ASR Atmospheric System Research

On the quantification of cumulus entrainment and detrainment

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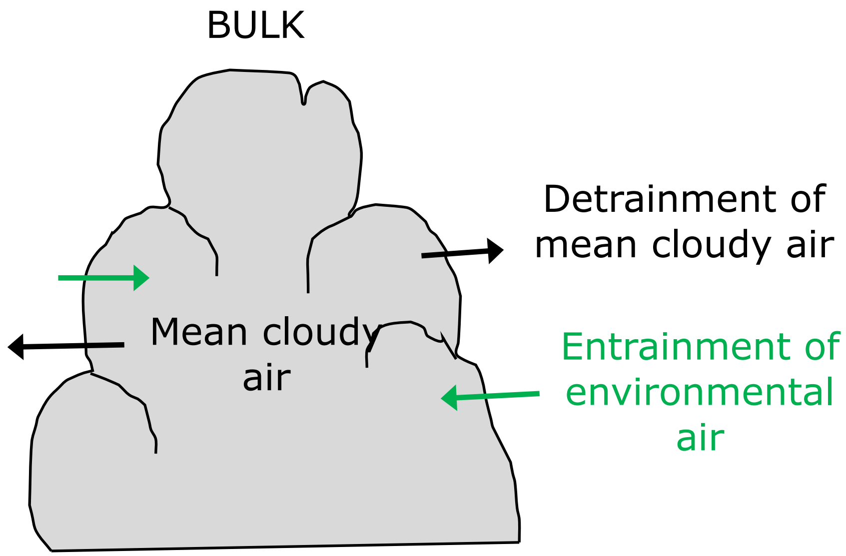
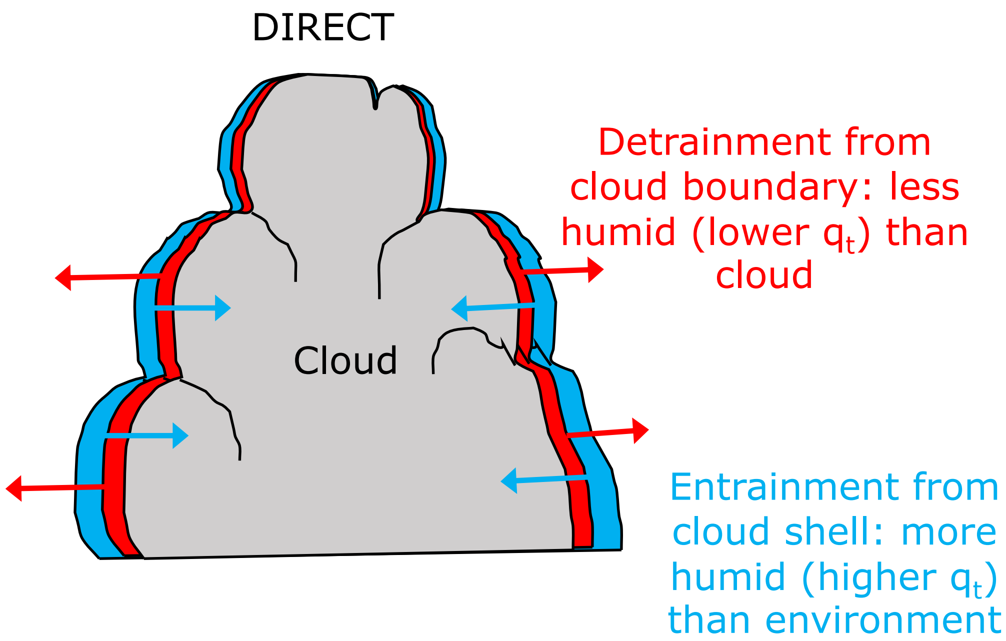
Bulk vs direct entrainment and detrainment

- Bulk: infer mixing based on cloud and environmental tracers (Siebesma and Cujpers 1995)
  - Quantification of cloud *dilution*

- Direct: evaluation of mass fluxes across cloud edges (Romps 2010)





Questions

1. Direct entrainment is cumbersome to code and expensive to compute. Can bulk formulation be improved to provide similar insights?

2. Despite recent progress, we still lack a causal explanation for entrainment, detrainment, and dilution
   - Difficult to disentangle cause and effect from correlations

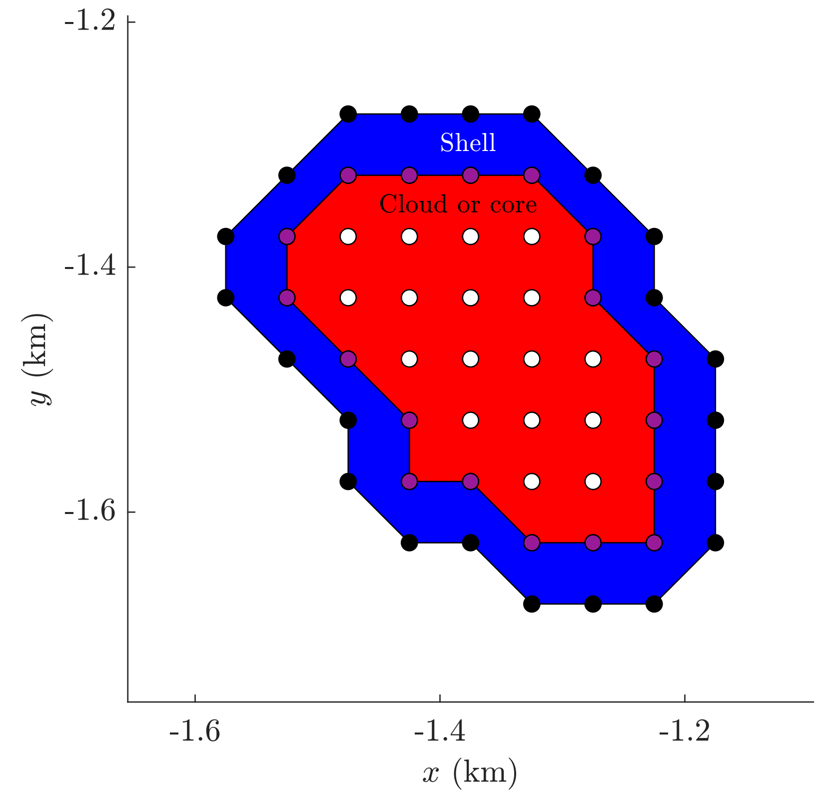
The “semi-direct” method

- A simple bulk estimate of *direct* E/D
  - Based on tracer-budget equation (e.g., SC95)

