Cumulus dilution: correlation vs causation

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Cloud dilution

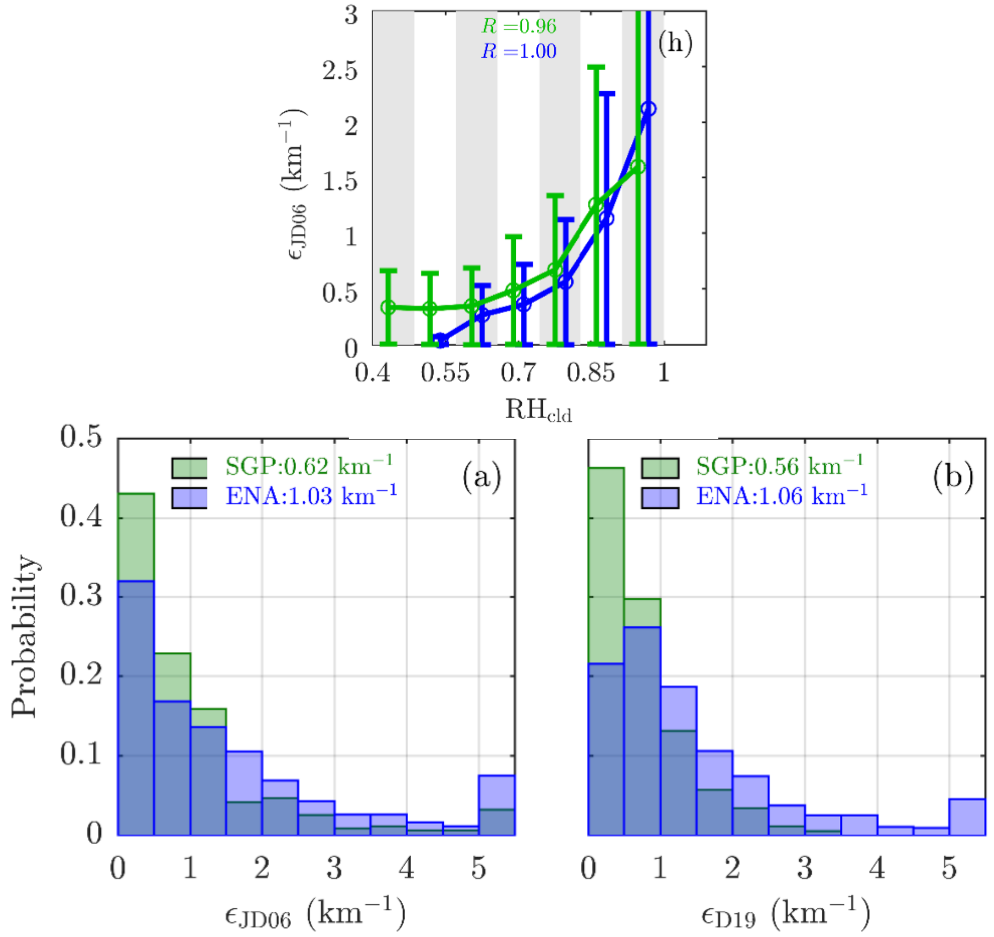
- May be loosely defined as the loss of cloud "adiabaticity" owing to mixing with surrounding air
    - Realized as reduced buoyancy, updraft speed, LWC

- Controlled by rates of entrainment and detrainment and properties of entrained and detrained air

$$\text{Bulk dilution} \longrightarrow \epsilon = \frac{\overset{\text{Core perimeter}}{C}}{\underset{\text{Core area}}{A_c}} \frac{\left[\overset{\text{Entrainment flux}}{\left(\overline{u_{\mathrm{ent}}\left(\phi_{\mathrm{ent}} - \phi_c\right)}\right)} - \overset{\text{Detrainment flux}}{\left(\overline{u_{\mathrm{det}}\left(\phi_{\mathrm{det}} - \phi_c\right)}\right)}\right]}{\underset{\text{Mean core vertical velocity}}{w_c}\left(\phi_c - \phi_e\right)}$$

