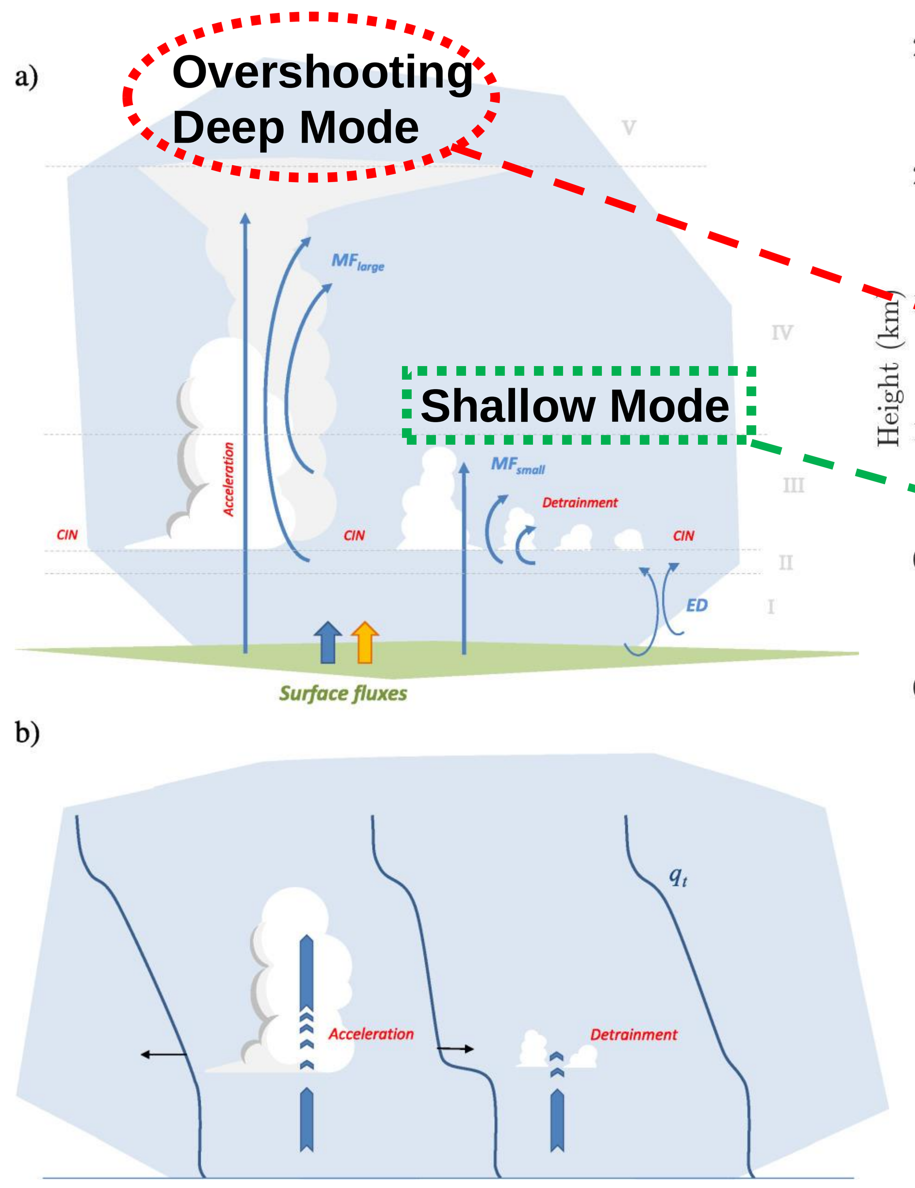
The impact of cloud-scale environmental variability on the shallow cloud size distribution