- Two key assumptions
  - Entrained air source: core shell (including top)
  - Detrained air source: core boundary

$$\epsilon_{\rm sd} = \left(\frac{\phi_b - \phi_e}{\phi_b - \phi_s}\right)\epsilon_{\rm SC95} + \left(\frac{\phi_c - \phi_b}{\phi_b - \phi_s}\right)\delta_{\rm SC95}$$

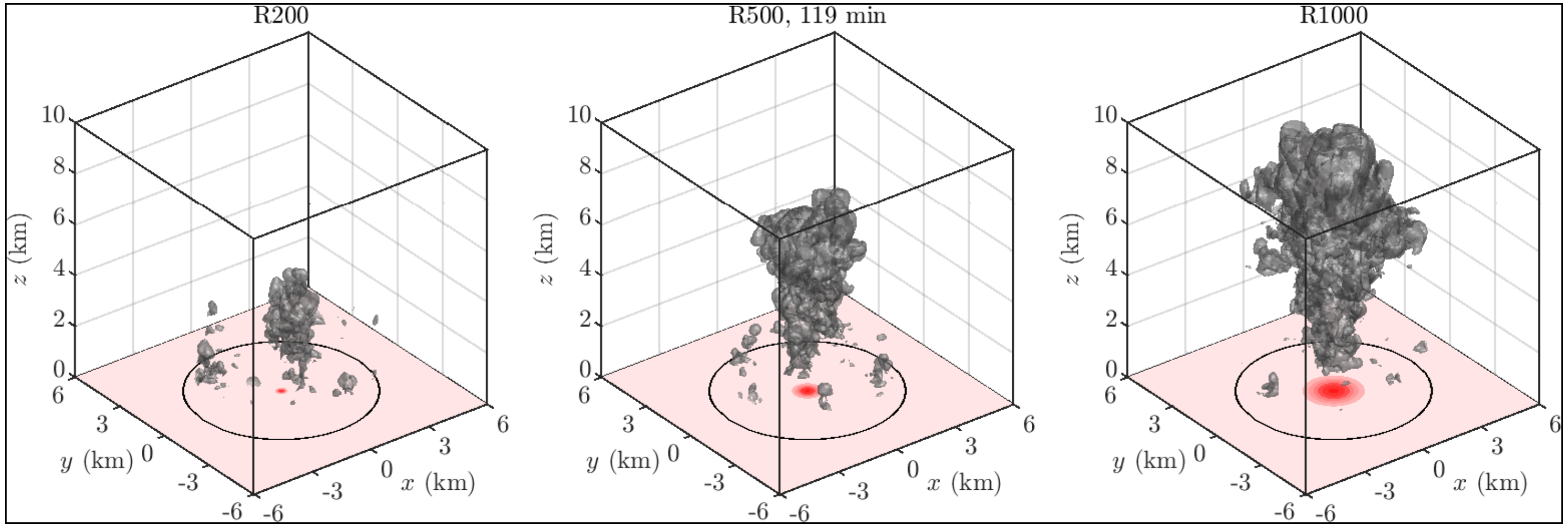
$$\delta_{\rm sd} = \left(\frac{\phi_c - \phi_s}{\phi_b - \phi_s}\right)\epsilon_{\rm SC95} + \left(\frac{\phi_s - \phi_e}{\phi_b - \phi_s}\right)\delta_{\rm SC95}$$



Numerical simulations

- cm1 model v21 (Bryan and Fritsch, 2002)
  - dx=dy=dz=50 m
  - Single-cloud configuration (central heat patch)
  - Modified LBA simulation (Amazonia)

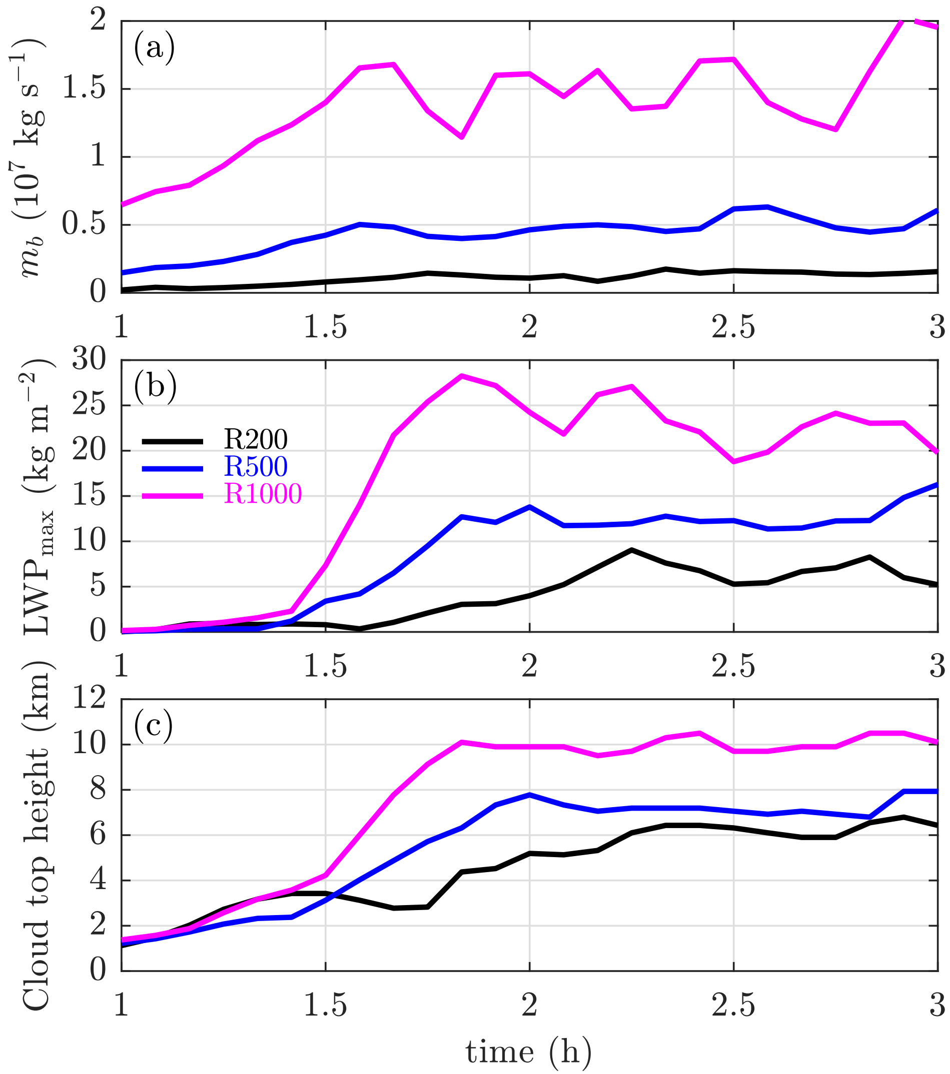
Vary surface heat patch radius
- R_h=[0.1,0.2,…,1] km
- ”R100”, “R200”, etc.