Sensitivity to environmental conditions

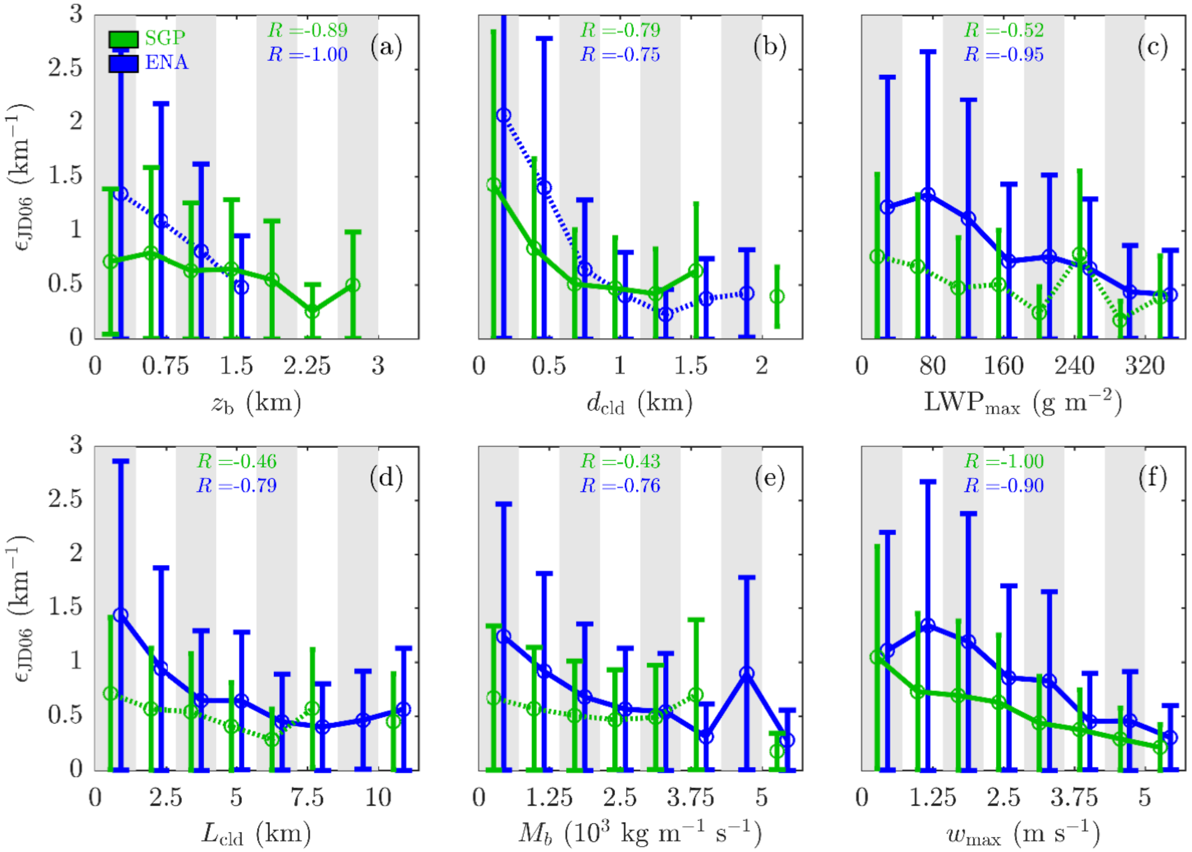
- Cloud-layer RH (e.g., Drueke et al 2021)
  - Robust positive correlation
- Cloud-layer dry stability (e.g., Stirling and Stratton 2012)
  - Negative correlation
- Land—ocean contrast (Kirshbaum and Lamer 2021)
  - Greatly reduced dilution over land



Kirshbaum and Lamer (2021)
Observations of shallow cumulus at SGP and ENA

Sensitivity to cloud properties

- Cloud cross-sectional area (A_c) (Khairoutdinov and Randall 2006)
  - Inverse correlation
- Cloud base height
  - Inverse correlation
- Cloud vigor (aka intensity)
  - Inverse correlation with w_c, cloud depth, LWP



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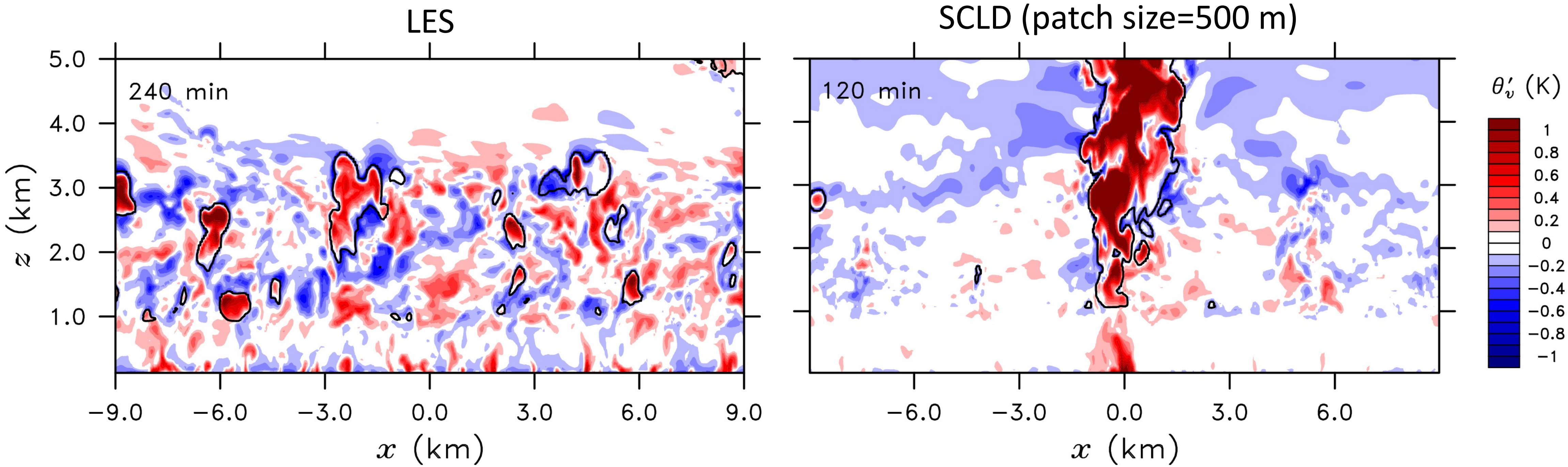
The problem

- Correlation does not imply causation
- Cloud vigor vs updraft speed: a “chicken and the egg” problem
  - Does vigor control dilution? Or does dilution control vigor? Or do they mutually interact?
  - The latter may imply a positive feedback loop, which could lead to extreme variability in mixing within cloud field
- **For parameterization of cloud-environmental mixing, must resolve causal controls on entrainment, detrainment, and dilution**

