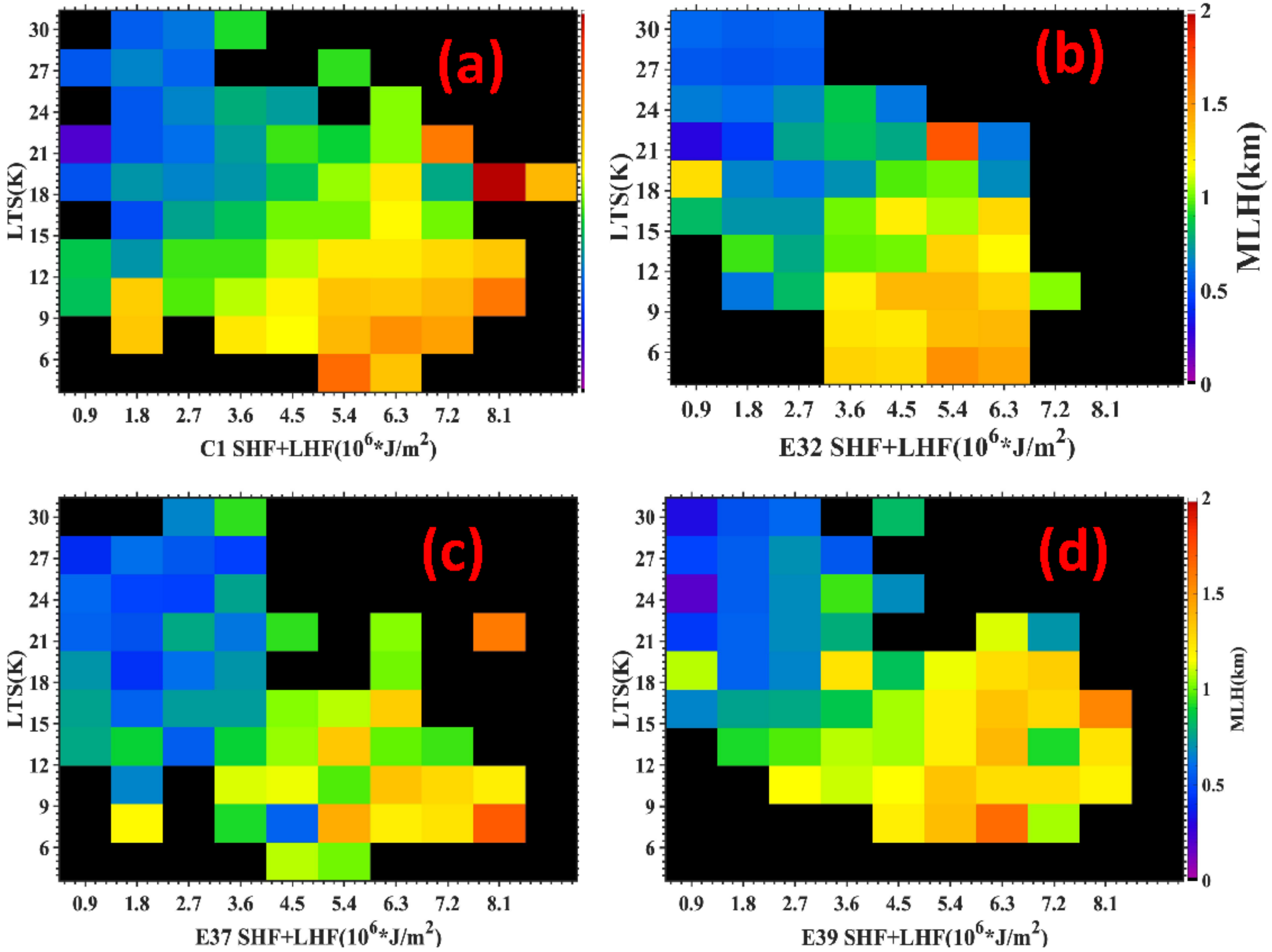
Observation Analysis: Controlling Factors

- MLH depends on the low-tropospheric stability (LTS) given the same energy supply, which indicates that the nocturnal PBL impacts the convective mixed layer development.
- Under the same LTS, the dependencies of MLH on the energy supply vary among sites.
- **The MLH variability along the energy supply (local forcing) seems to be stronger than that along the LTS (large-scale forcing or LSF).**



MLH as a function of total heat flux (SHF+LHF) and LTS for sites C1, E32, E37, and E39 are shown in panels (a-d), respectively. (Site E41 does not have LTS data.)