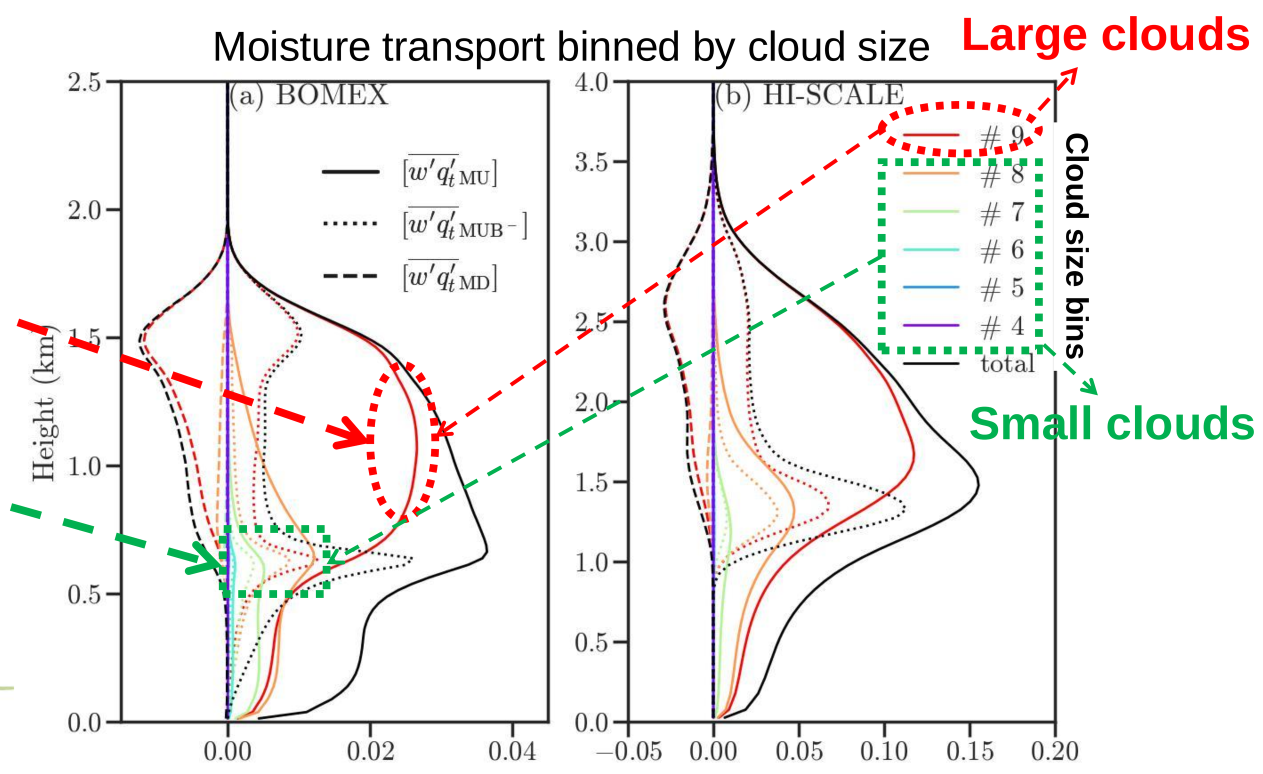
Heng Xiao, Adam Varble, Mikhail Ovchinnikov and Jerome Fast | Atmospheric, Climate and Earth Sciences Division, Pacific Northwest National Laboratory

Background – deep vs shallow modes of shallow convection

Recent observational and modelling studies (e.g., Albright et al. 2023, JAS; Xiao et al. 2025, JAMES) have provided more quantitative descriptions of the bi-modal shallow cloud size distribution than before (e.g., Neggers 2015, JAMES).

“Deep” vs “shallow” modes





(Left) Schematic depicting the deep and shallow modes in a shallow cloud population (Fig. 10, Neggers 2015).

(Top) Contributions to vertical moisture transport by the deep (top cloud size bin, #9) and shallow (bins #4–8) modes in marine (BOMEX) and continental (HI-SCALE at SGP) shallow convection. (Fig. 5, Xiao et al. 2025)