Methodology

- LES with cm1: LBA Amazonia case (Grabowski et al. 2006)
    - LES cloud ensemble (Kirshbaum 2022) on isotropic 50-m grid (60x60x20 km)
    - “Single-cloud” run (SCLD; Morrison et al. 2022): Gaussian surface heat patches of 10 different sizes (0.1 km -> 1 km)



LES

SCLD (patch size=500 m)

Quantifying dilution-related processes

- Based on tracer budget equation, solve for environmental dilution (traditional) and entrainment/detrainment (semi-direct; sd)

$$\epsilon = \frac{C}{A_c}\frac{\left[\left(\overline{u_{\mathrm{ent}}\left(\phi_{\mathrm{ent}} - \phi_c\right)}\right) - \left(\overline{u_{\mathrm{det}}\left(\phi_{\mathrm{det}} - \phi_c\right)}\right)\right]}{w_c\left(\phi_c - \phi_e\right)}$$

$$\delta = \epsilon - \frac{1}{M_c}\left(\frac{\partial \overline{\rho} A_c}{\partial t} + \frac{\partial M_c}{\partial z}\right)$$

Traditional bulk metrics (Siebesma and Cujpers, 1995)

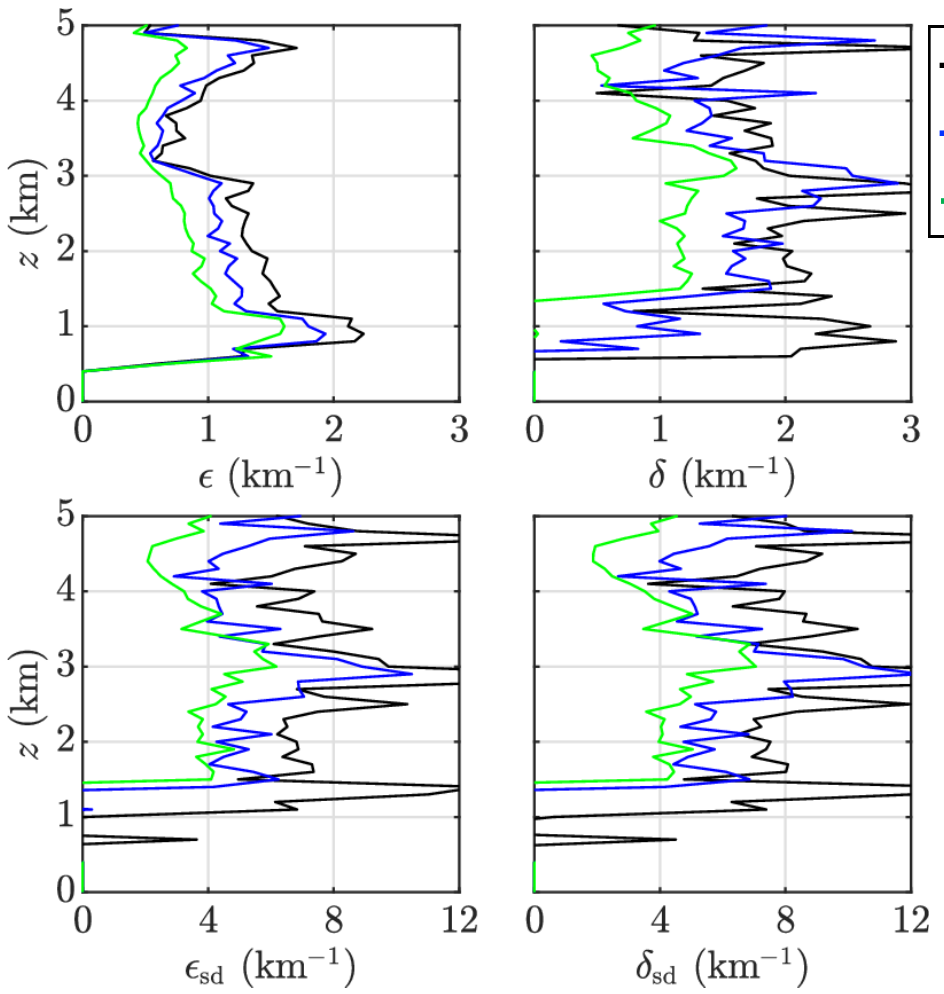
$$\epsilon_{\mathrm{sd}} = \left(\frac{\phi_c - \phi_e}{\phi_{\mathrm{det}} - \phi_{\mathrm{ent}}}\right)\epsilon - \left(\frac{\phi_c - \phi_{\mathrm{det}}}{M_c}\right)\left(\frac{\partial \overline{\rho} A_c}{\partial t} + \frac{\partial M_c}{\partial z}\right)$$

$$\delta_{\mathrm{sd}} = \epsilon_{\mathrm{sd}} - \frac{1}{M_c}\left(\frac{\partial \overline{\rho} A_c}{\partial t} + \frac{\partial M_c}{\partial z}\right)$$

“Semi-direct”: bulk analogs to direct entrainment and detrainment (e.g., Romps 2010; Dawe and Austin 2011)