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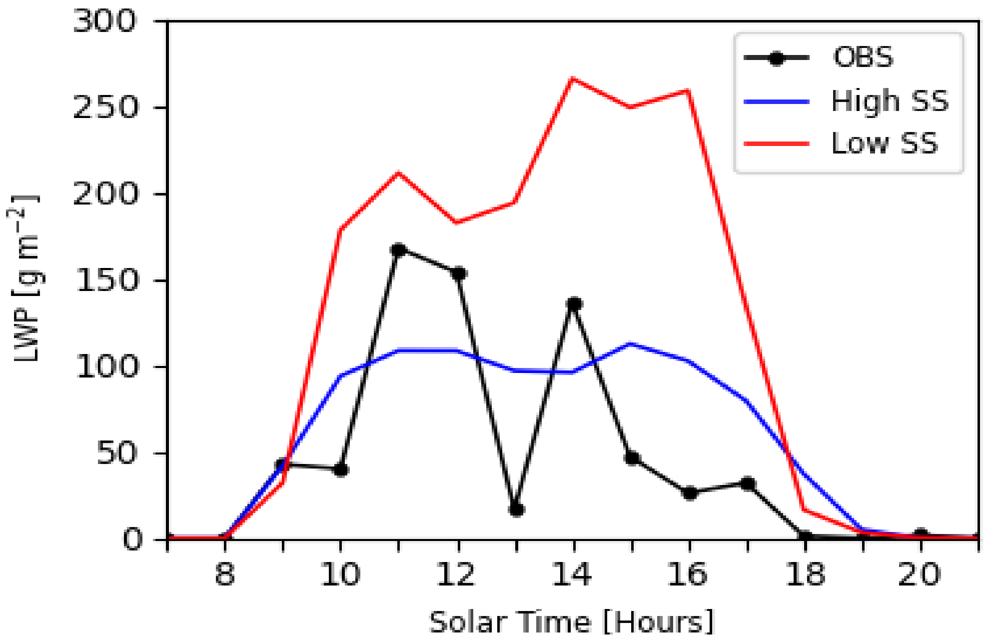
LASSO Analysis: Case Study

