Critical Updraft Quantities in LES Models of Shallow to Deep Convective Transitions

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1. Introduction

The cumuliform life cycle in the tropics typically progresses as follows: shallow convection → moderately deep convection with limited lateral growth → deep convective cores with limited lateral growth → deep convection with laterally extensive stratiform → decaying convection

In numerical models, the convective life cycle is largely controlled by cumulus parameterization, which attempts to replicate the convective life cycle based on assumed interactions between convective elements and their environments. This is often not done well, partially because controls on rain rate aren't purely thermodynamic.

The transition from shallow to deep cloud is critical to problems related to deep "convective initiation" on multiple spatial and temporal time scales. For example, rapid decreases in negative buoyancy between 850 and 700 hPa appears to coincide with the beginning of deep convective transition in the MJO during DYNAMO (see below from WRF simulations discussed by Powell 2016)[1].

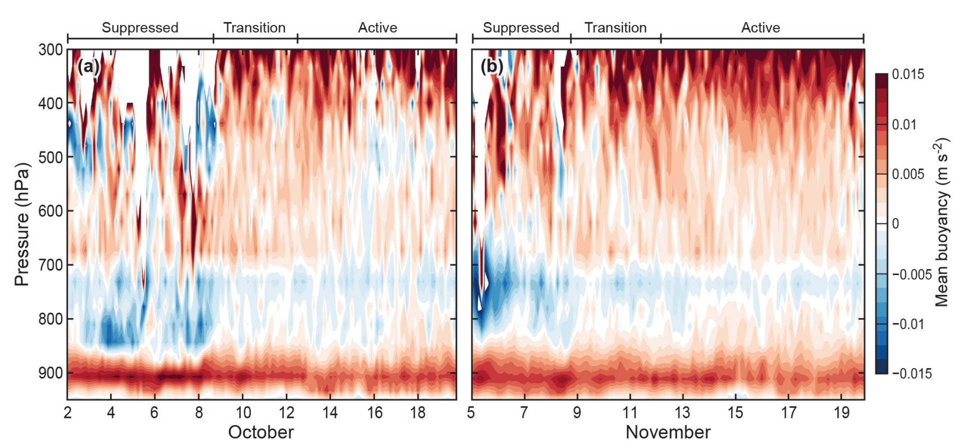


Figure 1: *Mean buoyancy of cloudy updrafts in WRF (Powell 2016).*

2. Model (CM1)

Domain size: 64 km x 64 km x 20 km
Grid spacing: 100 m, variable vertical with 50 m in boundary layer
Initial perturbations: White noise added to temperature in boundary layer at start
Integration time: 24 hours
Output frequency: 10 min (1 min for Base)
Boundary conditions: Periodic, fixed SST (301.5K)

TABLE 1. Physics options used for CM1 simulations.

Parameterization	*Selection*	*Reference*
Microphysics	Morrison	Morrison et al. (2009)
Boundary Layer	*None*	
Surface	MM5 similarity	Jiménez et al. (2012)
Radiation	NASA-Goddard	Chou and Suarez (1999) Chou et al. (2001)
Turbulence	Smagorinsky	Stevens et al. (1999)