Evolution of bulk cloud metrics

- All metrics evaluated over $|r| < 6R_h$
  - Cloud-base mass flux (m_b)
  - Maximum LWP (LWP_{max})
  - Maximum cloud-top height

- Systematic increase in all metrics with increasing R_h



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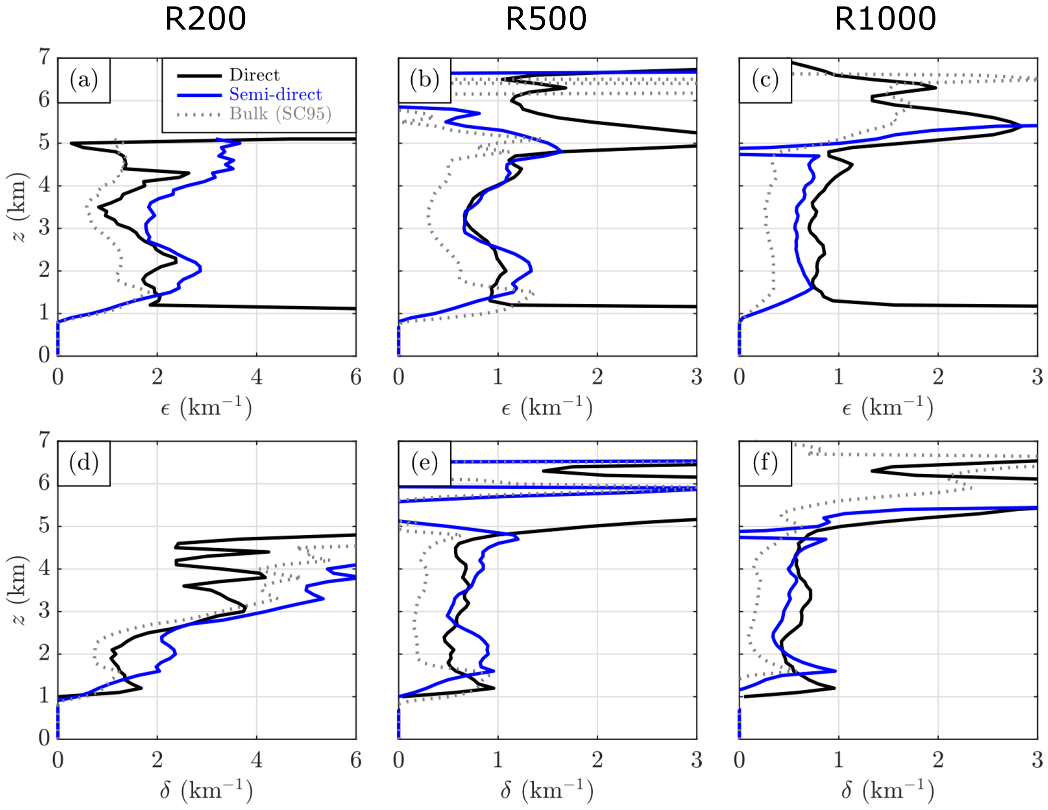
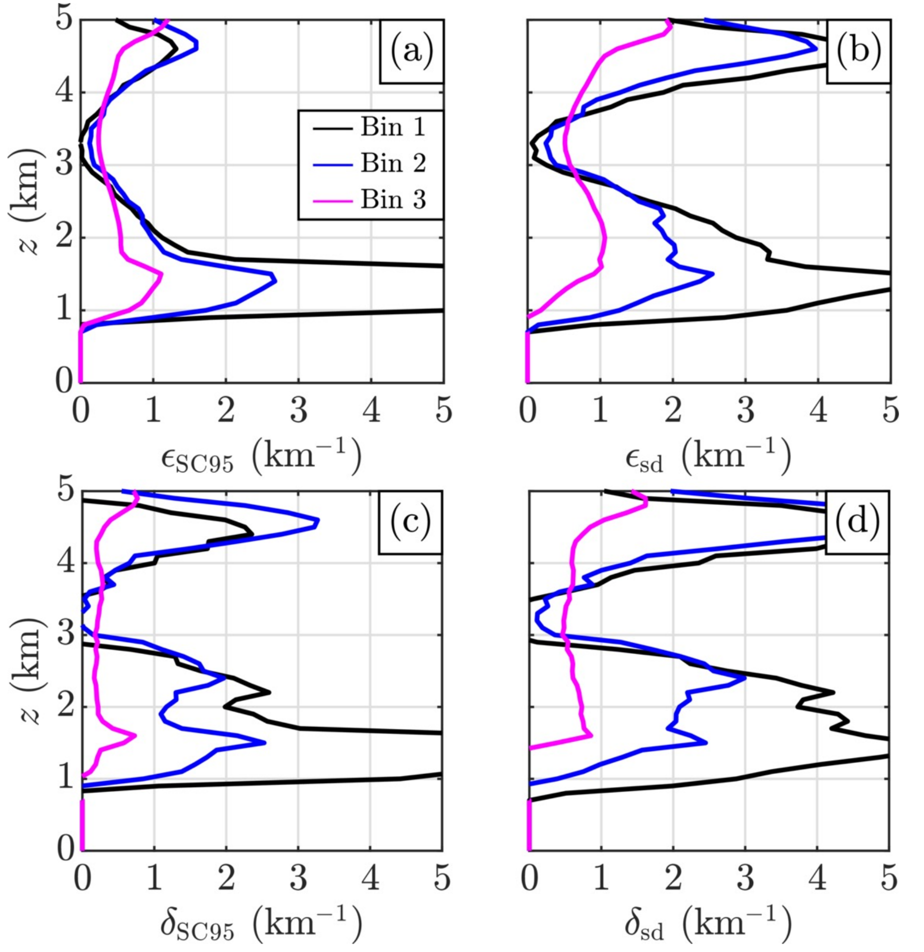
Verification of semi-direct method