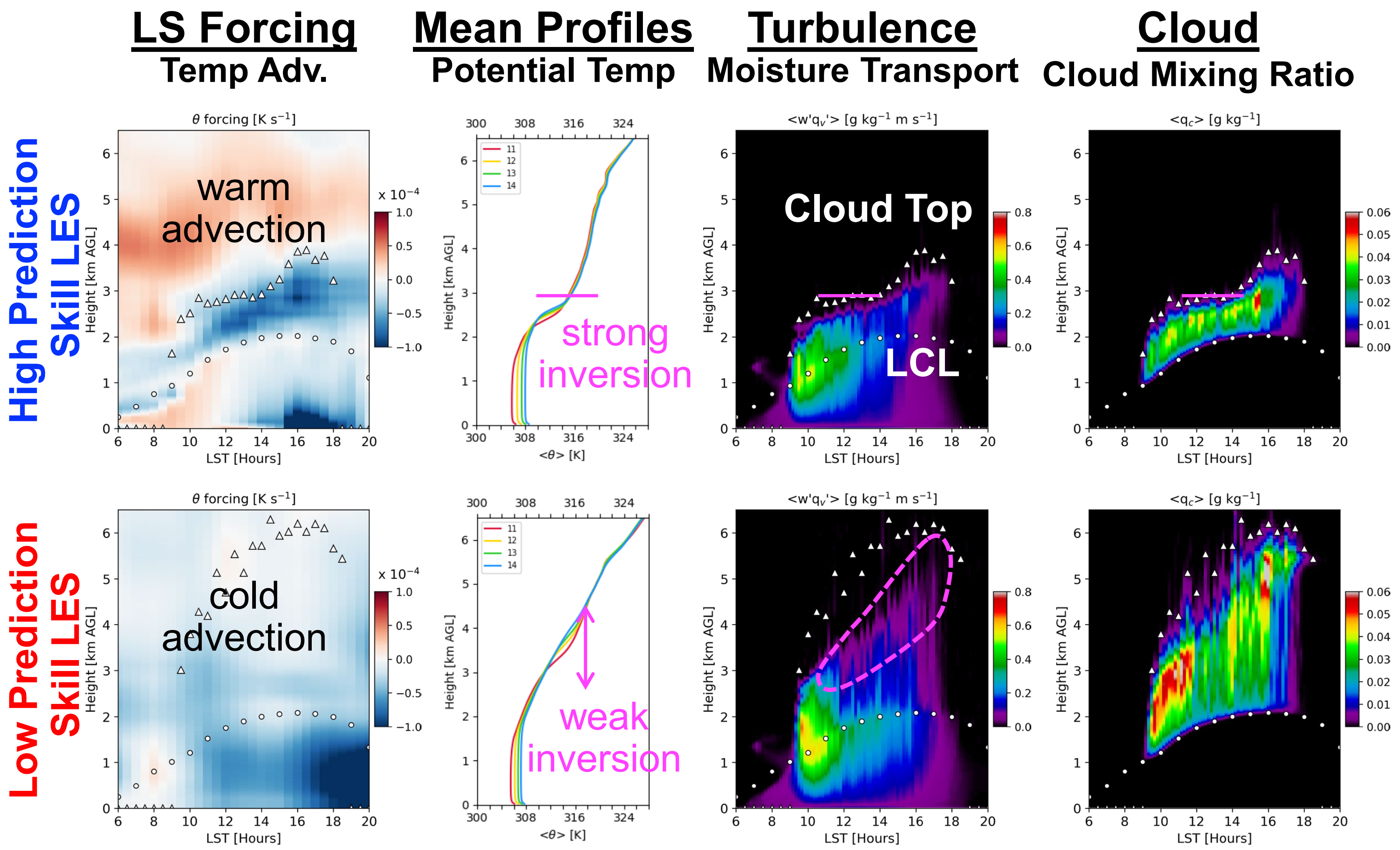
Process-Level Understanding

What are key parameters for successful simulations of ShCu over the SGP?

- **Uncertainty in large-scale forcing (LSF) is carried over to fine-scale simulations** (Gustafson et al. 2020).



Under the same initial and surface conditions but two different LSF, one developed *"false"* precipitating cumulus congestus and overestimated LWP.



LS Forcing
Temp Adv.

Mean Profiles
Potential Temp

Turbulence
Moisture Transport

Cloud
Cloud Mixing Ratio

High Prediction Skill LES

Low Prediction Skill LES

warm advection

strong inversion

Cloud Top

LCL

cold advection

weak inversion

SHIN ET AL. 2021, JGR, HTTPS://DOI.ORG/10.1029/2021JD035208

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LASSO Analysis: Statistical Analysis

Comparison between LES of High vs Low Prediction Skills

What are key parameters for successful simulations of ShCu over the SGP?

Objectives

- **Identify key meteorological parameters for accurate prediction of ShCu**: Comparison of LES grouped by prediction skill
- **Evaluate the performance of different LSF** in predicting the key parameters: Comparison of LES grouped by LSF sources

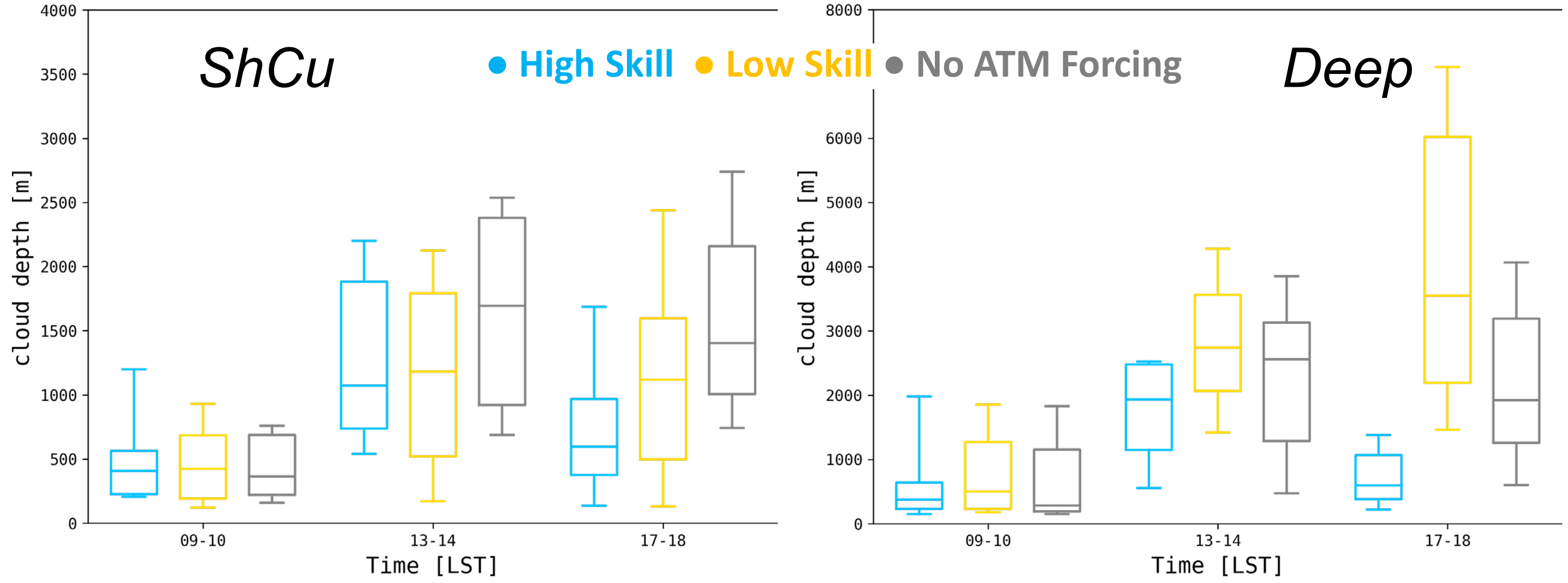
LASSO LES Data

- **84** ShCu Cases observed over the SGP during 2016-2019 warm seasons
- LES driven by **8** LSF sources (including no LSF) for each case

