A simple model for deep convection initiation

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Influences of Environmental Relative Humidity and Horizontal Scale of Subcloud Ascent on Deep Convective Initiation

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ABSTRACT: This study examines two factors impacting initiation of moist deep convection: free-tropospheric environmental relative humidity (ϕ_E) and horizontal scale of subcloud ascent (R_{sub}), the latter exerting a dominant control on cumulus cloud width. A simple theoretical model is used to formulate a "scale selection" hypothesis: that a minimum R_{sub} is required for moist convection to go deep, and that this minimum scale decreases with increasing ϕ_E. Specifically, the ratio of R^2_{sub} to saturation deficit $(1 - \phi_E)$ must exceed a certain threshold value that depends on cloud-layer environmental lapse rate. Idealized, large-eddy simulations of moist convection forced by horizontally varying surface fluxes show strong sensitivity of maximum cumulus height to both ϕ_E and R_{sub} consistent with the hypothesis. Increasing R_{sub} by only 300–400 m can lead to a large increase (>5 km) in cloud height. A passive tracer analysis shows that the bulk fractional entrainment rate decreases rapidly with R_{sub} but depends little on ϕ_E. However, buoyancy dilution increases as either R_{sub} or ϕ_E decreases; buoyancy above the level of free convection is rapidly depleted in dry environments when R_{sub} is small. While deep convective initiation occurs with an increase in relative humidity of the near environment from moistening by earlier convection, the importance of this moisture preconditioning is inconclusive as it is accompanied by an increase in R_{sub}. Overall, it is concluded that small changes to R_{sub} driven by external forcing or by convection itself could be a dominant regulator of deep convective initiation.

KEYWORDS: Entrainment; Buoyancy; Convective-scale processes; Cumulus clouds; Large eddy simulations

1. Introduction

A thermodynamic profile with convective available potential energy (CAPE) and a level of neutral buoyancy (LNB) in the upper troposphere (for an undilute lifted parcel) is a necessary ingredient for the initiation of moist deep convection. However, it is insufficient even when convective inhibition

2004; Takayabu et al. 2010; Zhang and Klein 2010; Nelson et al. 2021; Tian et al. 2021). For example, a transition from the shallow to deep convective phase of the MJO occurs concurrently with an increase in ϕ_E (e.g., Bladé and Hartmann 1993; Brown and Zhang 1997; Benedict and Randall 2007; Zermeño-Diaz et al. 2015; Chen and Zhang 2019). Sensitivity

Deep convection initiation is critical for many aspects of weather and climate

- **Obviously, a requirement is existence of CAPE with a LNB* in upper troposphere, and ability of parcels to overcome CIN.**

- **However… this doesn't tell the full story. It is very common to meet these conditions across a wide region but not have deep convection.**

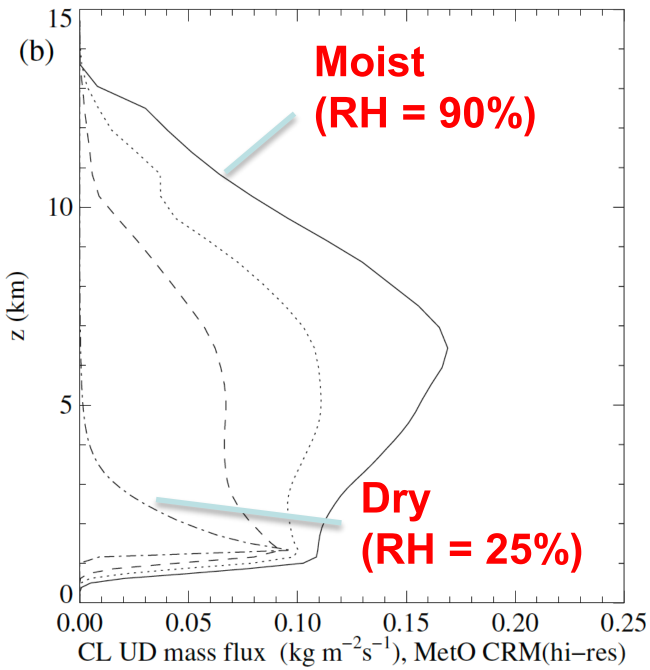
- **What are the additional factors controlling whether deep convection initiates?**

***For a pseudo-adiabatic ascending parcel**

The connection to free tropospheric environmental relative humidity

•Numerous studies going back decades have shown a close connection between the propensity for convection going deep and the environmental RH above the LFC*.