- Basic cloud entity: buoyant cloud “core”
- Parcel-based direct E/D (Yeo and Romps 2013)
  - R1000 case, SGS deactivated
- Highly accurate in low-to-mid troposphere
  - Some problems aloft, due to changing nature of mixing
  - Deferred to future work
- For now, exploit agreement below 5 km to investigate parameter sensitivities



Sensitivities of ϵ, δ to A_c

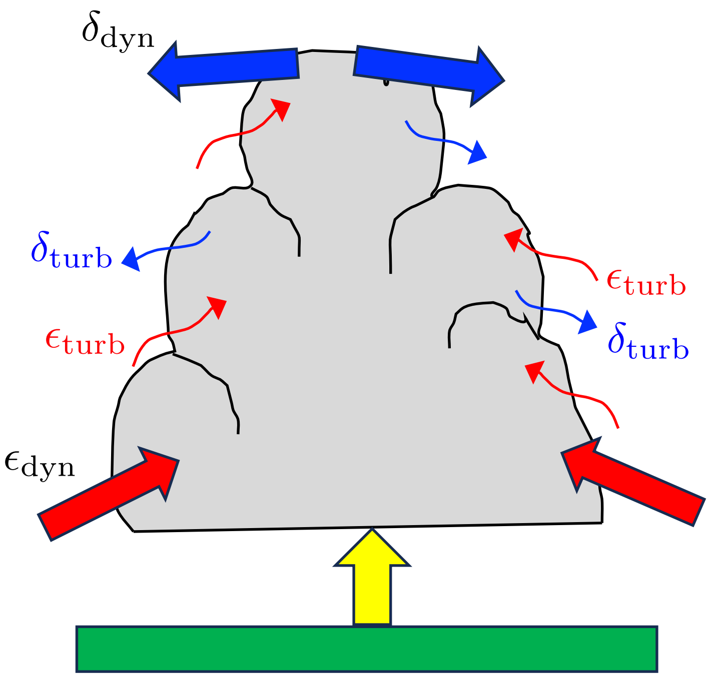
- Collect all cores over full R_h ensemble, separate into equal percentile bins, take average
- Mostly monotonic decrease in all measures with increasing cross-sectional area (A_c)
- ϵ, δ correlates similarly with core-mean w_c, b_c, M_c (not shown)
    - Which parameters actually *control* ϵ, δ?



Physical interpretation

- Entrainment and detrainment often decomposed as (e.g., de Rooy et al. 2013)

$$\epsilon = \epsilon_{\mathrm{turb}} + \epsilon_{\mathrm{dyn}}$$
$$\delta = \delta_{\mathrm{turb}} + \delta_{\mathrm{dyn}}$$



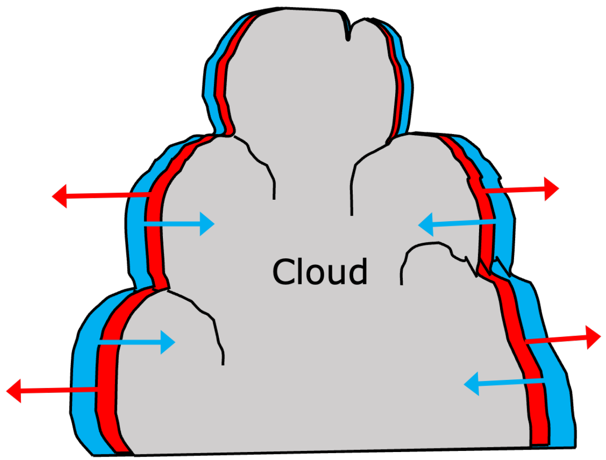
- Shortcomings
  - Most mass transfer is absorbed into turbulent component
  - But not all of this transfer is *actually* turbulent
  - ➢ Simple turbulence scaling arguments may not accurately quantify this component

A complementary decomposition

- Reversible vs irreversible

$$\epsilon = \epsilon_{\rm rev} + \epsilon_{\rm irr}$$
$$\delta = \delta_{\rm rev} + \delta_{\rm irr}$$

  - Builds on semi-direct assumptions to gain insight
  - Can estimate from *instantaneous* 3D data, assuming scale separation between smaller drafts and larger cloud