LES results (I): percentile binning

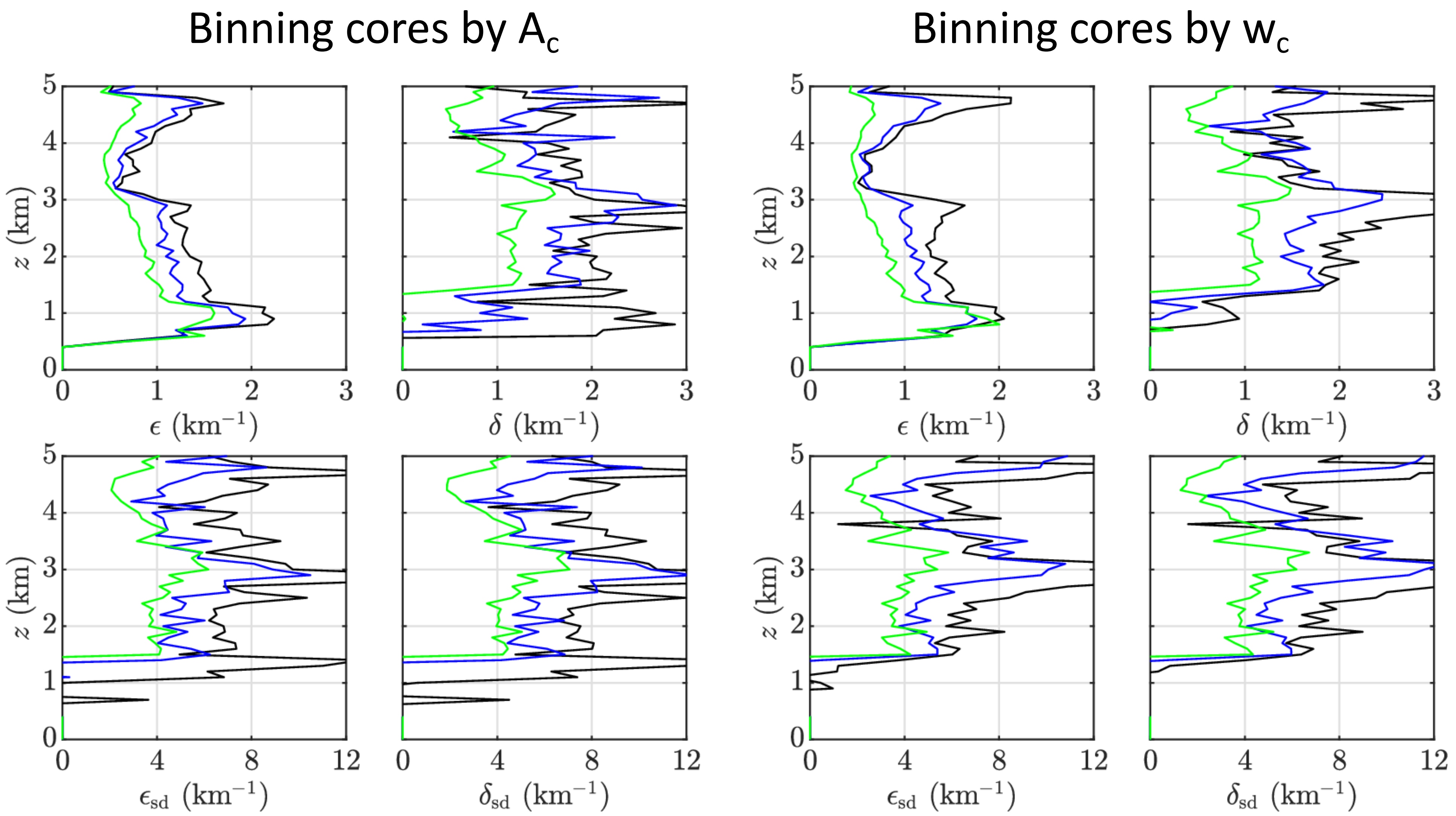
Binning cores by A_c



- As A_c increases, dilution, entrainment, and detrainment all decrease

- Bulk dilution (ϵ) is 2-4 times smaller, with different vertical structure, than semi-direct entrainment and detrainment (ϵ_{sd} and δ_{sd})
  - Consistent with Romps (2010) and Dawe and Austin (2011)