Bulk Cloud Characteristics

[%]	High Skill	Low Skill
Shallow	**91.46**	47.56
Deep	4.88	**29.27**
Clear Sky	0.00	4.88
Misc.	3.66	18.29

Accurate meteorological conditions are needed to capture the ShCu



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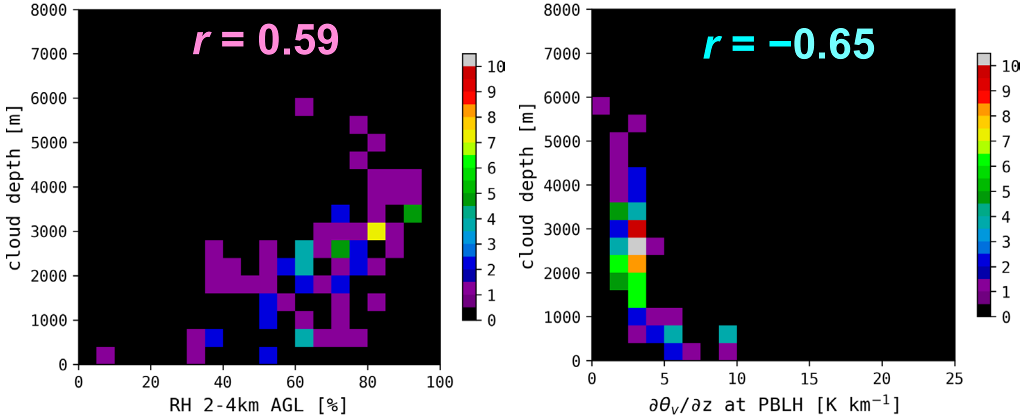
LASSO Analysis: Statistical Analysis

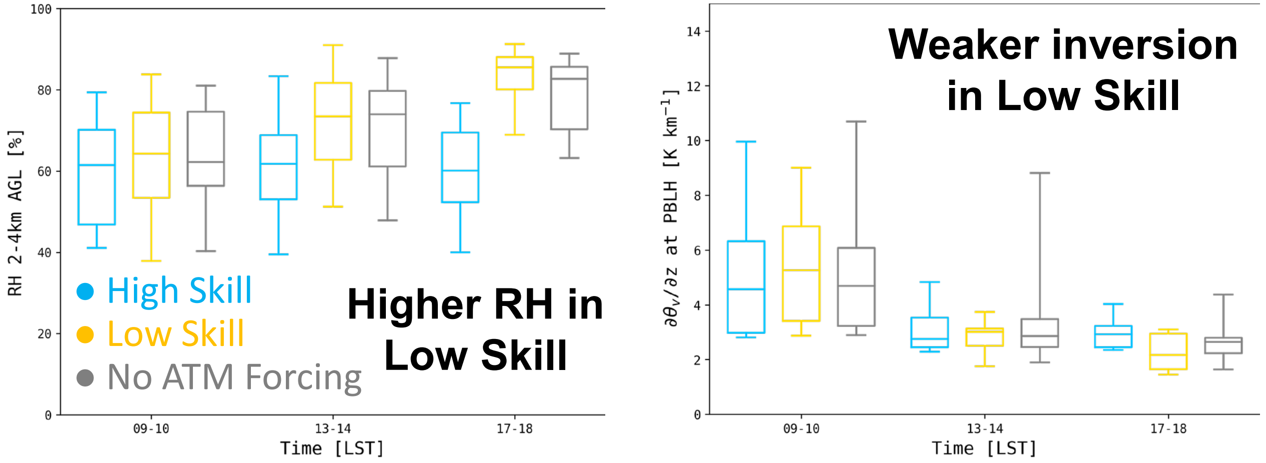
Implications for Parameterization Development

What are key parameters for successful simulations of ShCu over the SGP?