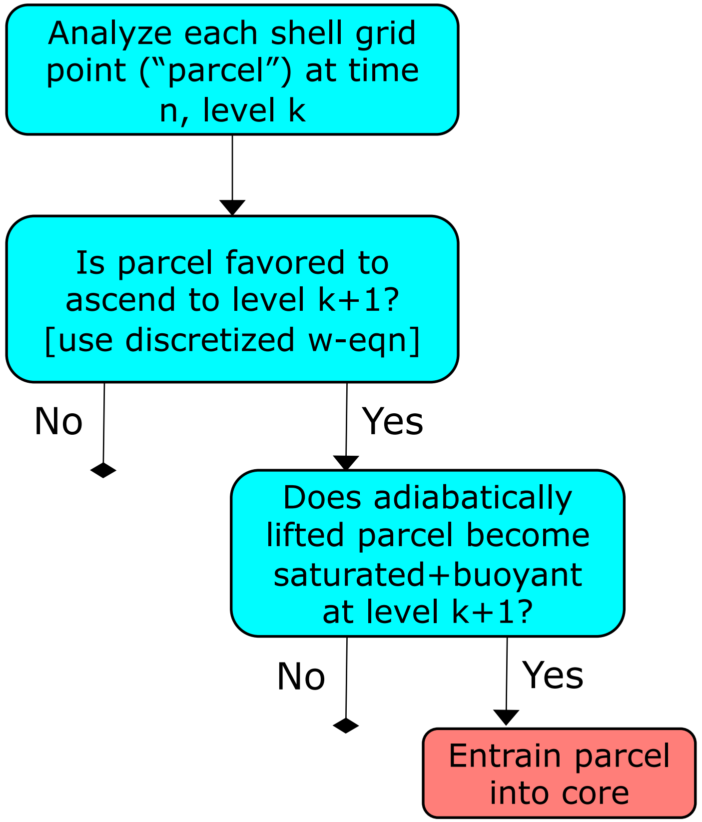


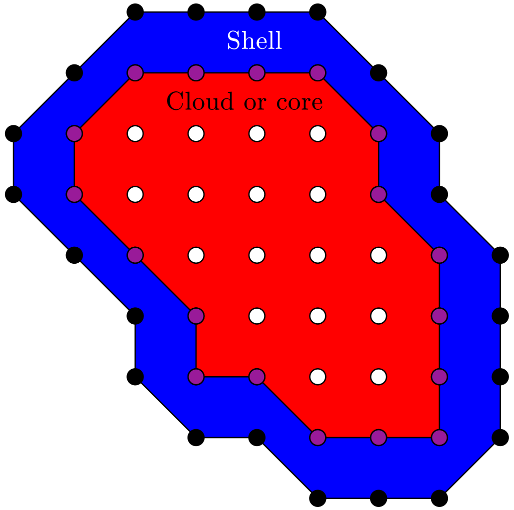
- How do shell parcels "activate"?
  1. REVERSIBLE lifting to level of free convection
  2. IRREVERSIBLE turbulent mixing with core boundary

- How do boundary parcels "deactivate"?
  1. REVERSIBLE loss of buoyancy or vertical momentum
  2. IRREVERSIBLE turbulent mixing with core shell

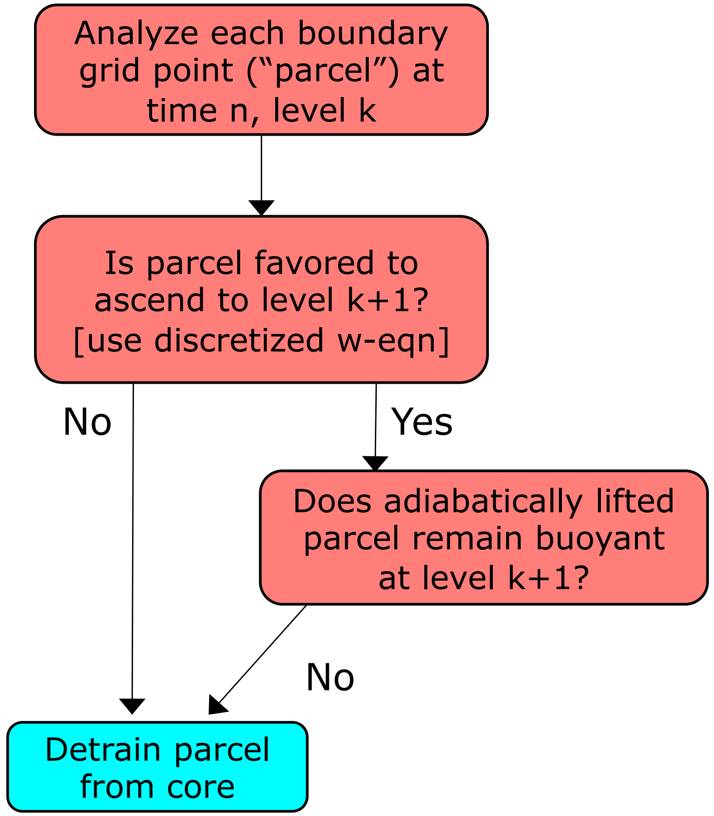
The adiabatic component (conceptually)

- Entrainment: core shell





- Detrainment: core boundary



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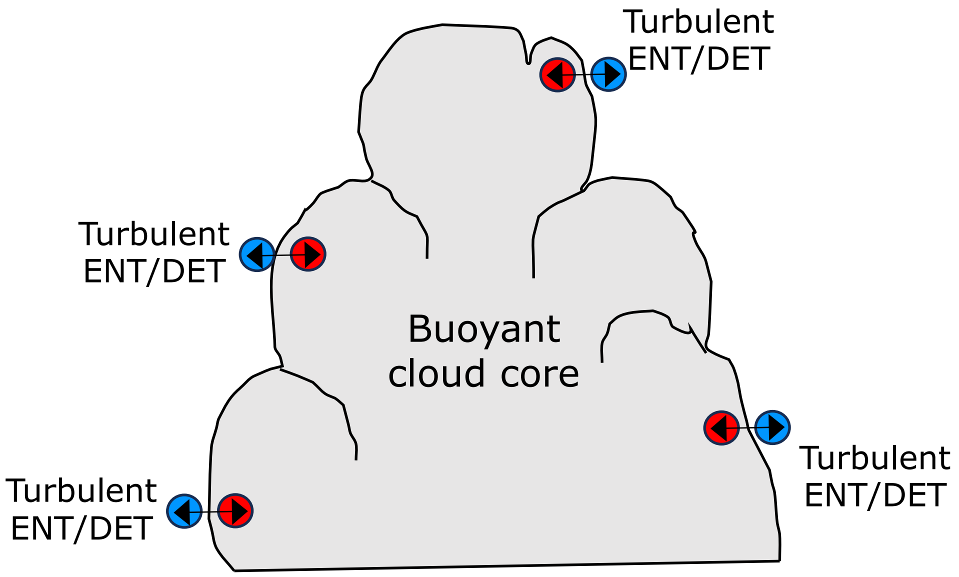
The diabatic component (conceptually)

