Maximum updraft velocity beyond CAPE:

the role of boundary layer dynamics and pressure perturbations

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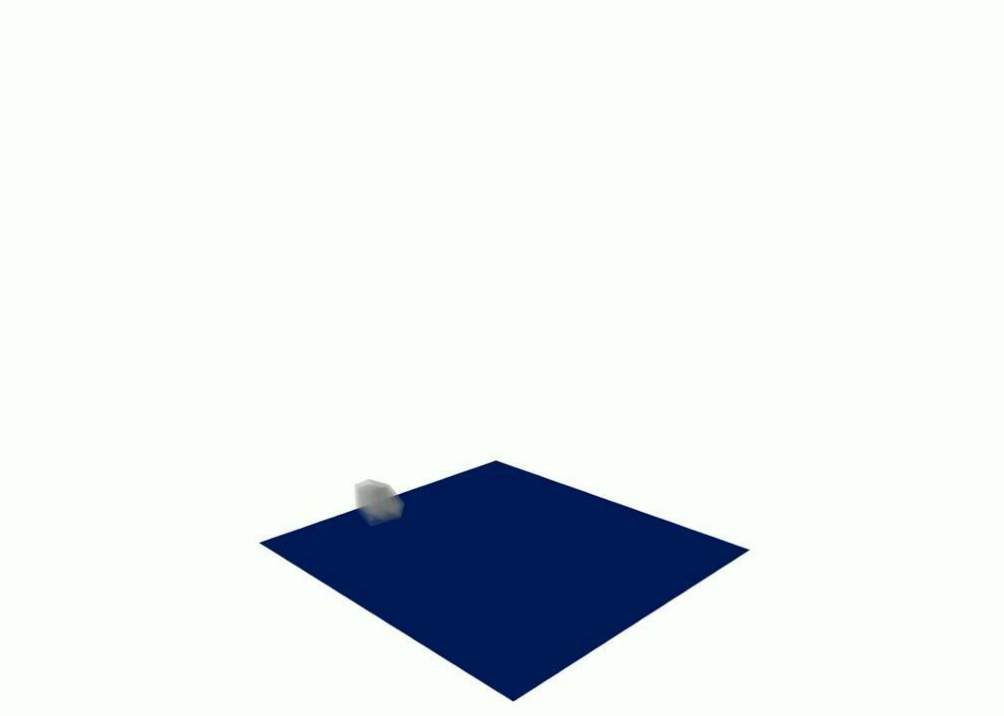
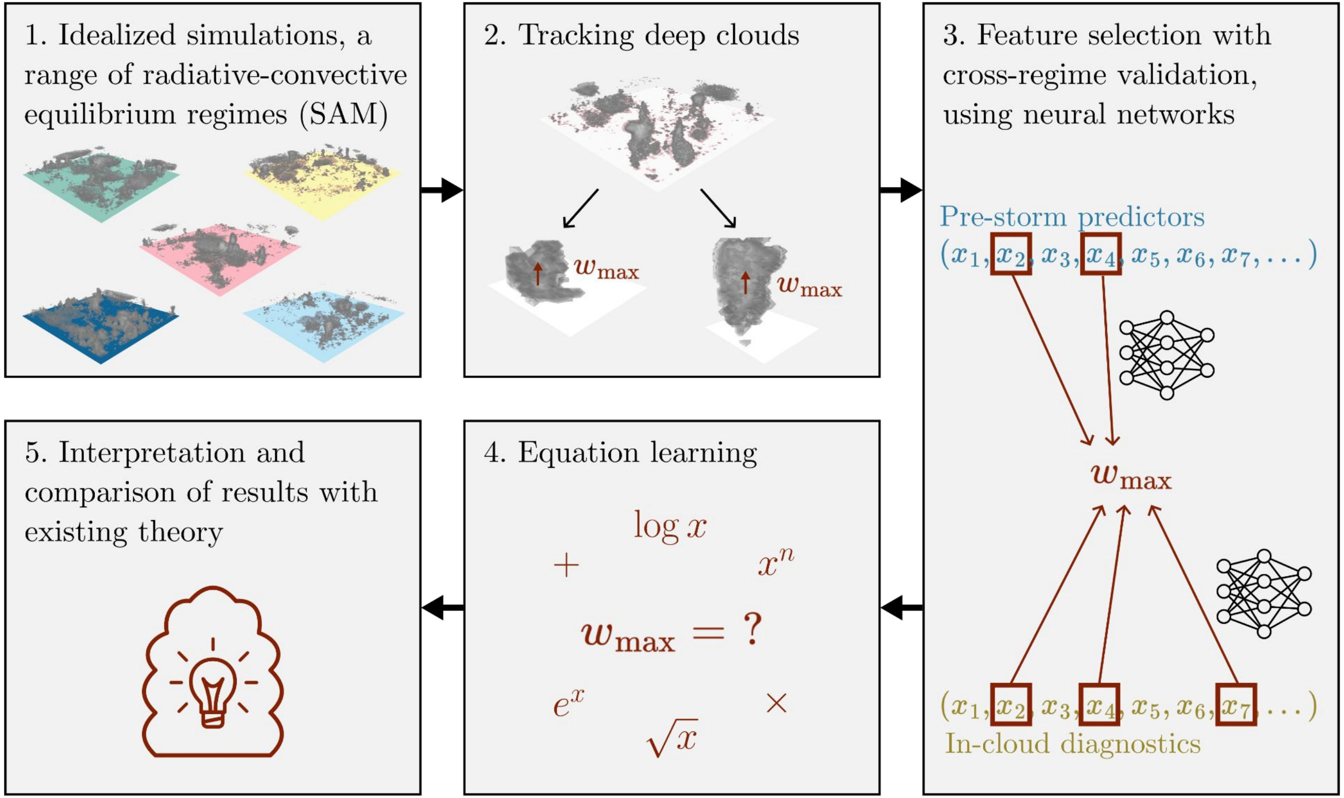
What sets the maximum updraft velocity (w_{max}) in idealized deep convection?