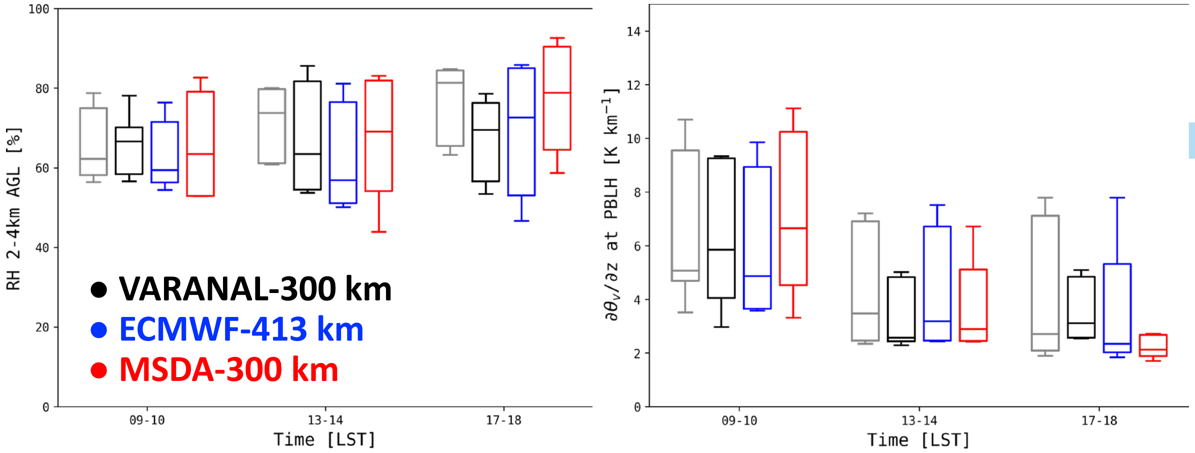
Large Scale Conditions

- The bulk cloud characteristics are highly correlated with **large-scale conditions near or right above the PBL top**, explaining differences between high- and low-skill LES.





Evaluation of the Performance of Different LASSO LSF



[%]	ShCu	Deep
V300	81.71	10.97
E413	76.83	12.19
M300	70.73	**15.85**

MSDA forcing with higher RH above the PBL top and weaker inversion leads to a larger chance of “*false*” Deep Cu.

These results stress the importance of improving PBL-top processes in the model

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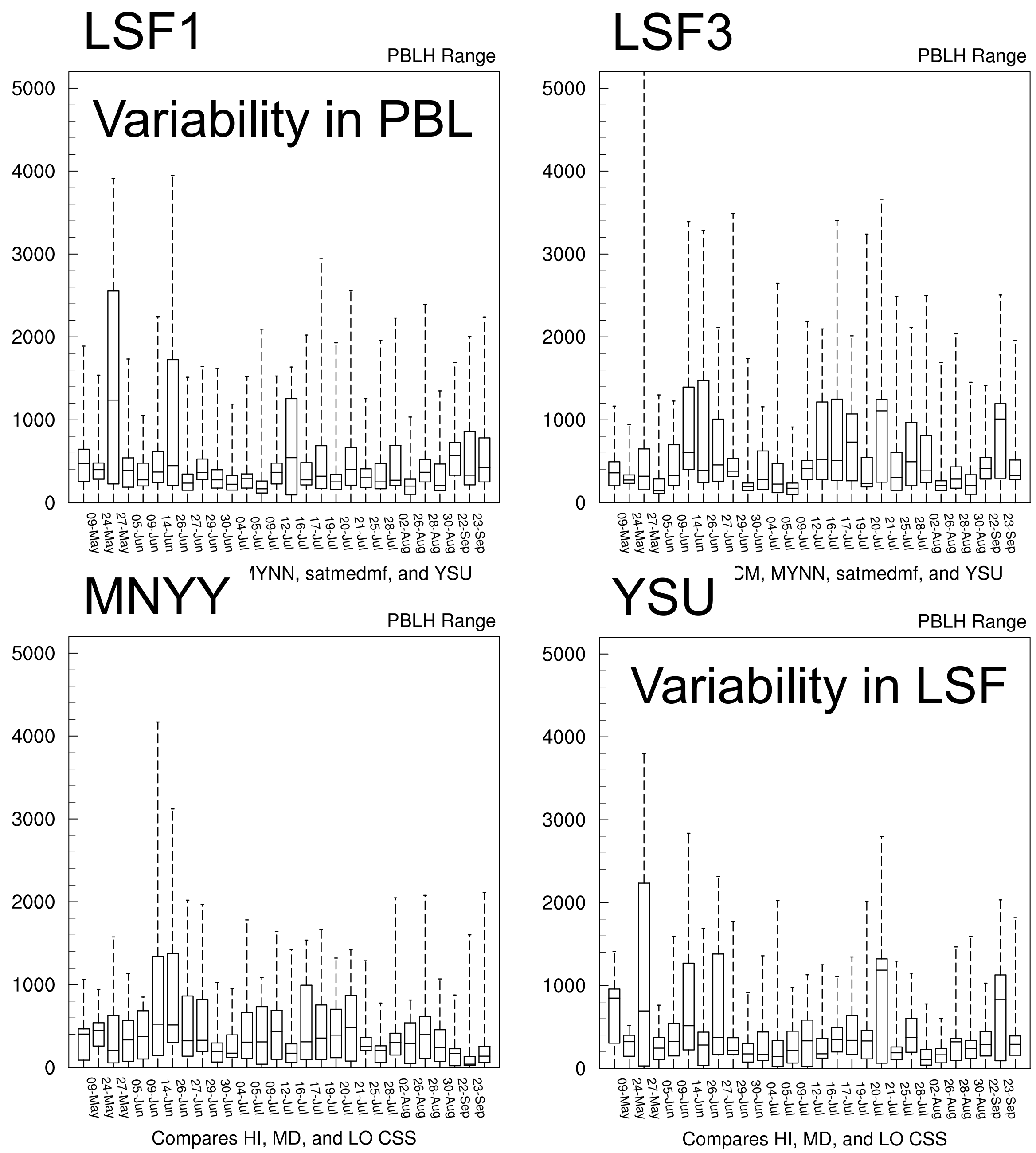
MLH Day-to-Week Variabilities: PBL vs LSF