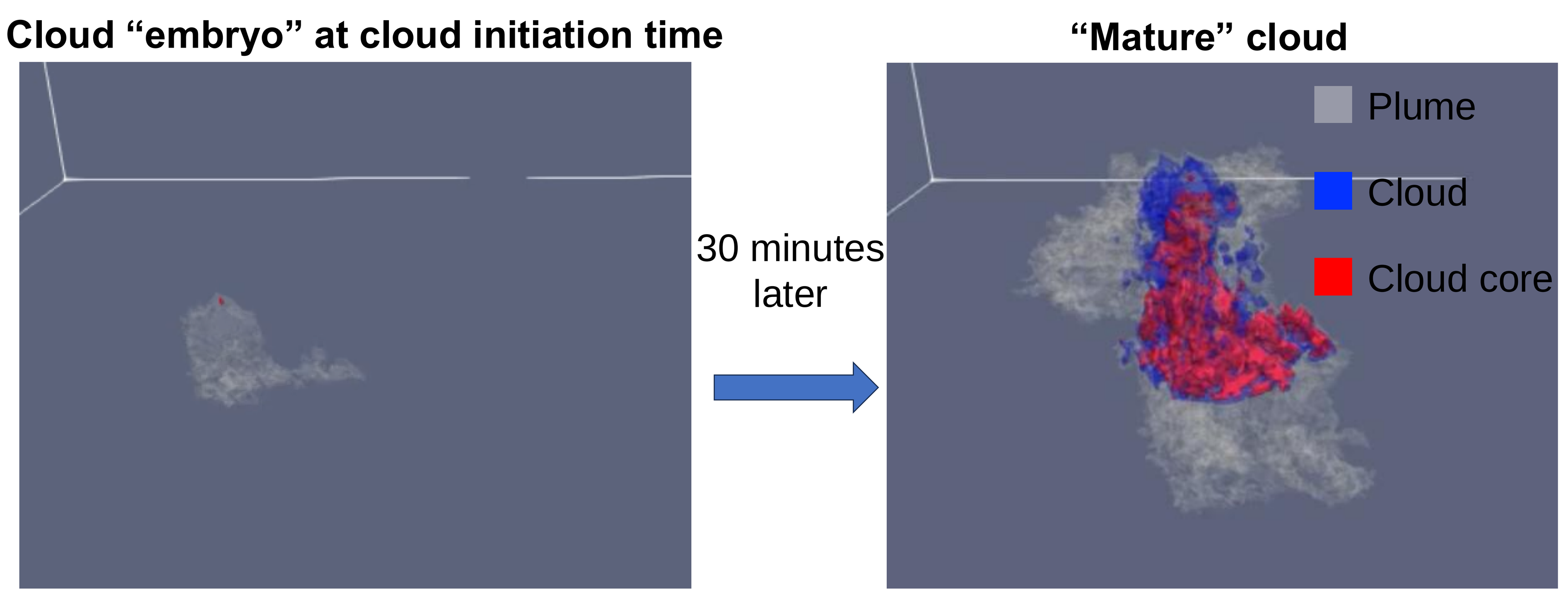
Motivation – cloud- vs subcloud-layer controls

However, **it is still unclear on the process level what determines such a bi-modal cloud size distribution in shallow and shallow-to-deep transitioning convection.**

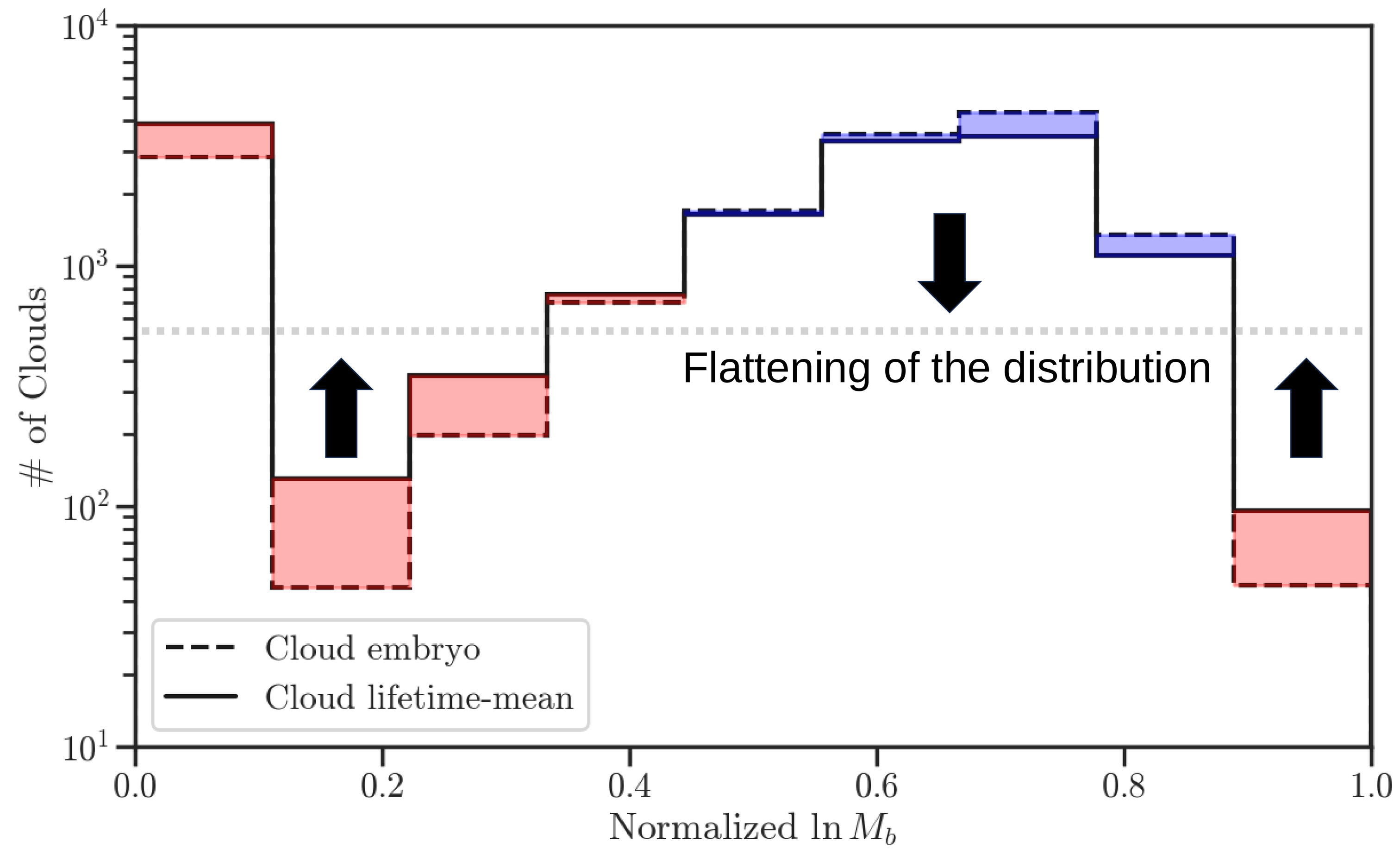
Recent debates (e.g., Brast et al. 2016, JAMES; Kurowski et al. 2019, GRL; Vraciu et al. 2025, JAMES) also point to unclear understanding on the role of **the cloud-layer environmental variability versus that of the subcloud-layer thermal or eddy properties** in controlling the shallow cloud population and its transition to deep convection.