LES results (I): comparing A_c and w_c


Binning cores by A_c

Binning cores by w_c

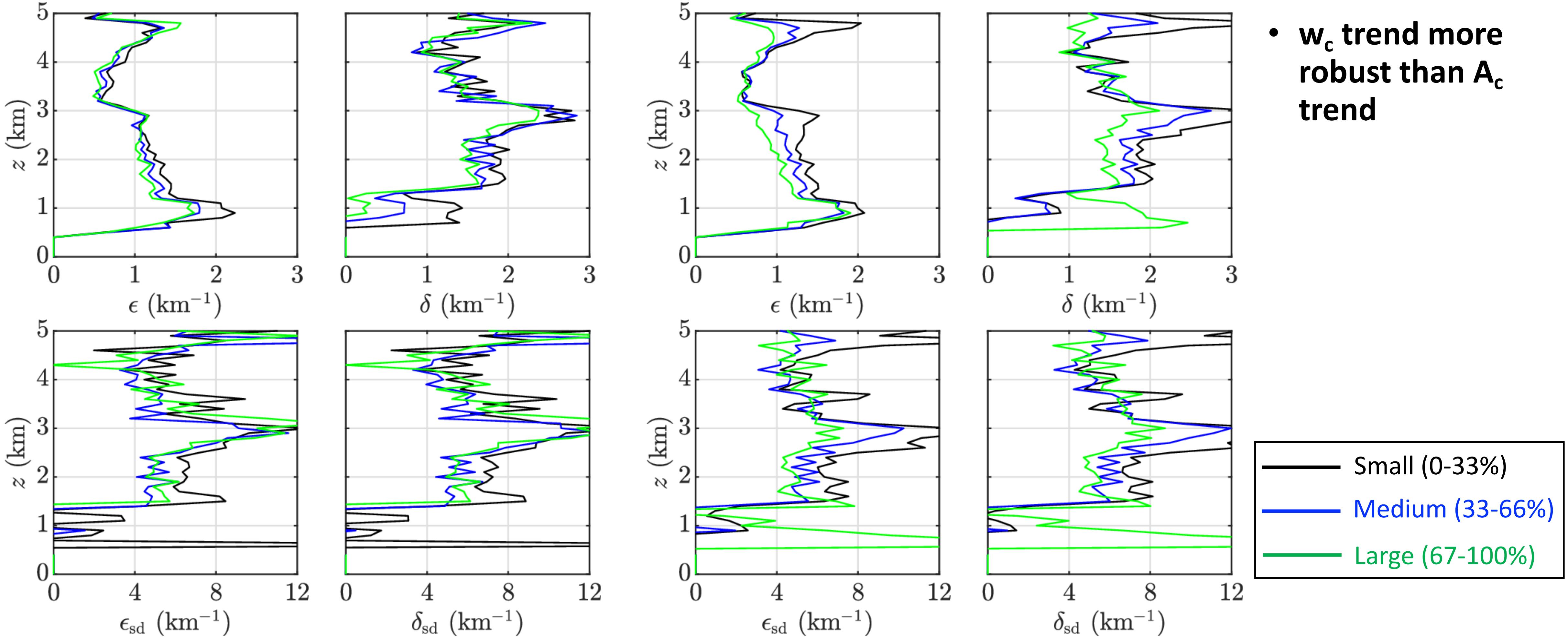
- Similar results for A_c, w_c, (b_c): larger control parameter -> weaker mixing
- Which, if any, causally control(s) mixing?

LES results (II): controlling for A_c, w_c

- **w_c trend more robust than A_c trend**

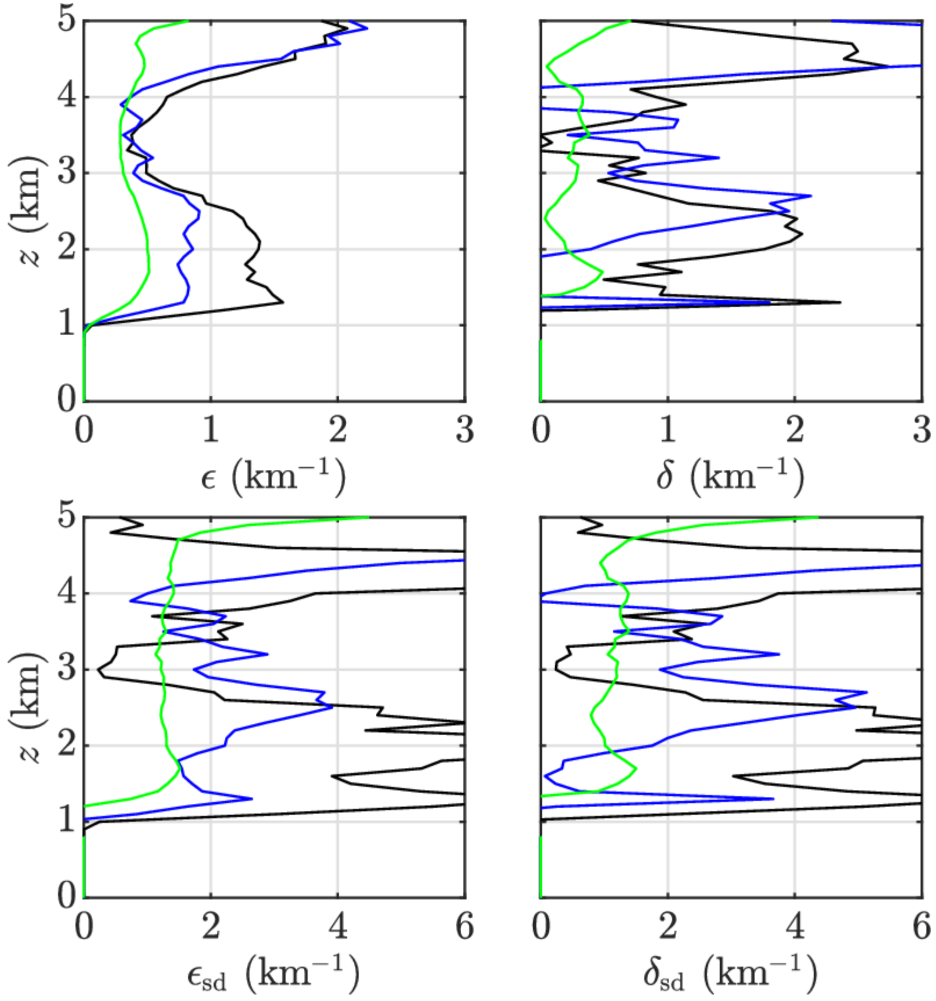
A_c (controlling for w_c)

w_c (controlling for A_c)