•This occurs main because of effects on cloud evaporation from entrainment/mixing, not virtual effects of water vapor on density (buoyancy) which are small.

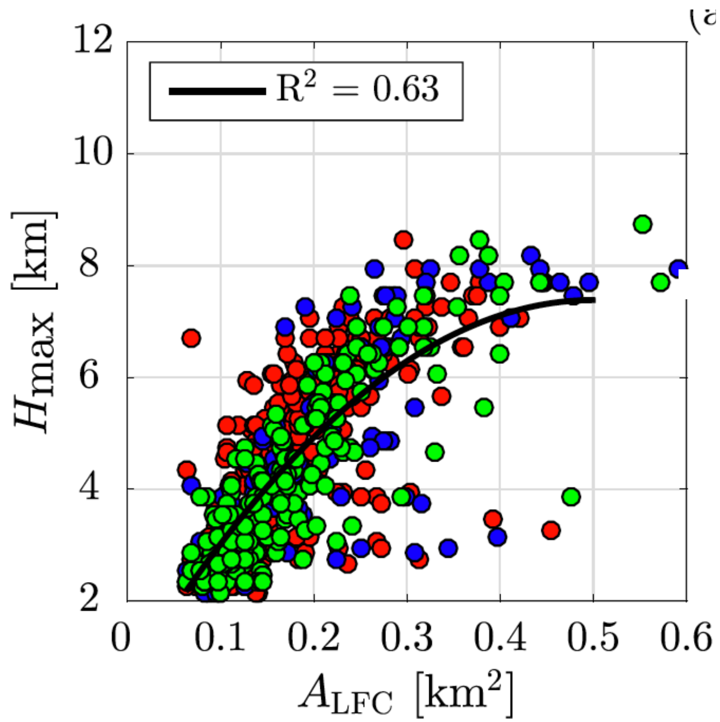


Derbyshire et al. 2004, QJRMS

*This includes idea of moisture pre-conditioning, where shallower clouds deposit mid-tropospheric moisture which enhances subsequent cloud development.

Other studies have suggested the role of cloud base width *R*

•**Wider clouds → relatively less dilution by entrainment.**



Rouseau-Rizzi et al. 2017, JAS

•**Cloud width probably controlled by many things: PBL depth, width of convergence lines, topography, cold pools, etc.**

Basic science questions

•Are these two factors (RH and *R*) related in how they influence deep convection initiation? What are their relative roles? Is the relation of *R* to cloud depth causal?

•Can a simple scaling explain how these factors impact deep convection initiation?

Methods:

•<u>Theoretical analysis</u> based on entraining parcel
•Idealized <u>large eddy simulation</u> (LES) using CM1

Theory

(follows from *Morrison 2017, JAS*; *Morrison et al. 2020; 2022, JAS*)

•Apply first-order k-theory to lateral mixing of a passive scalar *C* in a parcel near top of a rising updraft. Approximate horizontal derivates as a simple linear finite difference. Neglect vertical mixing. This gives analytic expression:

$$\frac{dC}{dz} = -\frac{2k^2L}{P_rR^2}(C - C_E) = -\varepsilon(C - C_E) \qquad \varepsilon \equiv \frac{2k^2L}{P_rR^2}$$