We use a **data-driven, per-cloud** approach to **discover equations** and improve our **understanding** of w_{max}

Framework



Method inspired by Beucler et al. 2025; Grundner et al. 2024; Shamekh et al. 2025; Zanna and Bolton 2020

What would we expect from theory?

1. **CAPE?**
   (convective available potential energy, Johns and Doswell 1992)

2. **Initial velocity or kinetic energy?**
   (e.g. Abramian, Muller and Risi 2023)

3. **Dominant terms from momentum balance?**
   (e.g. slippery (Sherwood et al. 2013) vs. sticky (Romps and Charn 2015) thermals)

What equations did we find?

And what did we learn?

1

rediscovered scaling

$$w_{\text{max}} \sim \sqrt{\text{CAPE}}$$

2

pre-storm predictive

$$w_{\text{max}} \sim \text{CAPE}\left(\log \frac{\overline{w_{\text{bl}}}^2 + b}{\text{CAPE}} + c\right)$$

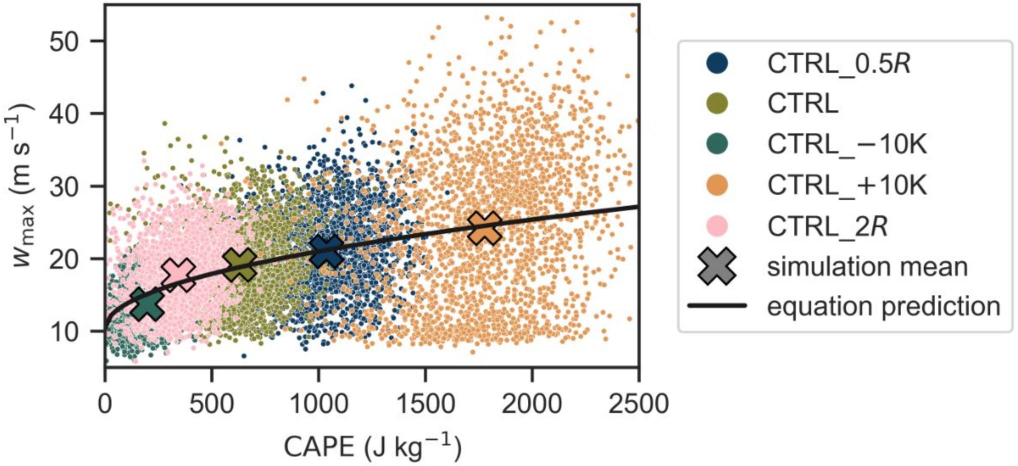
3

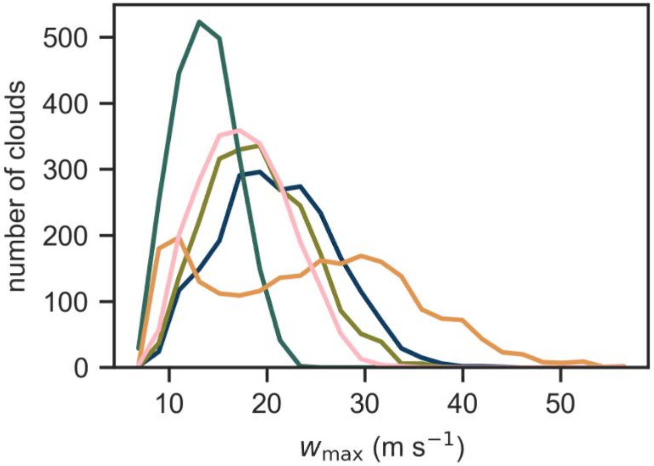
in-cloud diagnostic

$$w_{\text{max}} \sim \sqrt{a\left(\frac{p'}{\bar{p}}\right)_{\text{max}} + b\, q_{c,\text{max}} + c}$$