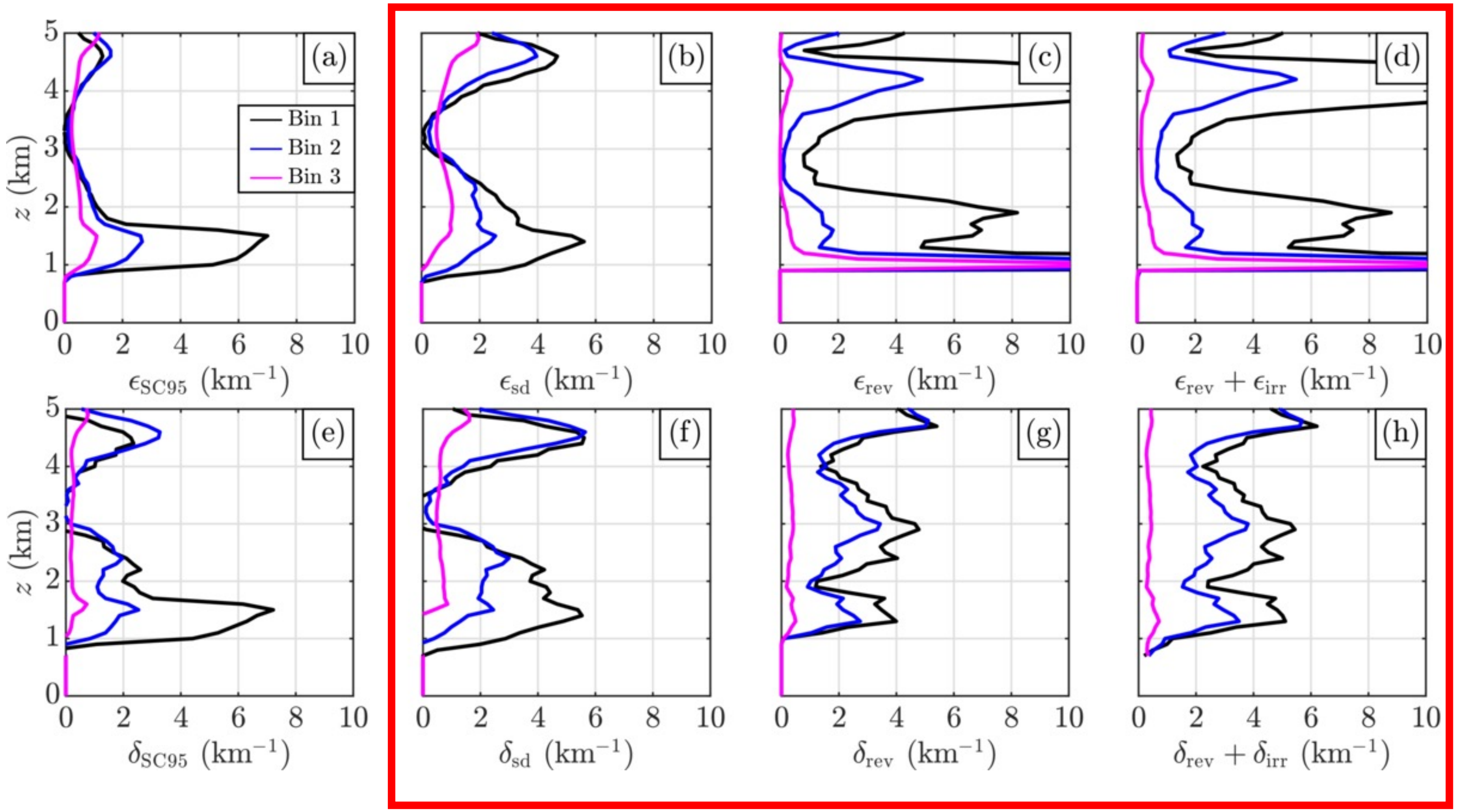
- Estimate turbulent scalar fluxes between boundary and shell, using same formulation as subgrid-scale (TKE) mixing
- Integrate fluxes around core perimeter, partition into E_{di}/D_{di} using boundary-shell critical mixing fraction (χ_{bs})



Decomposition results (sensitivity to A_c)

- Reversible component shows key similarities to semi-direct
  - Magnitudes ✓
  - A_c sensitivity ✓
  - Vertical variations ✓✗

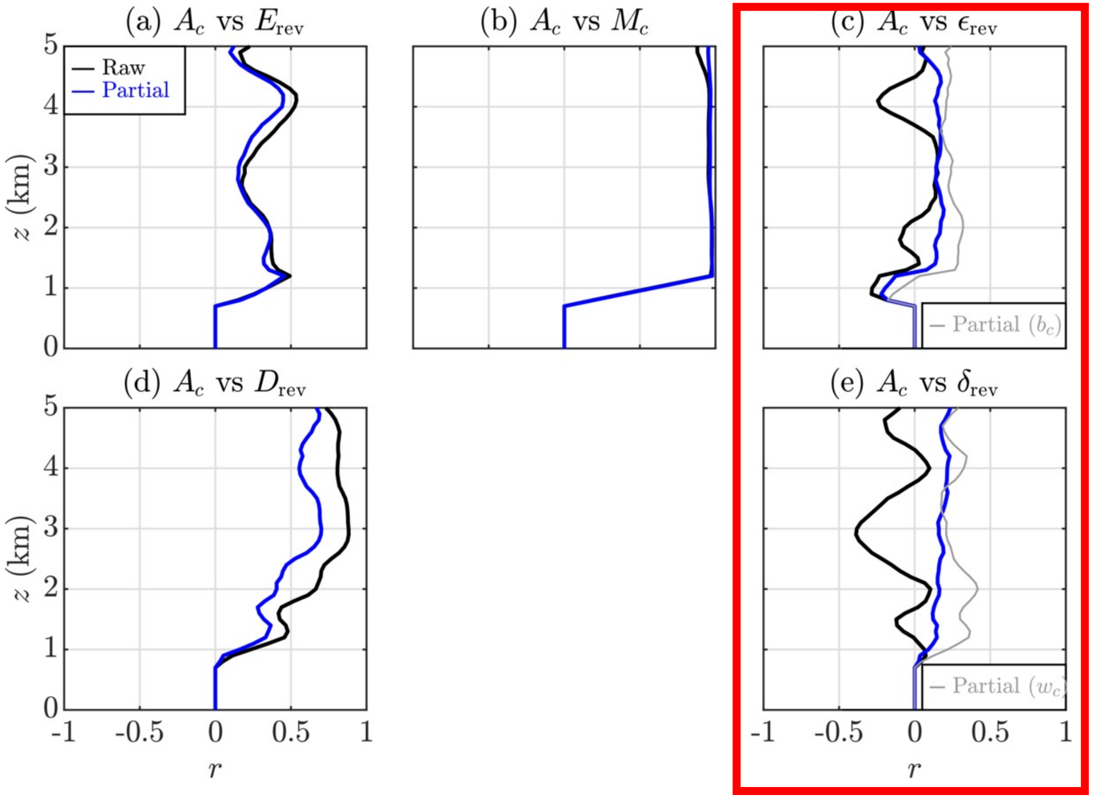
- Analyze the dominant reversible component to gain some insight