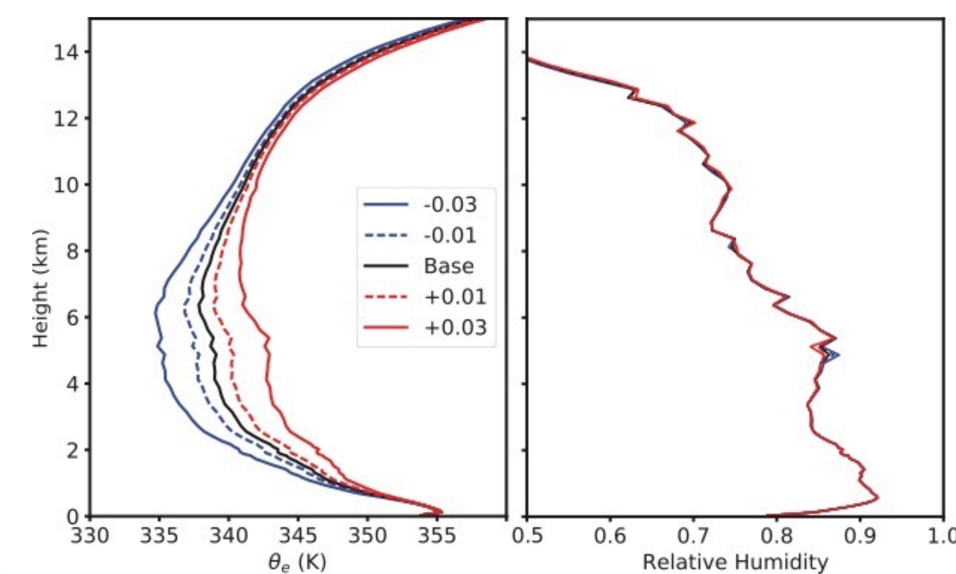


Figure 2: *Initial profiles of a) θ_e and b) relative humidity used to force the simulations.*

Five simulation were run with identical RH profiles and variable temperature profiles. Black line represents the "Base" or control simulation that is based on DYNAMO soundings during rainy periods. Variations in temperature profiles are related to those caused by variability in large-scale vertical velocity associated with the MJO (Powell and Houze 2015)[2]. (This is not a study about the MJO, but MJO partially motivates it!)

3. What does the model produce?

A simple validation

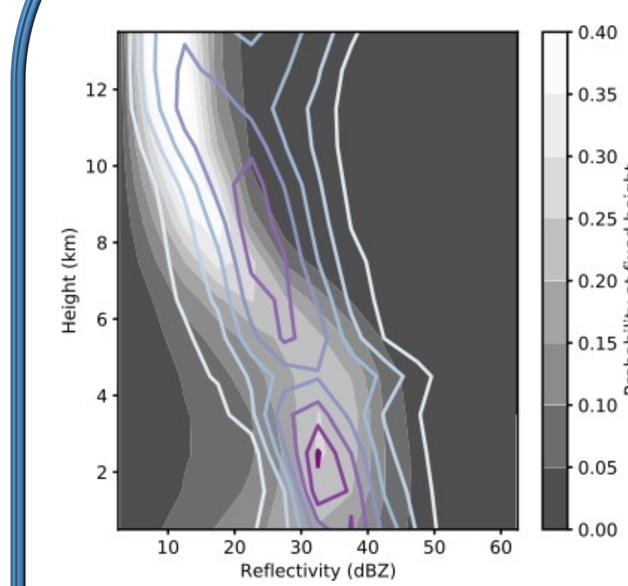
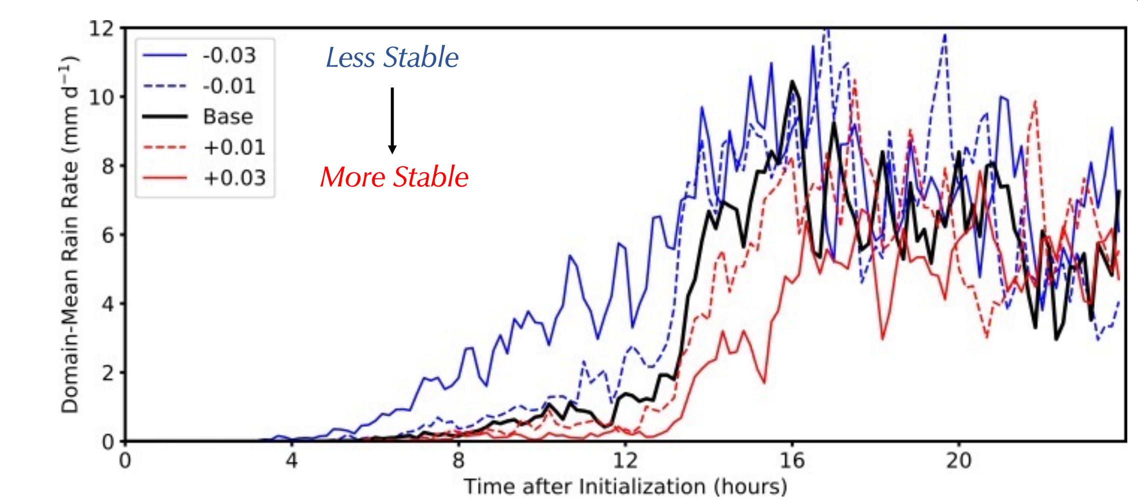