1. CAPE scaling: useful but not enough

$$w_{\max} = a\sqrt{\mathrm{CAPE}} + b$$





R^2 = 0.25 across regimes

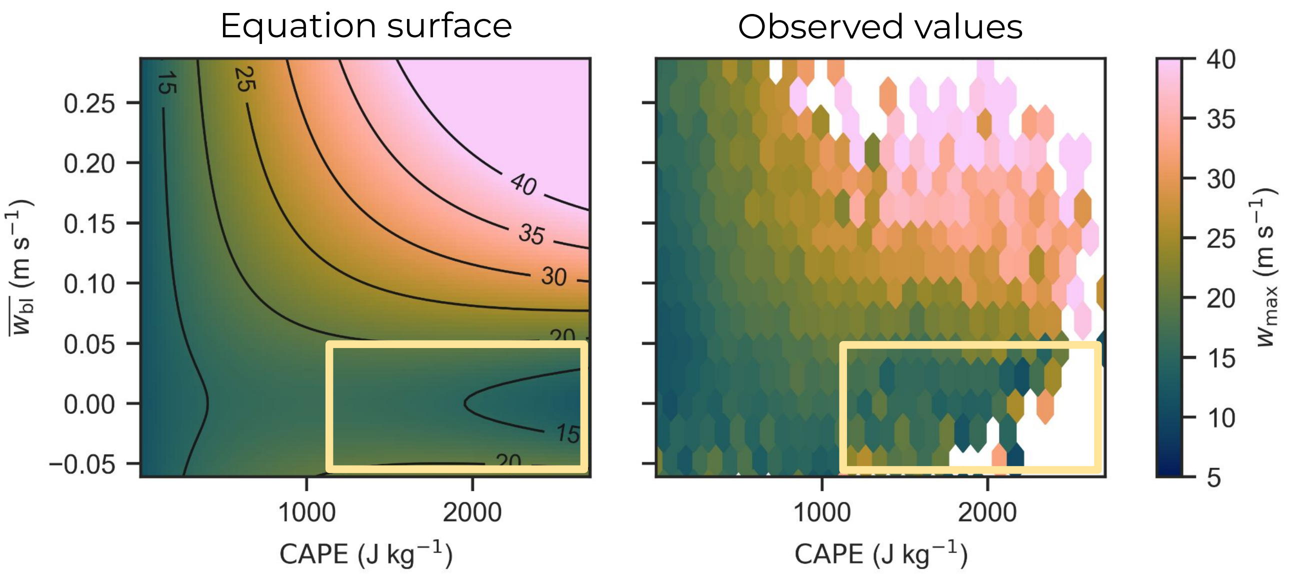
R^2 ≈ 0 within a simulation

Large cloud-to-cloud variability within each simulation

2. Beyond CAPE: boundary layer dynamics

$$w_{\max} = a\,\mathrm{CAPE}\left(\log\frac{\overline{w_{\mathrm{bl}}}^{2} + b}{\mathrm{CAPE}} + c\right) + d$$

$R^2 = 0.48$



$\overline{w_{\mathrm{bl}}}$ =
boundary-layer vertical velocity
30 min before w_{max}

What equations did we find?

And what did we learn?