Sensitivity to A_c: interpretation

- Larger A_c → smaller ϵ_{rev}
  - E_{rev} increases linearly due to enhanced mixing, but M_c increases even faster
  - Relation vanishes when controlling for w_c or b_c
- Larger A_c → smaller δ_{rev}
  - D_{rev} increases nearly linearly with A_c, but M_c increases even faster
  - Relation vanishes when controlling for w_c or b_c
- Detrainment trend stronger due to differing feedbacks of ϵ, δ on A_c

Raw and partial Spearman correlations
(partial controls for [w_c, b_c, P_c))



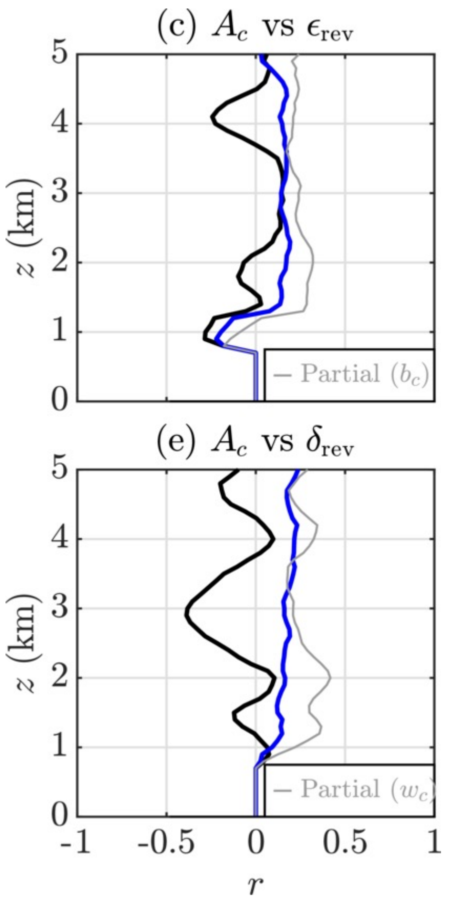
Sensitivity to A_c: interpretation (cont)

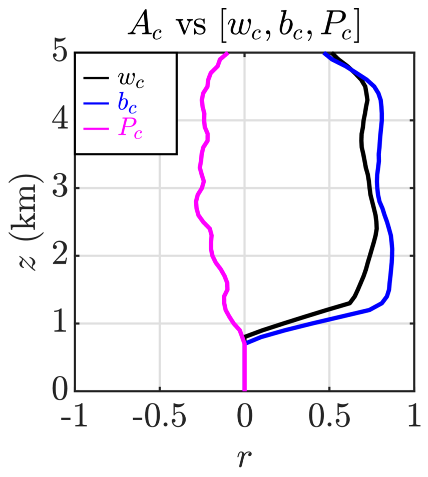
- Mostly negative trend between A_c and $[\epsilon, \delta]_{rev}$ is consistent with percentile-binning analyses shown earlier

- Why do correlations vanish when controlling for w_c, b_c, and P_c?
  - Strong correlation between A_c and b_c

- Possible explanations:
  1. A_c controls ϵ, δ. Larger A_c → smaller ϵ → larger b_c ✓
  2. b_c controls ϵ, δ. Larger b_c → smaller ϵ → larger A_c ✗

➢ **A_c must causally control ϵ, δ**



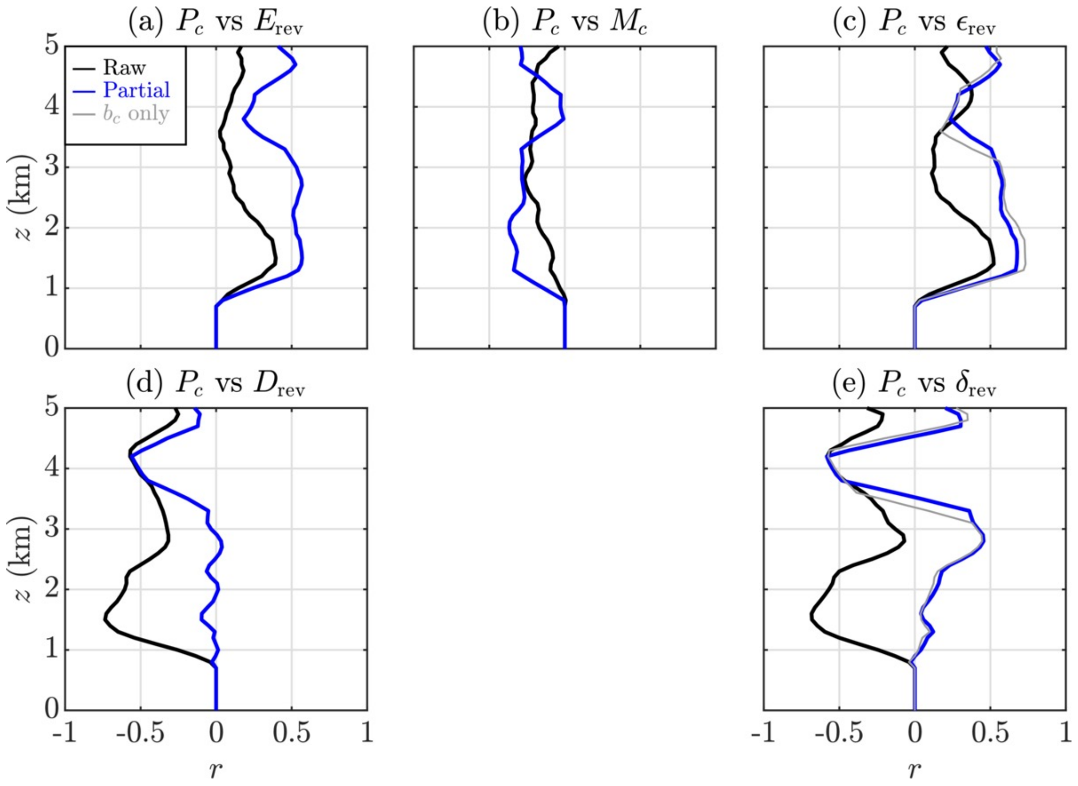


Sensitivity to P_c

- Larger P_c → larger ϵ (raw and partial)
  - Forced ascent of shell air → activation
  - Trend strengthens when controlling for b_c or A_c
- Larger P_c → smaller δ (raw)
  - Forced ascent of boundary air → less deactivation
  - Trend reverses when controlling for b_c
  - ➢ Enhanced ϵ at larger P_c reduces core-boundary b, promoting increased δ