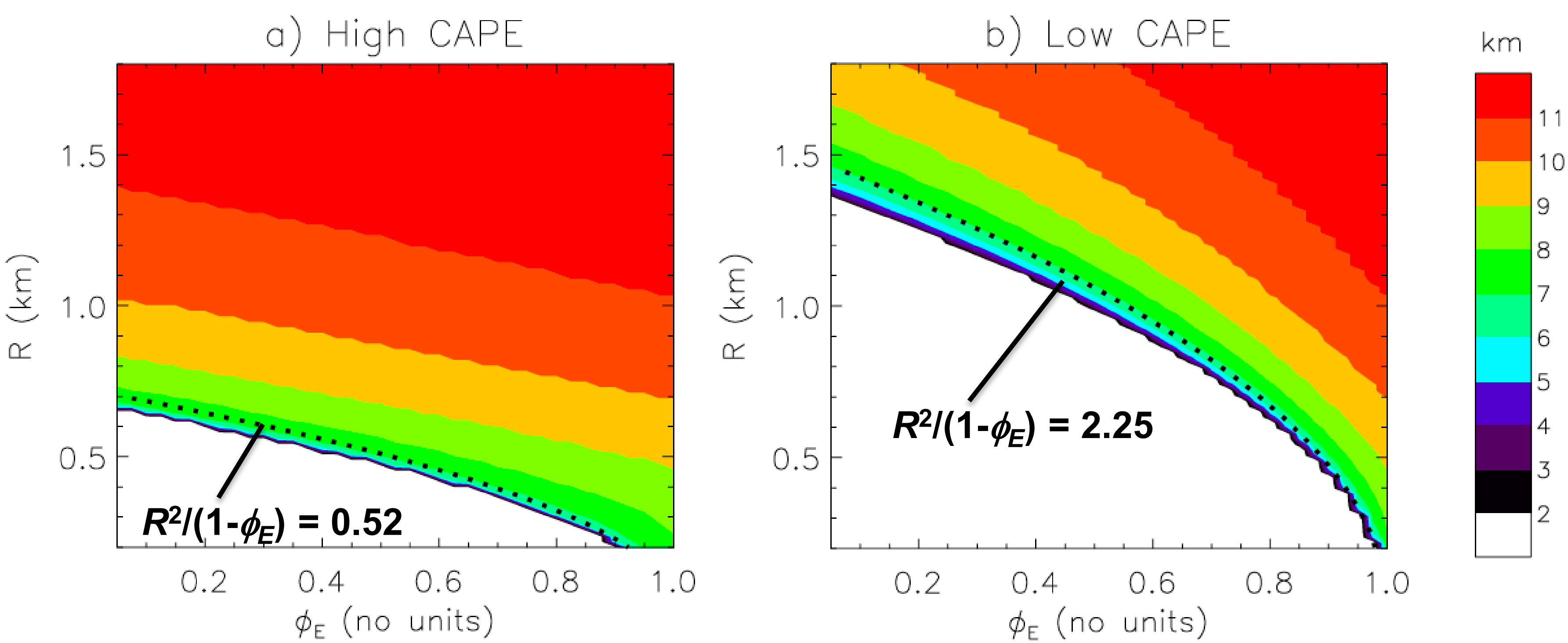
•Similar for buoyancy *B* → not a passive scalar though! Apply mixing separately for *T* and q_v, apply Clausius-Clapeyron, arrive at:

$$\frac{dB}{dz} = \underbrace{gQ}_{\text{term 1}} - \underbrace{\varepsilon B}_{\text{term 2}} - \underbrace{\frac{gL_vq_{sE}(1-\phi_E)\varepsilon}{c_pT_E\Gamma}}_{\text{term 3}}$$