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$$w_{\max} \sim \sqrt{\mathrm{CAPE}}$$

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$$w_{\max} \sim \mathrm{CAPE}\left(\log \frac{\overline{w_{\mathrm{bl}}}^2 + b}{\mathrm{CAPE}} + c\right)$$

3

in-cloud diagnostic

$$w_{\max} \sim \sqrt{a\left(\frac{p'}{\bar{p}}\right)_{\max} + b\, q_{c,\max} + c}$$

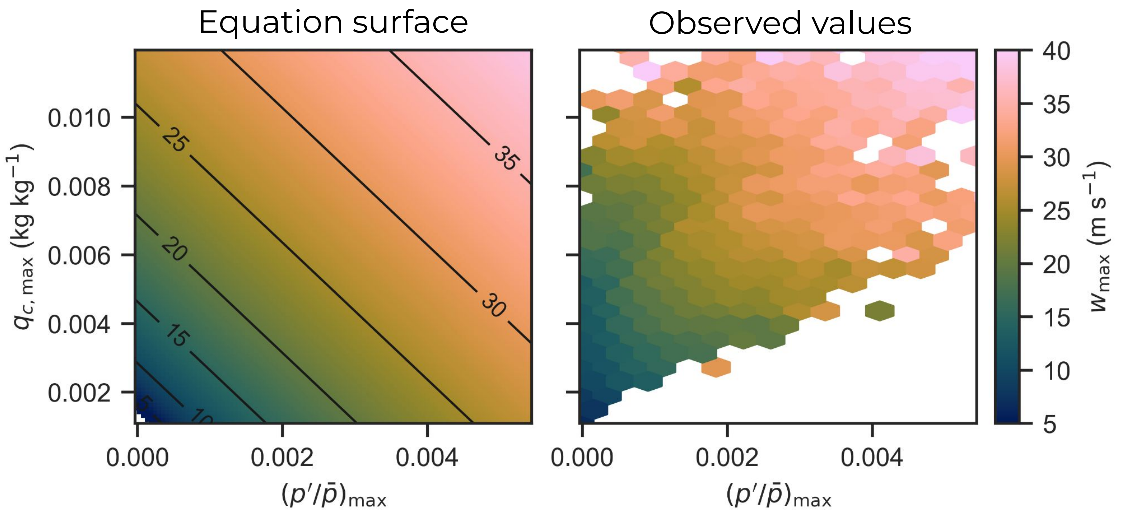
3. In-cloud extrema – evidence for sticky thermals

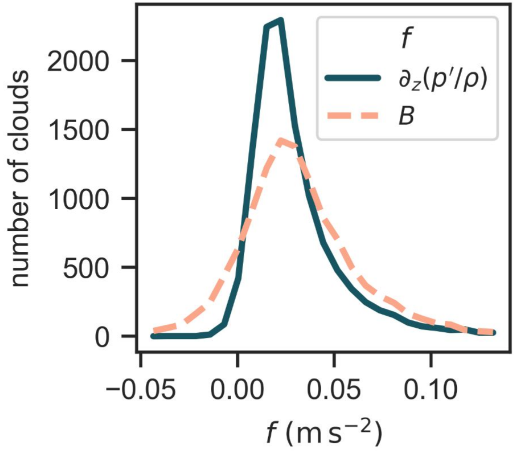
$$w_{\max} = \sqrt{a\left(\frac{p'}{\bar{p}}\right)_{\max} + b\, q_{c,\max} + c} + d$$

