Cloud Updraft Dynamics and Growth in Terrain-Forced Convection

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1. Introduction and Objective

Deep convection is both one important regulator of Earth's climate, and it is also the process that drives many extreme weather events. However, it remains difficult to reliably represent in numerical weather and climate prediction models because we lack a full process-level understanding of how cumuliform clouds evolve from weak, shallow cumuli to deep cumulonimbi that have important implications on the transport of mass, water, and momentum through the troposphere. While environmental humidity is an important regulator on growth of deep convection (Nelson 2022), updraft size likely also impacts the rate at which dilution of buoyancy occurs in an updraft (Morrison et al 2022, Peters et al 2022). However, the governor(s) of updraft size remain unclear.

Research Questions/Hypotheses:

What controls which cumulus clouds in a population grow and those that do not?

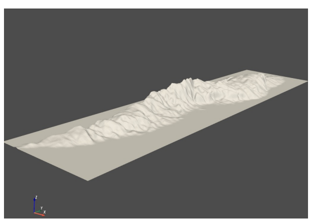
1) Updrafts deepen because they they have stronger vertical velocity near cloud base (akin to a "nature" argument from Romps and Kuang 2010).
2) Updrafts deepen because they experience more upward acceleration/less downward acceleration in cloud (similar to the Romps and Kuang "nurture" paradigm)
3) What controls cloud base updraft properties that cause some updrafts to experience different accelerations than other similar updrafts in the same general location?

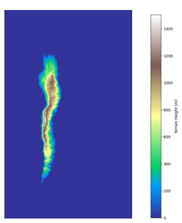
2. Model Simulation

- Large eddy simulations (100 m grid spacing) were executed with Cloud Model 1 (CM1) V21.0 of cumuliform convection forced by terrain with low-level easterly flow. A realistic representation of the Sierra de Córdoba in Argentina was placed along the bottom boundary surrounded by flat terrain. Lateral boundary conditions were periodic. The western and eastern boundaries were stretched (to a maximum grid spacing of 5900m) to prevent cloud from advecting back around to the mountain range. Deep convection primarily developed along the eastern slope of the terrain feature.

- Lagrangian analysis was conducted by using parcel trajectories. These trajectories were advected passively during model integration and their three-dimensional position was recorded every minute. This enabled analysis of cloud and updraft properties during ascent but also properties of fluid in the sub-cloud layer before ascent.

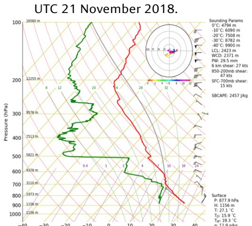
- Similarly to Powell (2023), parcels were categorized as either "growers" (defined as parcels that reached the upper 5th percentile heights) or "non-growers" (they started to ascend in-cloud but stopped doing so between 2000m and 3500 m). Analysis was restricted to times when the parcels were ascending inside a cloud plus the 15 minutes prior to this ascent if the parcel was located below the LCL.





3D representation of Sierra de Córdoba used in CM1 using 100 m grid spacing

Input Sounding- Observed during CACTI campaign at 2100 UTC 21 November 2018.



4. Ongoing/Future Work

- Why is fractional dilution less for grower parcels? Are they located in larger updrafts? Is there a fundamental relationship between boundary layer convergence and updraft size? If so, what is the arrow of causality?

- How does the Sierra de Córdoba range modulate the horizontal distribution of low-level convergence and sub-cloud layer properties? Does any such distribution impact the size and strength of updrafts forming along the terrain?

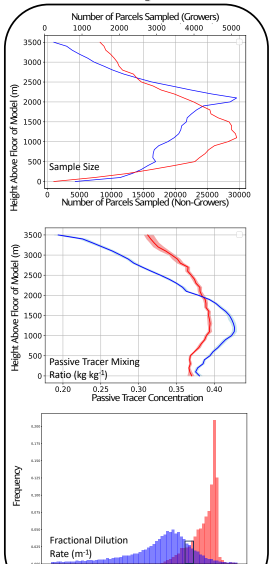
- If so, are there favored locations along the Sierra de Córdoba where convection tends to initialize (observations suggest yes) because of horizontal variability in boundary layer dynamic processes, Do these locations change based on low-level wind direction/magnitude?

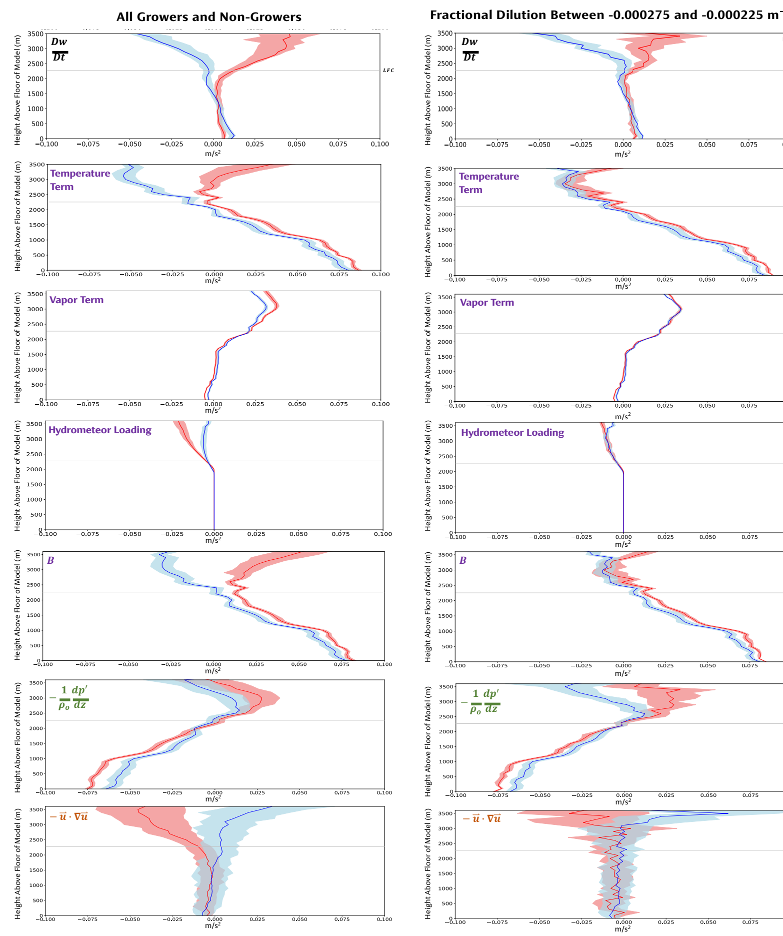
3. Parcel Properties in Convection

= Growers   = Non-Growers

$$\frac{Dw}{Dt} \cong B - \frac{1}{\rho_o}\frac{dp'}{dz} - \vec{u}\cdot\nabla\vec{u}$$

$$B = g\left[\underbrace{\frac{\theta^*}{\theta_o}}_{\text{Temperature Term}} + \overbrace{\varepsilon(q_v - q_{vo})}^{\text{Vapor Term}} - \underbrace{q_{Li}}_{\text{Hydrometeor Loading}}\right]$$





Conclusions

- Fractional dilution was significantly different between ascending and not-ascending parcels. Grower parcels were warmer and contained more water vapor than non-grower parcels.

- Among growers and non-growers with the same dilution rate, buoyancy terms were similar. Decelerations due to vertical PGF instead appeared primarily responsible for the difference between growers and non-growers.

- Effective buoyancy ($B - \frac{1}{\rho_o}\frac{dp'}{dz}$) partially balanced by momentum advection.

References

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