- Common Community Physics Package
  - CCPP Physics: A library of physics parameterizations
  - CCPP Framework: Software that allows using the CCPP-Physics in a host model
  - CCPP Single Column Model: A host model using the CCPP Physics and Framework
  - Interoperability at the code level / Code management / Hierarchical system development
- CCPP-SCM simulations with different LSFs
  - MYNN, YSU*, ACM2* and SATMEDMF PBL schemes (TKE-based, eddy diffusivity, local/non-local, etc.).
  - 84 LASSO cases with high, middle, and low cloud skill scores (3 LSFs)
  - Driven by observed surface fluxes

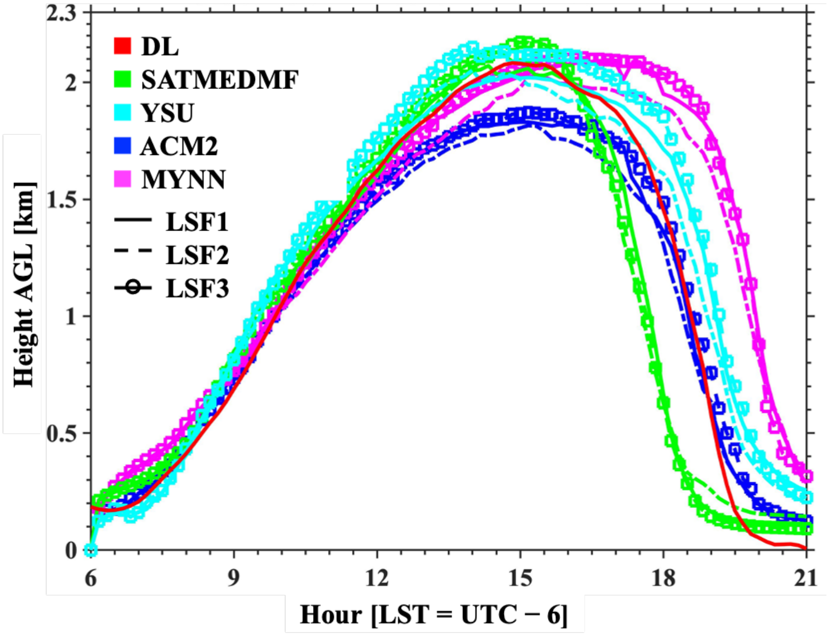
* Were implemented in the CCPP by the team