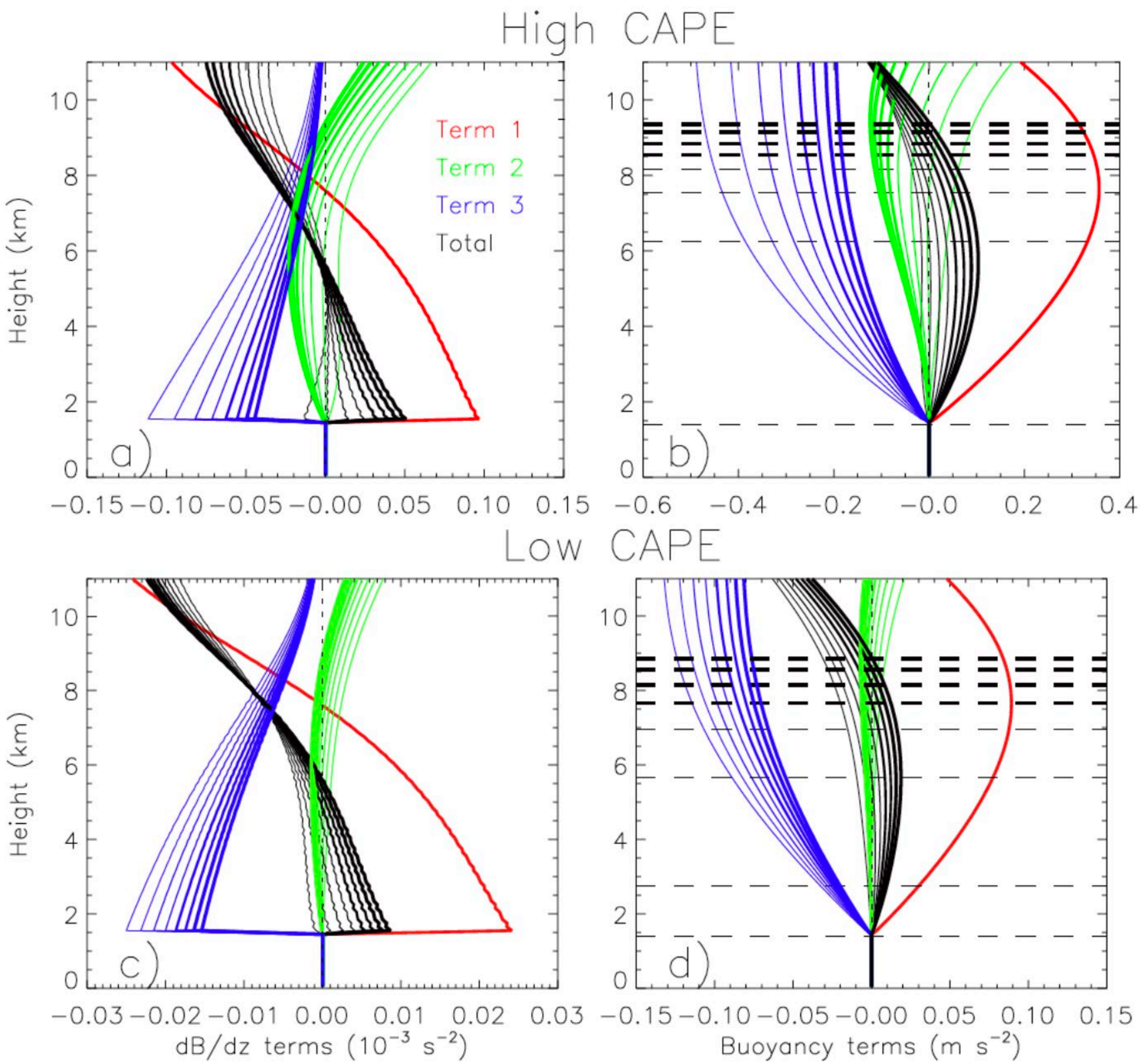
Results: theory

•Use two thermodynamic soundings: 1) Weisman-Klemp modified with constant RH above 2 km (*High CAPE*), 2) reduced lapse rate above LFC so that pseudo-adiabatic buoyancy (and thus CAPE) is uniformly reduced by a factor of 4 (*Low CAPE*).

•Integrate *dB/dz* equation numerically, find equilibrium height (height above LFC where buoyancy goes to 0).



Why such a sharp transition with *R* (consistent with LES of Rousseau-Rizzi et al. 2017)?



Since the *B* profile is mainly a balance between production by term 1 and sink from term 3, this implies *B* < 0 when |term 1|/|term 3| < 1.

This implies the *transition to deep convection occurs when the ratio $R^2/(1-\phi_E)$ is greater than a certain lapse rate-dependent threshold value* (dashed lines in the figure in the previous slide).