Figure 3: *Two-dimensional normalized histograms of reflectivity as a function of altitude. Distributions are normalized in each vertical bin. Shading denotes observed distributions as seen by S-PolKa during DYNAMO, and contours denote distributions simulated. The two are roughly in agreement, especially below the 0°C level. However, the model does not produce the appropriate reduction in the large tail of the hydrometeor size distribution at the 0°C level, and as a result, reflectivity in the model is biased high against observations above 5 km.*

Figure 4: *Domain-mean rain rate as a function of time for each of the five simulations.*



All but the most unstable (blue) simulation exhibit some sort of rapid transition to higher rain rates. This implies existence of some sort of criticality in the system[3]. Prior to transition, rain rate is related directly to instability of initial sounding. All simulations approach a similar state by 18 hours.

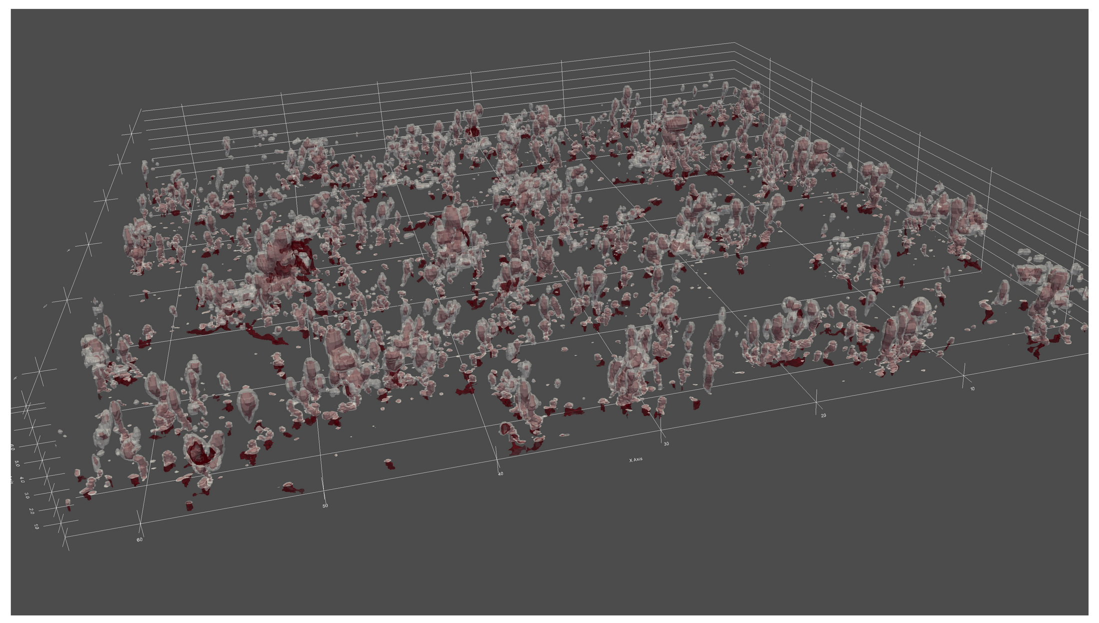


Figure 5: *Snapshot of cloud population (white shading) with updrafts stronger than 1 m s^{-1} (red shading) in clouds or contiguous with them in the Base simulation about one hour before the rapid increase in rainfall at 13 hours.*

Or click link below: https://www.youtube.com/watch?v=r4crrNR3IPU

Scan me with phone or tablet to view animation.