MLH variabilities in PBL schemes and LSF are similar

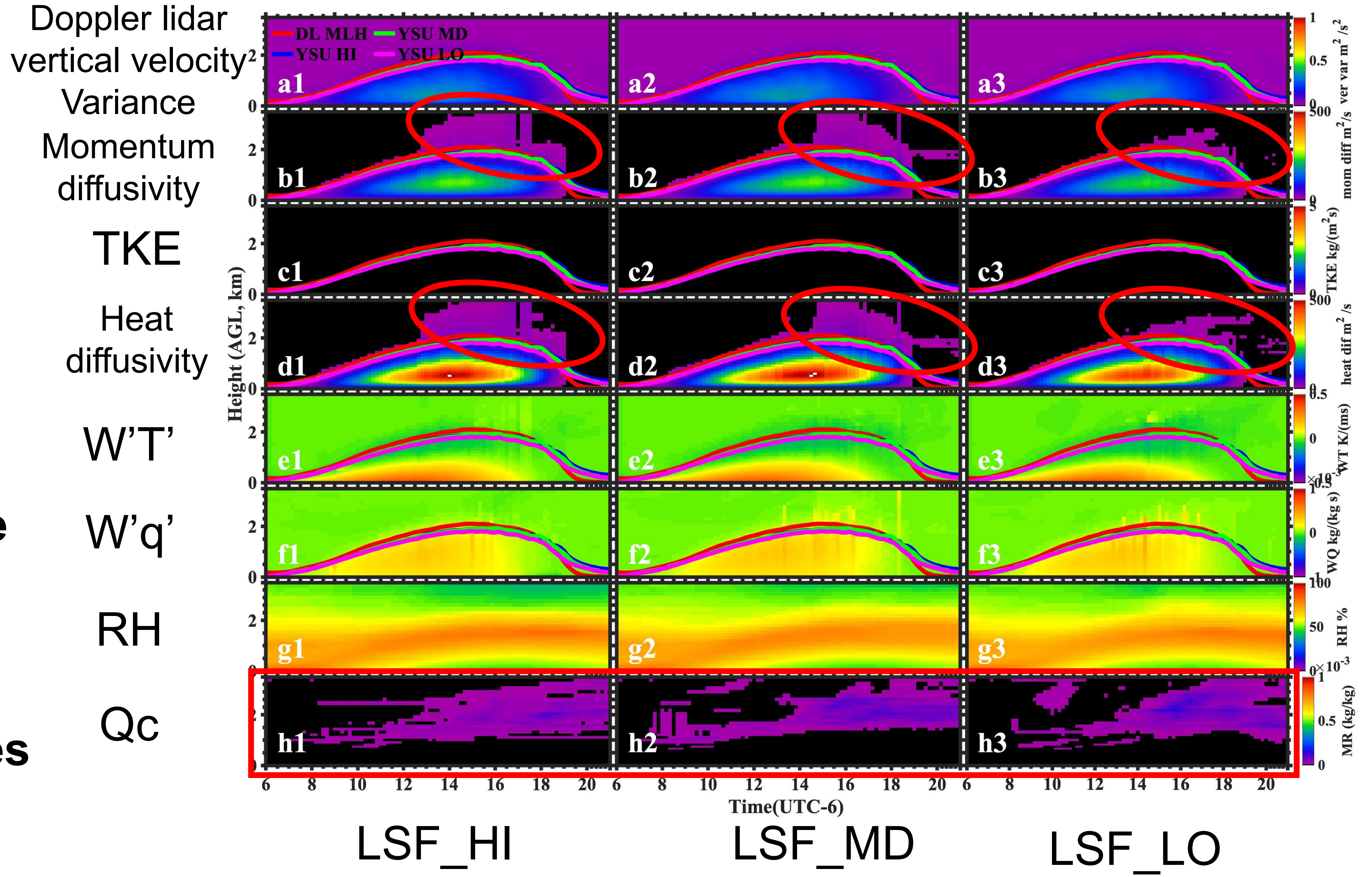
HEINZELLER ET AL. 2023, GMD; XUE ET AL. 2023, IN PREPARATION

MLH Seasonal Statistics: PBL processes



- **The mean MLHs of 4-year LASSO cases are sensitive to PBL schemes mostly in the afternoon but not very sensitive to LSF.**
- **Simulated cloud differences are mainly associated with PBL top entrainment.**

YSU: Non-TKE, non-local



XUE ET AL. 2023, IN PREPARATION

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PBL and Cloud Processes: Entrainment Effect

In YSU, the turbulent diffusion equation when z <= h (MLH) is:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[K_c\left(\frac{\partial C}{\partial z} - \gamma_c\right) - \overline{(w'c')}_h\left(\frac{z}{h}\right)^3\right]$$