From this, we propose a "*scale selection" hypothesis* regarding the transition to deep convection:

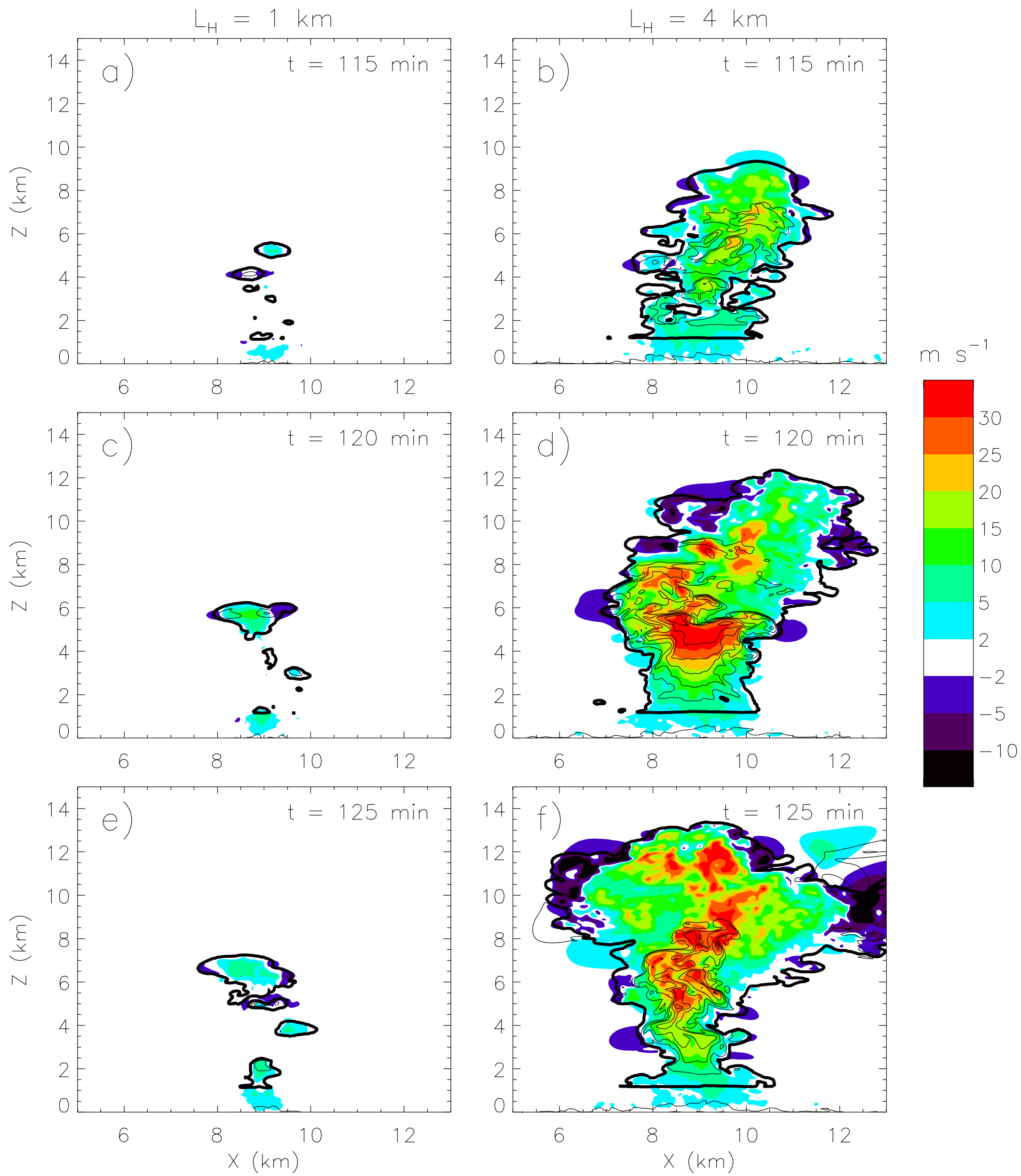
In environments potentially supporting deep convection, initiation occurs when cloud base width exceeds a certain threshold scale, and this scale decreases with an increase in free tropospheric relative humidity (and lapse rate).