➢ P_c correlates positively with *both* ϵ and δ

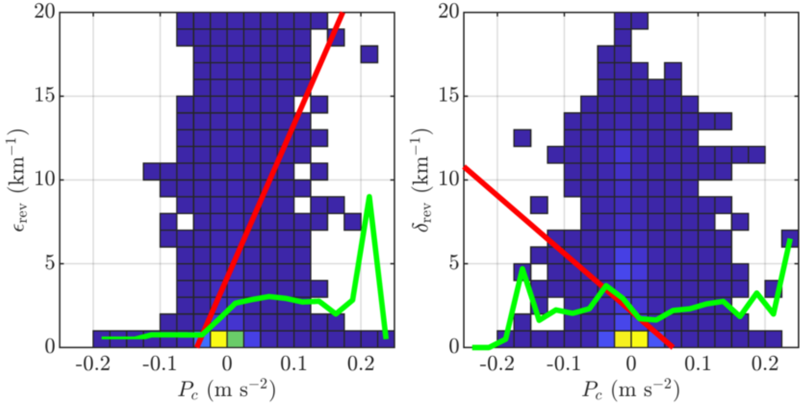
Raw and partial Spearman correlations
(partial controls for [w_c, b_c, P_c])

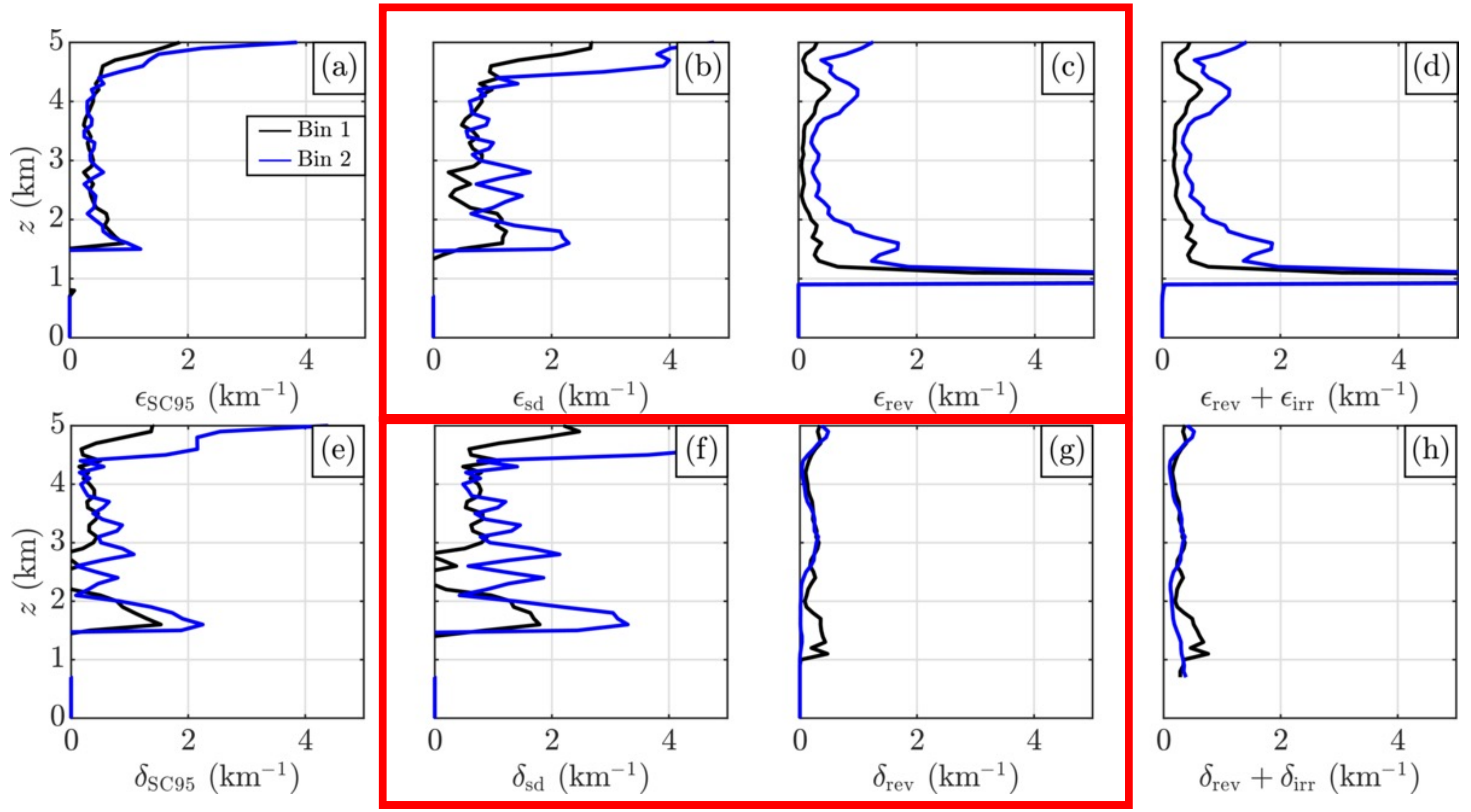


Sensitivity to P_c: further interpretation

- Reversible ϵ reasonably matches semi-direct trend
- Reversible δ inconsistent with semi-direct trends
  - Again, increased ϵ reduces b in core boundary, favoring stronger δ

Histograms of P_c vs $[\epsilon, \delta]_{rev}$





Conclusions

- Semi-direct provides a simplified method for estimating direct entrainment
  - Exploits that entrained and detrained air drawn from immediate core exterior and interior, respectively
- Reversible—irreversible decomposition builds on semi-direct assumptions to facilitate physical understanding
  - Adiabatic component dominant in current experiments
- Decomposition facilitates physical interpretation of controls on ϵ, δ
  - Inverse trend of ϵ with A_c: increased mixing can't keep pace with increased M_c
  - Positive trend ϵ with P_c: forced ascent induces activation of cloud-shell parcels