In this study, **we examine quantitatively how the cloud-scale environmental variability in the cloud layer affects the cloud size distribution** in shallow and transitioning convection.

Cloud embryos vs mature clouds



The evolution of a cloud tracked by applying the algorithm of Dawe and Austin (2012, ACP) to a BOMEX LES simulation. Note the ”plume” (gray) volume at the cloud initiation time.



The cloud-base massflux (M_b) distributions of the cloud embryos and the cloud lifetime means for tracked clouds in a BOMEX LES. The X-axis is $\ln M_b$ normalized by its corresponding maximum value for each distribution.

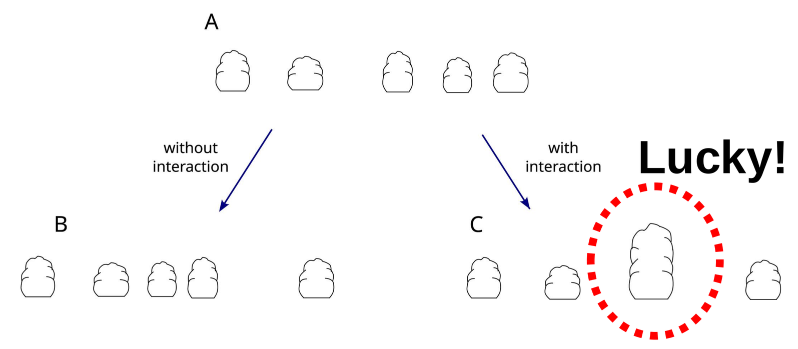
The shape of the lifetime-mean cloud-base massflux distribution is flatter compared to that of cloud embryos. In other words, there are less medium-sized clouds (Bins #5–8) and more small (Bins #1–4) and large (Bin #9) clouds. This indicates that:

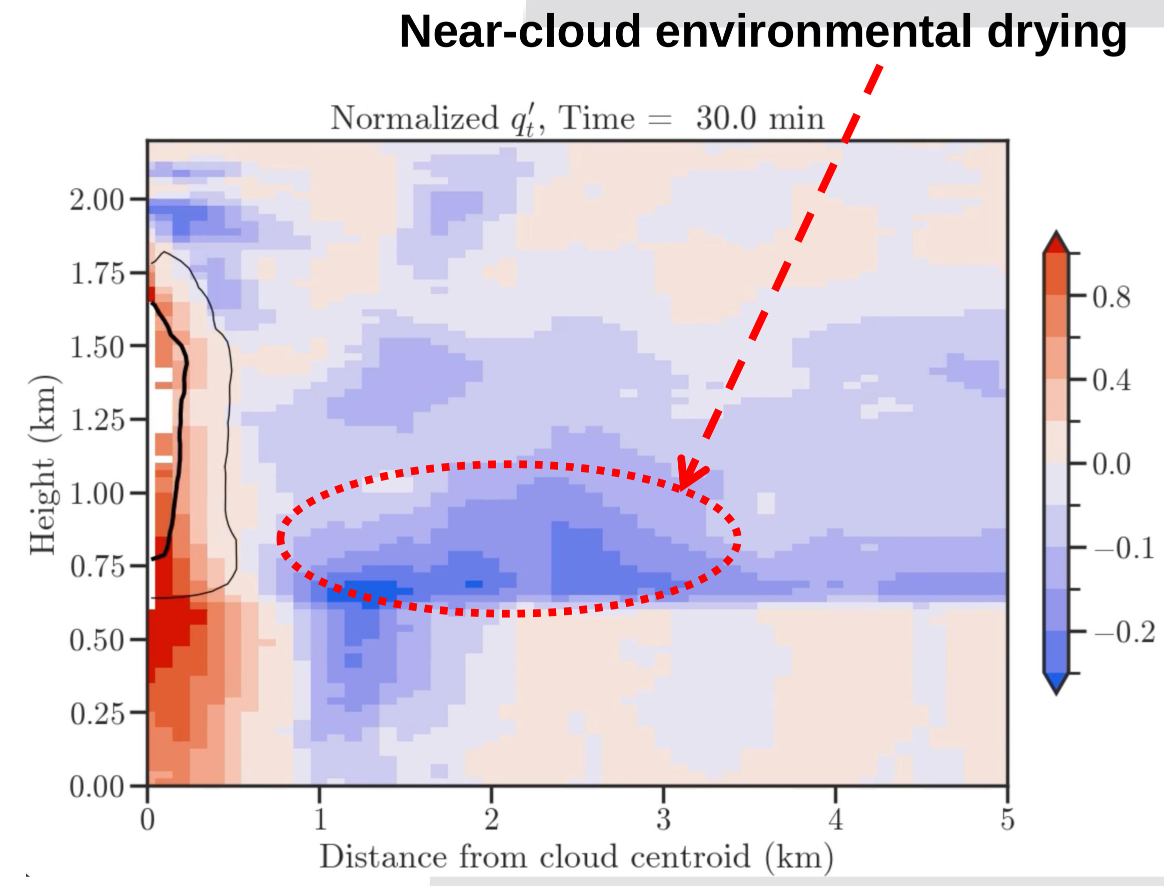
(1) the lifetime-mean cloud size distribution is not fully determined by the initial cloud (cloud embryo) size distribution, which can be seen as mostly determined by the variability in the subcloud thermal size and properties;

(2) the cloud-scale environmental variability in the cloud layer plays a role in shaping the lifetime-mean cloud size distribution. What are the processes involved?

As next steps, we plan to perform “environment homogenization” experiments to further quantify the impact of environmental variability on the shallow cloud size distribution and extend our analysis to shallow-to-deep transitioning convection.

Preconditioning vs suppression





(top) Schematic showing local moisture preconditioning by small clouds that leads to stronger growth of a cloud rising into the preconditioned volume. (Fig. 1, Vraciu et al. 2025)

(left) Snapshot (at t=30 minutes) of composite environmental moisture anomaly (q_t') surrounding tracked clouds lasting longer than 45 minutes in a BOMEX LES. q_t' is normalized by the horizontal standard deviation of q_t.

In our ongoing work, we examine the importance of two hypothesized cloud-scale processes that can impact the cloud size distribution:

- Local moisture preconditioning by small/shallow clouds in the lower cloud layer leads to stronger growth of cloud(s) rising into the moister volume;
- Drying of the local environment around a large/deep cloud suppresses the growth of surrounding clouds.

References

Xiao, H., A. Varble, C. Kaul, J. Mülmenstädt, 2025: Downward Convective Moisture Transport Dominated by a Few Overshooting Clouds in Marine and Continental Shallow Convection. *In Production, JAMES.* DOI: 10.1029/2024MS004489

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Heng Xiao | heng.xiao@pnnl.gov