Now we look at this with LES…

CM1 (Bryan and Fritsch 2002) model setup:

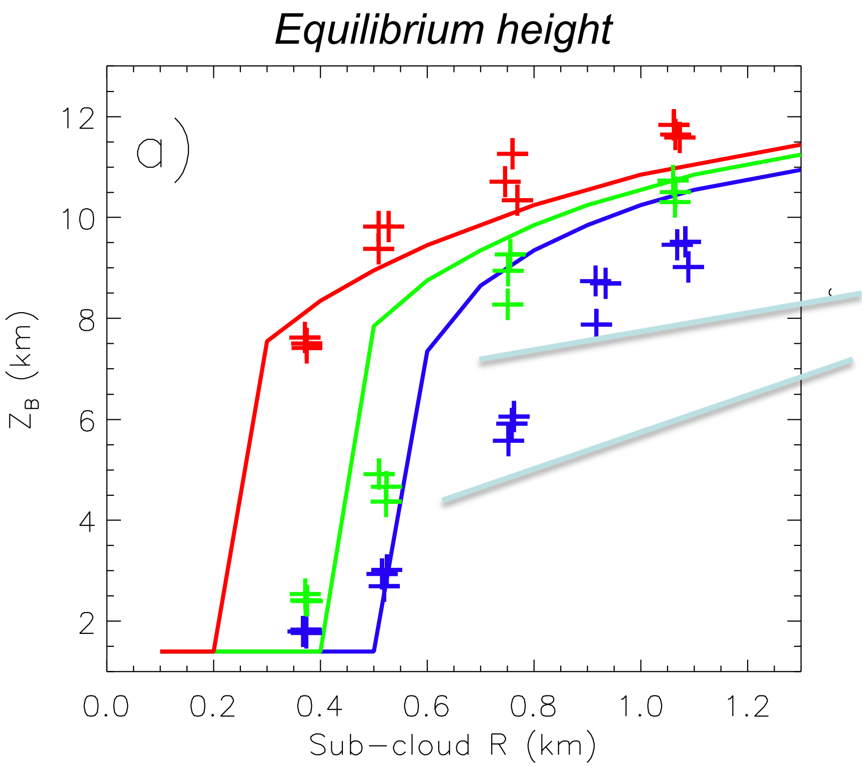
- **18 x 18 x 18 km^3 domain, Dx = Dy = Dz = 50 m**
- **Microphysics with saturation adjustment only (cloud condensation/evaporation) → <u>no precip</u>!**
- **Initial environment is <u>unsheared</u>, <u>modified WK</u> sounding**
- **<u>Forced by surface fluxes</u> following 10th International Cloud Modeling Workshop cumulus congestus case (similar to Lasher-Trapp et al. 2005) →**
  - **- horizontally-unform 1st hour (to spin up BL turbulence)**
  - **- horizontally-varying (Gaussian-shaped) after 1 hour to generate low-level circulation.**
- **Scales of <u>surface flux forcing</u>: 1, 1.5, 2.5, 4 km.**
- **<u>Environmental RH</u> above 2 km: 30, 60, 90%.**
- **<u>Three ensemble members</u> for each configuration (different seeds for initial noise applied to theta field).**

CM1 Results



Vertical cross section snapshots at the times indicated of vertical velocity (color fill) and buoyancy (black contour lines) for narrow (left) and wide (right) updrafts at cloud base, for the humid (RH = 0.9) environment.

Comparison of CM1 simulations and theory



Rapid shift from shallow to deep with changes in *R* of ~200-400 m, *R* where this happens increases with decreasing *RH*

Lines: theory
Crosses: CM1 LES for each ensemble member averaged from 140-180 min

Red (RH = 0.9)
Green (RH = 0.6)
Blue (RH = 0.3)

Conclusions

- **From theory, we proposed a *scale selection hypothesis* that exceeding a certain threshold cloud base width is required for deep convective initiation, and this threshold width decreases with increasing environmental RH (and cloud layer lapse rate).**

- **The transition to deep in the space of (R, ϕ_E) is well described by curves of constant $R^2/(1 - \phi_E)$ that vary with lapse rate, supported by a large set of CM1 LES runs.**

- **Transition from shallow to deep convection happens with changes to cloud base width of as little as a few hundred meters.**