maximum pressure perturbation

maximum cloud condensate

$R^2 = 0.88$





buoyancy and pressure-gradient force comparable in magnitude

Summary

- √CAPE scaling rediscovered, but CAPE alone misses cloud-to-cloud variability **R^2 = 0.25**
- Boundary layer dynamics interact nonlinearly with CAPE to shape updraft intensity **R^2 = 0.48**
- In-cloud extrema of condensate and pressure scale tightly with w_{max} – evidence for sticky thermals **R^2 = 0.88**

Next: realistic simulations, w_{bl} role, pressure effects

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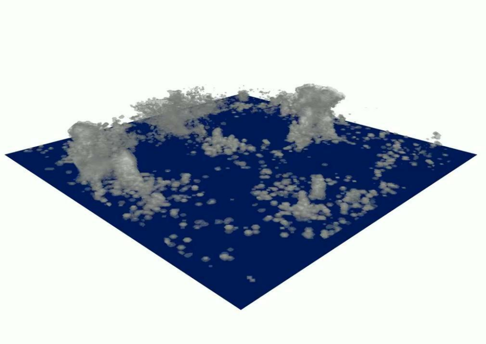
Preprint coming soon!

Framework – details

Simulations:

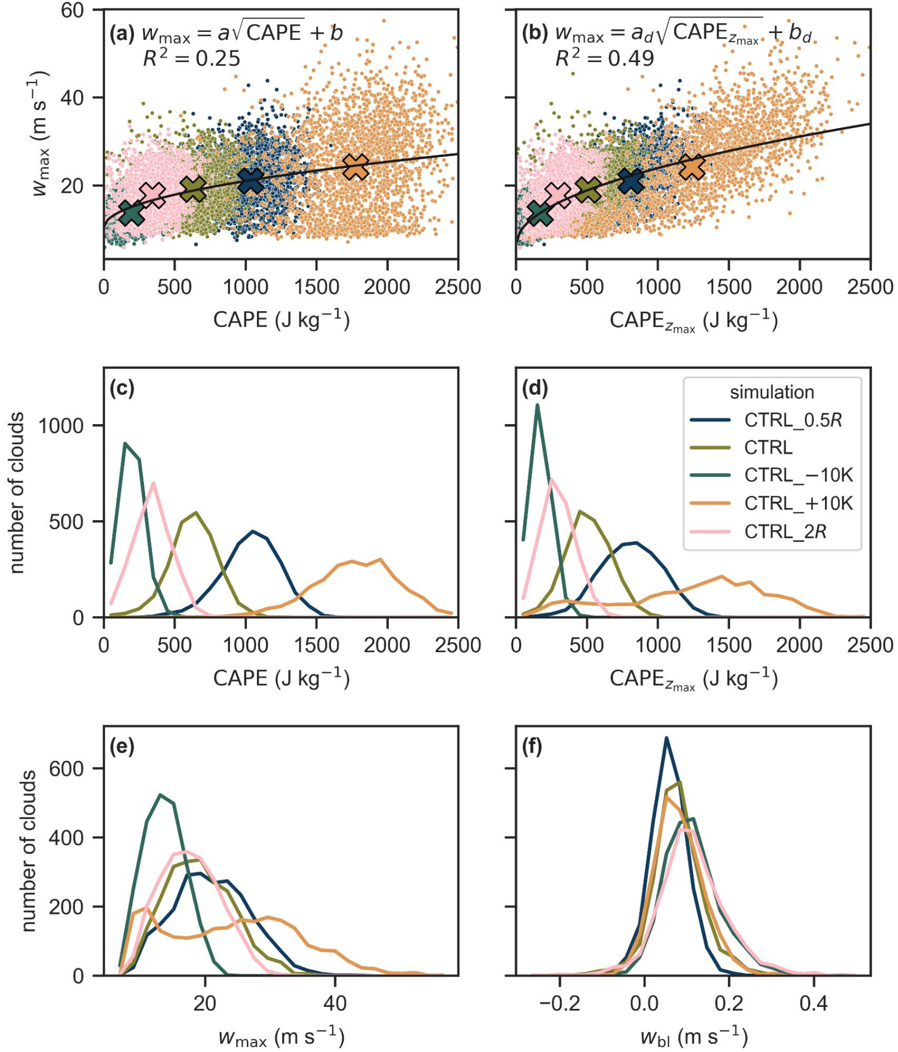
- **SAM** v6.10.8 (Khairoutdinov and Randall 2003), 128×128 km, 1 km horizontal resolution, 5 minute averaged outputs
- **5 RCE regimes**:
  CTRL (SST = 300 K, *R* = 1.5 K/day),
  CTRL_–10K, CTRL_0.5*R*,
  CTRL_+10K, CTRL_2*R*