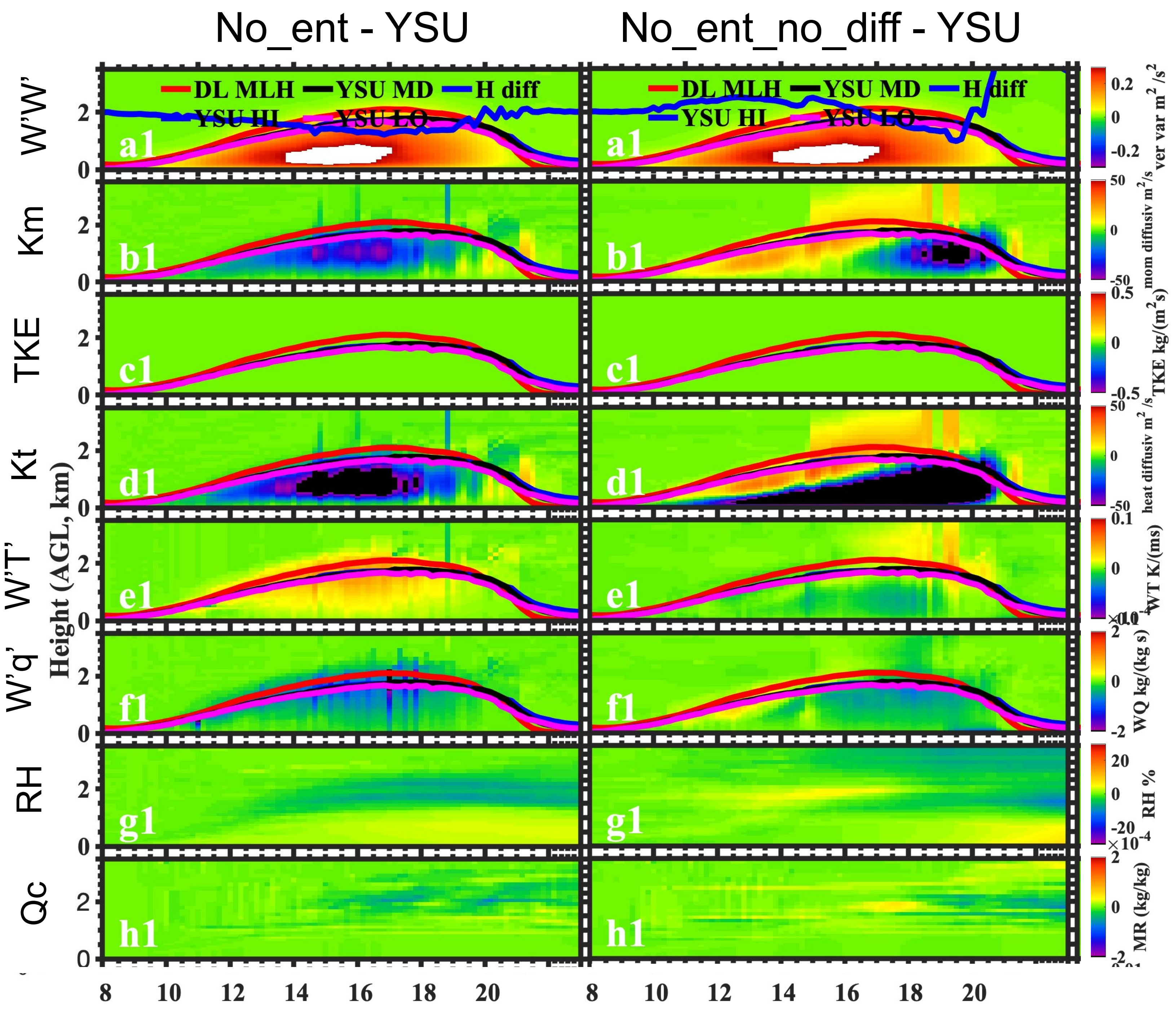
Where $-\overline{(w'c')}(z/h)^3$ is the entrainment flux at the inversion layer.

In the entrainment layer (δ), the diffusion coefficients in the entrainment zones are:

$$K_{t\_ent} = \frac{-\overline{(w'\theta_v')}_h}{(\partial\theta_v/\partial z)_h}\exp\left[-\frac{(z-h)^2}{\delta^2}\right],$$

$$K_{m\_ent} = \Pr_h\frac{-\overline{(w'\theta_v')}_h}{(\partial\theta_v/\partial z)_h}\exp\left[-\frac{(z-h)^2}{\delta^2}\right],$$

Entrainment is critical to ShCu simulation and poorly constrained by observations



XUE ET AL. 2023, IN PREPARATION

Summary: Take Home Messages

- Mixed layer height variability depends on both local and large-scale forcing.
  - LSF strongly impacts MLH on a day-to-week basis (Obs, LASSO, and SCM agree).
  - On the seasonal scale and statistically, **MLH is mostly regulated by the local forcing (total flux) and less so by the LSF** (Obs, LASSO, and SCM agree).
- PBL schemes produced similar MLH evolutions but different shallow cumulus indicating that **MLH observations are not enough to constrain PBL and cloud processes**.
  - Both observations and SCM results show high MLH variability in the afternoon probably due to PBL-cloud interactions.
- Shallow cumulus formation in LASSO simulations is strongly correlated with conditions around the PBL top.
- Entrainment process in PBL schemes has a strong impact on shallow cumulus simulation but is poorly constrained by observations.

ARM is well situated to address this important issue!

THIS WORK IS FUNDED BY DOE THROUGH GRANT DE-SC0020171

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Products and Acknowledgements

Chu et al., 2022, Optics Express.
Chu et al., 2023, GRL (to be submitted).
Li et al., 2023, MWR (to be re-submitted).
Morrison et al., 2020, JAMES.
Muñoz-Esparza et al., 2022, JAMES.
Sarkadi et al., 2022, JAMES.
Shin et al., 2021, JGR-A.
Shin et al., 2023, JGR-A (to be submitted).
Xue et al., 2023, in preparation.

Observational-based MLH and PBLH over SGP sites will be submitted as PI products.

Bug fix in the YSU scheme to handle the calm condition.

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