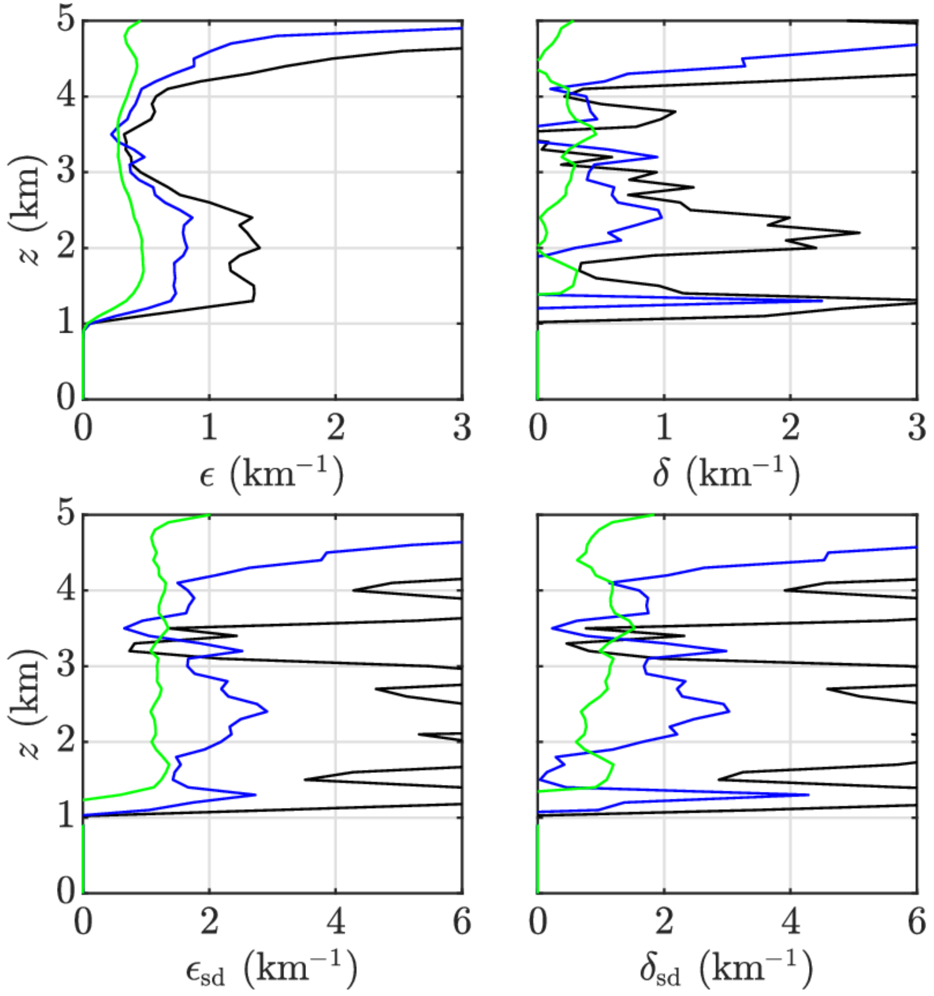


Single-cloud results (I): percentile binning

Binning cores by A_c



Binning cores by w_c

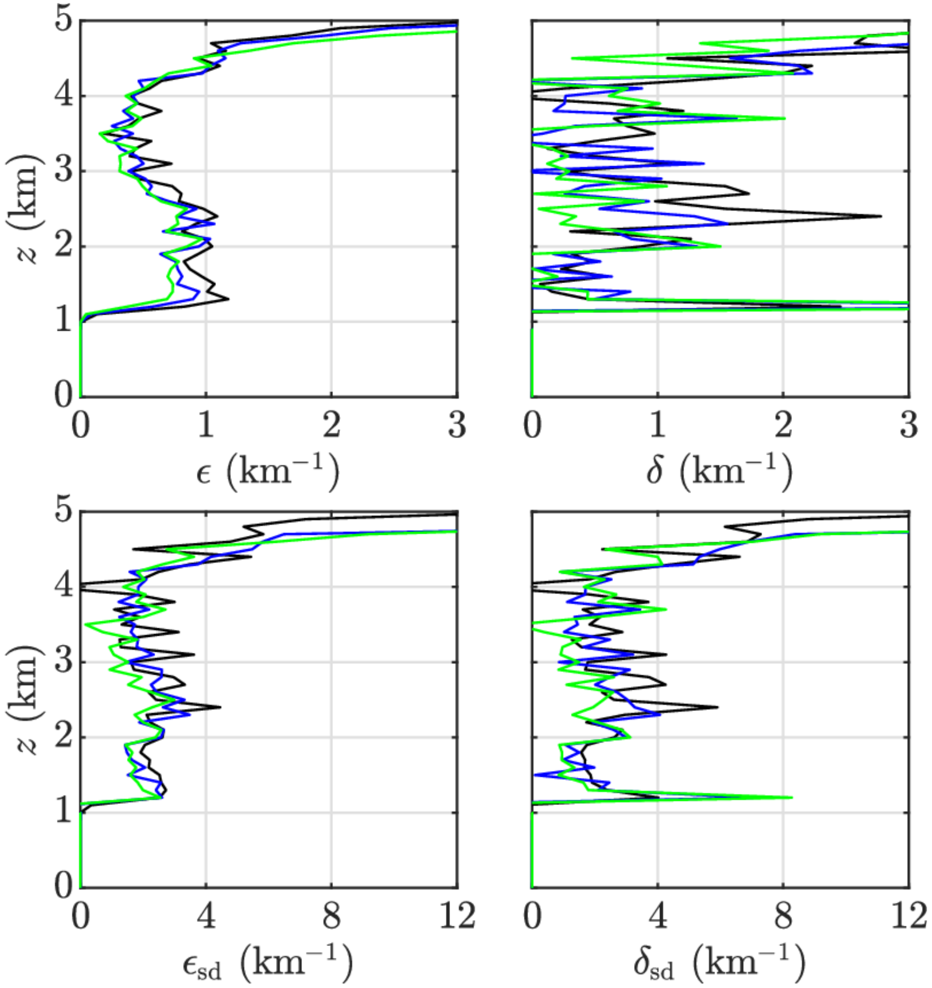


- Similar results for A_c, w_c, (b_c): larger control parameter -> weaker mixing
- Which, if any, causally control(s) mixing?