Methods:

- Watershed-based cloud tracking algorithm (Casallas et al. 2025)
- **Two tracks: Pre-storm** (lagged predictors) and **In-cloud** (concomitant diagnostics)
- Feature selection: Neural networks + leave-one-simulation-out CV
- **Equation discovery: PySR** (Cranmer 2023) and **pySINDy** (Kaptanoglu et al. 2022)

The role of the height where the maximum updraft velocity occurs



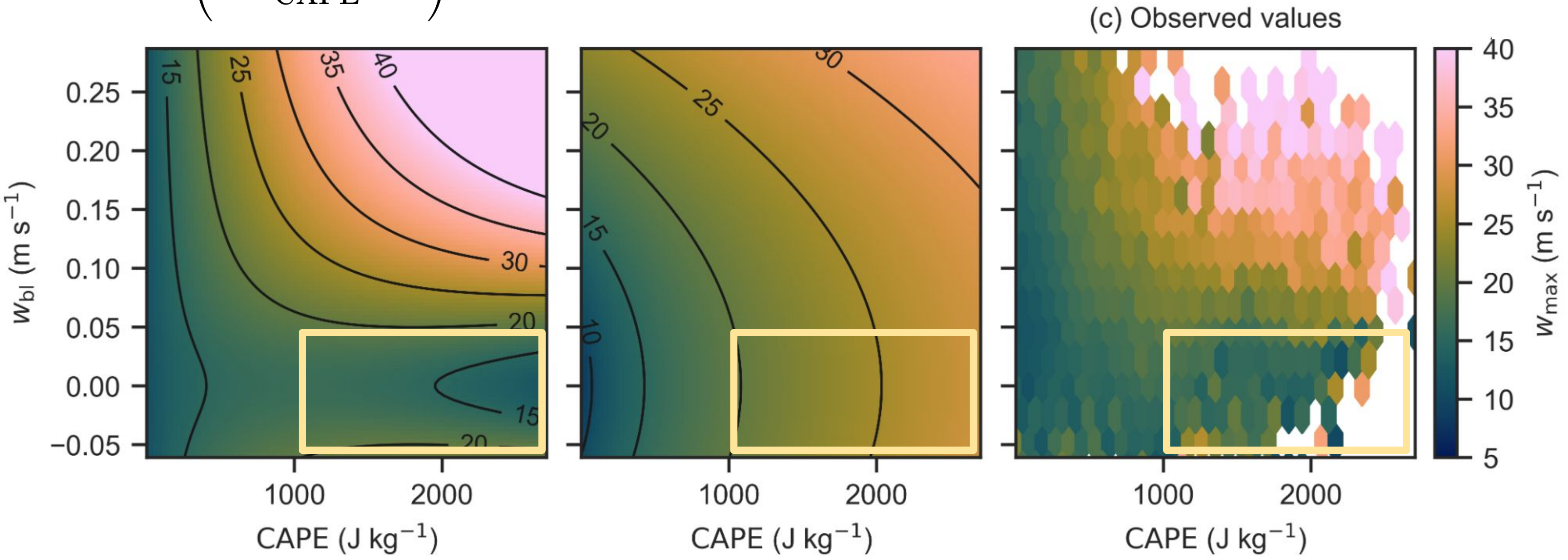
Pre-storm two-variable predictive equations