- **Overall, suggests that small changes to cloud base width from low-level circulations driven by external forcing or convection itself (e.g. cold pools) could be dominant regulator of deep convection initiation.**

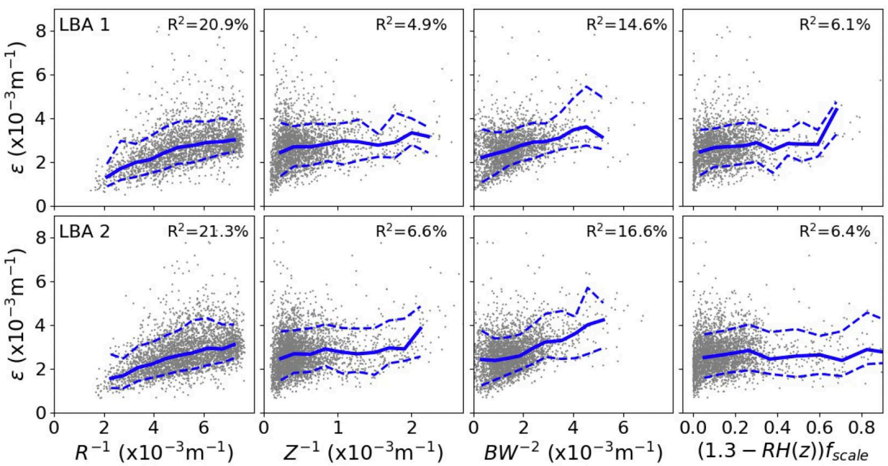
- **Environmental <u>wind shear</u> is also a critical aspect. Not addressed in the simple model here, but see Peters et al. (2022a,b).**

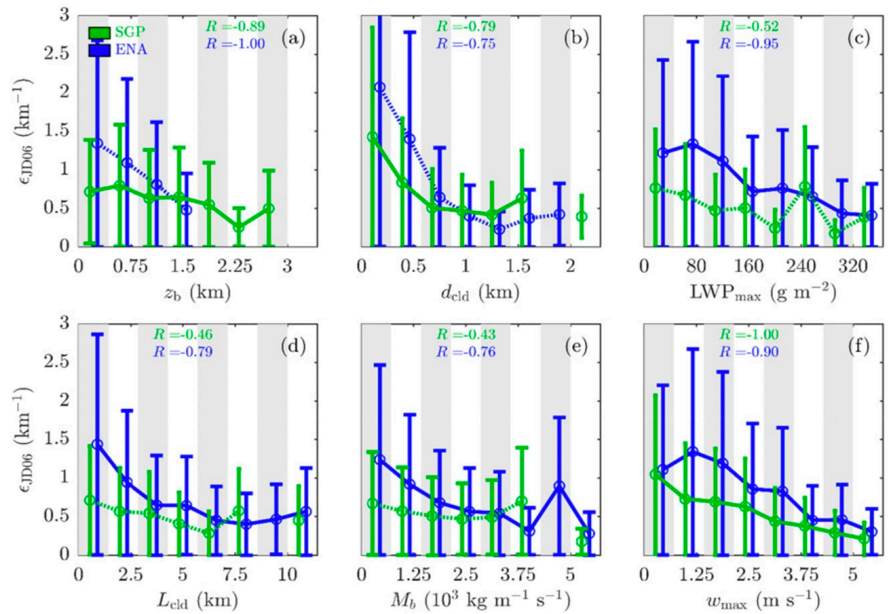
Caveats and Future Work

- **This work has focused primarily on theory and highly idealized LES modeling.**
- **Our idealized results are relative "clean" --> less idealized LES or observations of real clouds have much more variability. (see Dan's talk)**

Kirshbaum and Larmer (2021), JAS (<u>Obs</u>)

Hernandez-Deckers and Sherwood (2018), JAS (<u>LES</u>)





- **How much of entrainment variability is simply from quasi-stochastic nature of entraining eddies in turbulent clouds?**
- **Use LASSO-CACTI and observations to test the scale selection idea.**

Thank you!

Questions?

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Comparison of CM1 simulations and theory for the passive tracer