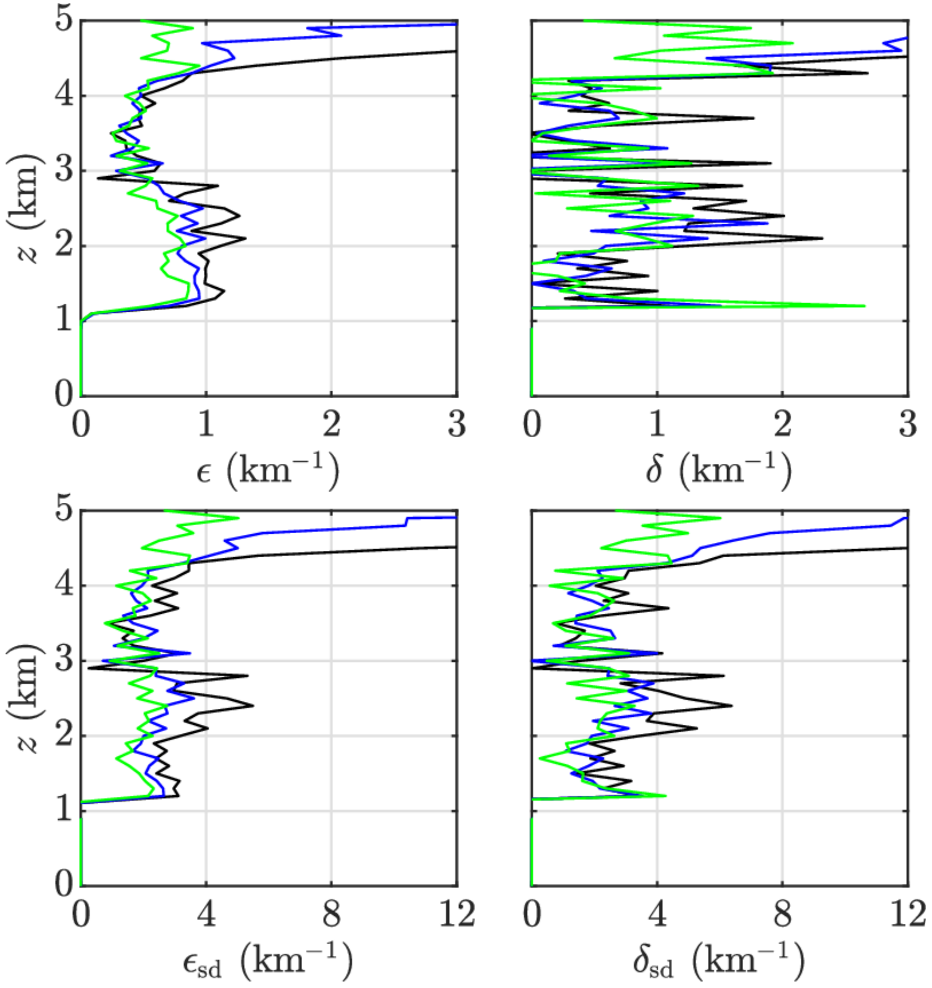
Small (0-33%)
Medium (33-66%)
Large (67-100%)

Single-cloud results (II): controlling for A_c, w_c

A_c (controlling for w_c)



w_c (controlling for A_c)