(a) Discovered PySR equation

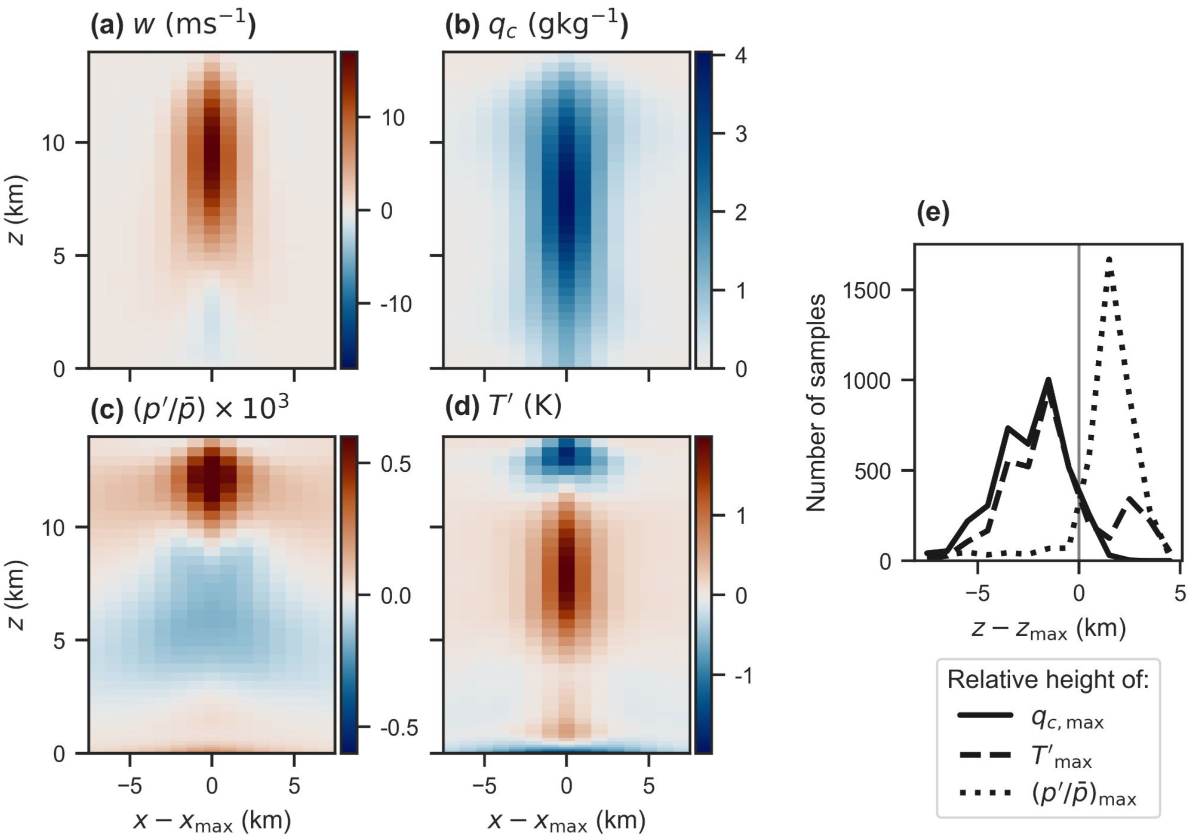
$$w_{\max} = a\,\mathrm{CAPE}\left(\log\frac{\overline{w_{\mathrm{bl}}}^2 + b}{\mathrm{CAPE}} + c\right) + d$$

(b) Baseline equation

$$w_{\max} = a\sqrt{\mathrm{CAPE} + b\,\overline{w_{\mathrm{bl}}}^2} + c$$



Composite plots at the time of peak intensity



Role of pressure perturbations in updrafts