- **w_c trend again more robust than A_c trend**

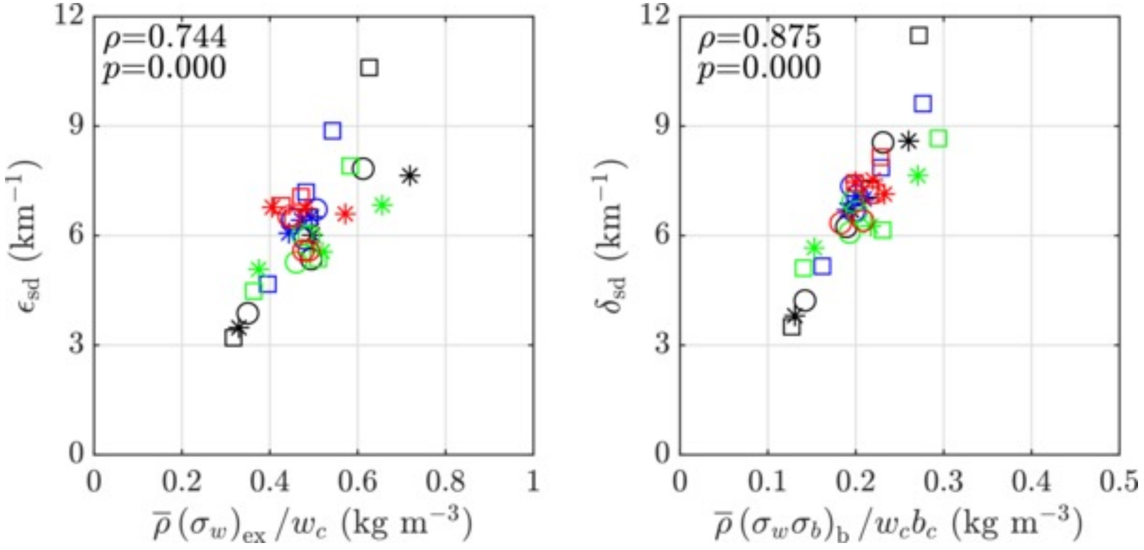
Hypothesis

- What *should* control $\boldsymbol{\epsilon}_{\mathrm{sd}}$ and $\boldsymbol{\delta}_{\mathrm{sd}}$?
  - Horizontal inflow? Not necessarily. Horizontal motions do not lead to saturation or buoyancy gain (without turbulent mixing)
  - Evidence favors the importance of *vertical* inflow: air in surrounding shell rises to saturation, joins core (e.g., Dawe and Austin 2011; Savre 2022)

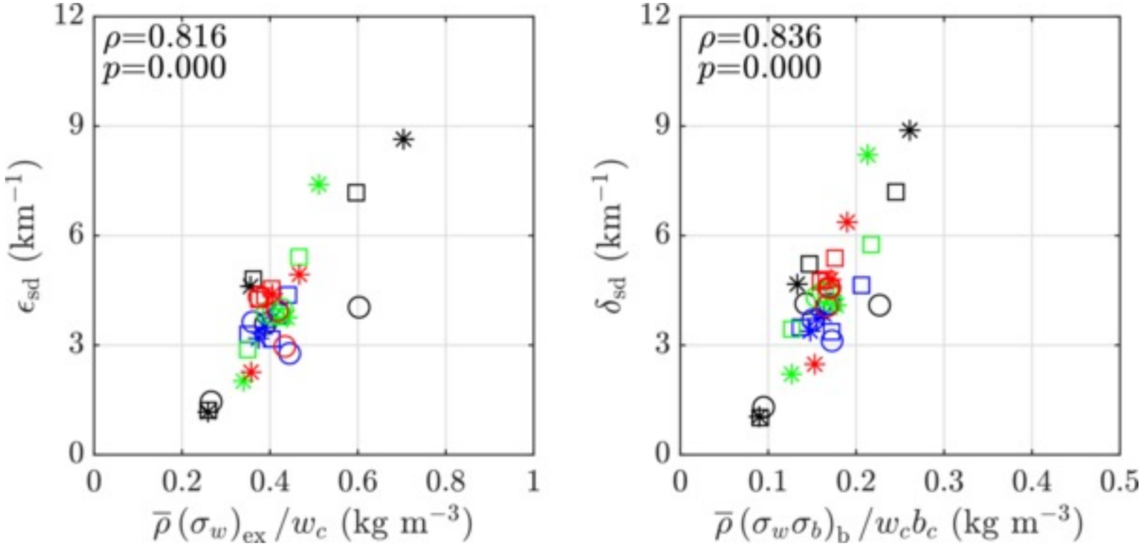
- Simple hypothesis: $\boldsymbol{\epsilon}_{\mathrm{sd}}$ roughly depends on $\boldsymbol{\sigma}_{\mathrm{w}}$ within core shell and mean cloud-core updraft speed (w_{c})
  - Larger $\boldsymbol{\sigma}_{\mathrm{w}}$ in shell: greater likelihood of “activating” new core points
  - Larger w_{c}: reduced time scale for mixing

Control parameters for $\boldsymbol{\epsilon}_{\mathrm{sd}}$ and $\boldsymbol{\delta}_{\mathrm{sd}}$

LES ensembles (mean over 0-5 km)



Single-cloud runs (mean over 0-5 km)



- Entrainment well described by ratio of exterior $\boldsymbol{\sigma}_{\mathrm{w}}$ to w_{c}
    - R-value decreases to 0.54 using w_{c} alone
- Detrainment well described by ratio of core-boundary $\boldsymbol{\sigma}_{\mathrm{w}}\,\boldsymbol{\sigma}_{\mathrm{b}}$ to $\mathrm{w}_{\mathrm{c}}\mathrm{b}_{\mathrm{c}}$
- Common trends, but mean $\boldsymbol{\epsilon}_{\mathrm{sd}}$ and $\boldsymbol{\delta}_{\mathrm{sd}}$ 40-50% smaller in single-cloud

Conclusions

- Performed LES experiments to quantify sensitivity of bulk $\boldsymbol{\epsilon}$, $\boldsymbol{\delta}$ (and their “semi-direct” versions) to cloud-core parameters
- Found a greater sensitivity to w_c than to A_c on a level-by-level basis
    - Does this simply reflect that $\boldsymbol{\epsilon}$, $\boldsymbol{\delta}$ control w_c? Possibly.
- Hypothesis: semi-direct $\boldsymbol{\epsilon}_\mathrm{sd}$, $\boldsymbol{\delta}_\mathrm{sd}$ can be described by nondimensional ratios of shell/boundary variance to core mean
    - Correlations larger than either parameter alone (not shown)

Future work

- Why does detrainment depend on both *w* and *b* while entrainment depends solely on *w*?

- Why is entrainment/detrainment so much smaller in “single-cloud” runs than in LES ensembles?
  - Bubble vs plume?

- Still need to test causal hypothesis on single-cloud runs
  - Ideas are there, just lacking the time