4. Vertical Accelerations During Convective Transitions

$$\frac{Dw}{Dt} = \underbrace{-\frac{1}{\rho}\frac{\partial p'}{\partial z}}_{A} + \underbrace{B}_{B}$$

"Total" vertical acceleration (anelastic, no friction): Approximate balance between relative buoyancy and vertical pressure gradient acceleration. Similar quantities computed previously.[4,5,6]

$$B = g\left[\frac{\theta^*}{\theta_0} + \left(\frac{R_v}{R_d} - 1\right)q_v^* - q_{lf}\right]$$

Buoyancy relative to arbitrary reference state; in case of CM1, the initial sounding

How does Dw/Dt in updrafts (defined as w > 0.1 m s^{-1} in cloud and > 1 m s^{-1} if out of cloud and connected to in-cloud updraft) evolve?

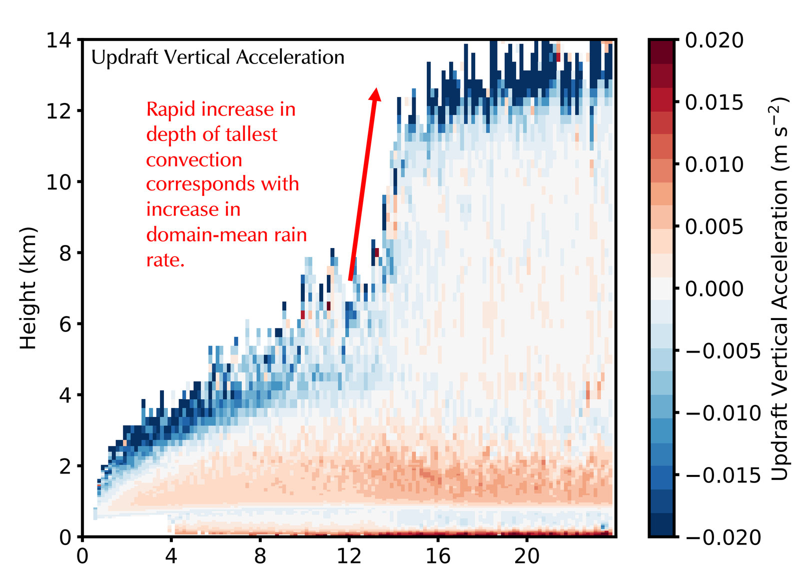


Figure 6: *Time series of vertical profiles of domain-mean Dw/Dt in updrafts only. Uncolored regions indicate altitudes and times at which no cumuliform cloud was present. Blue = deceleration; Red = acceleration*

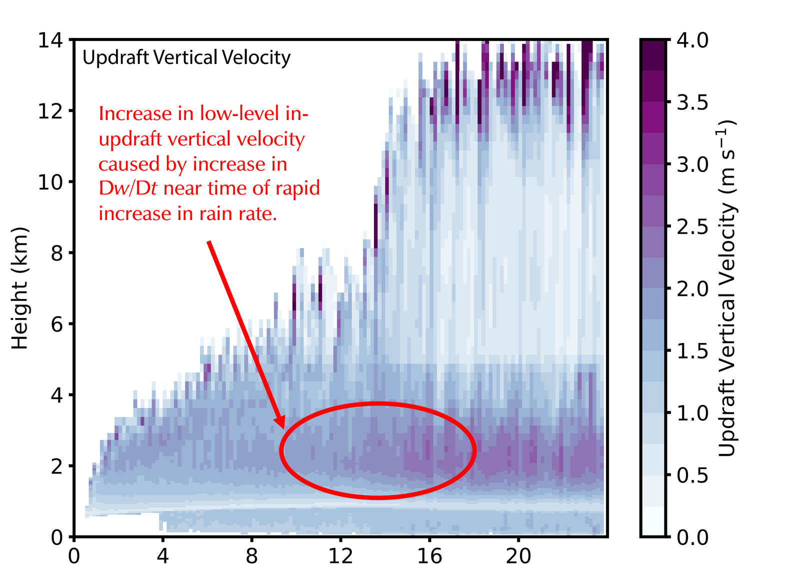
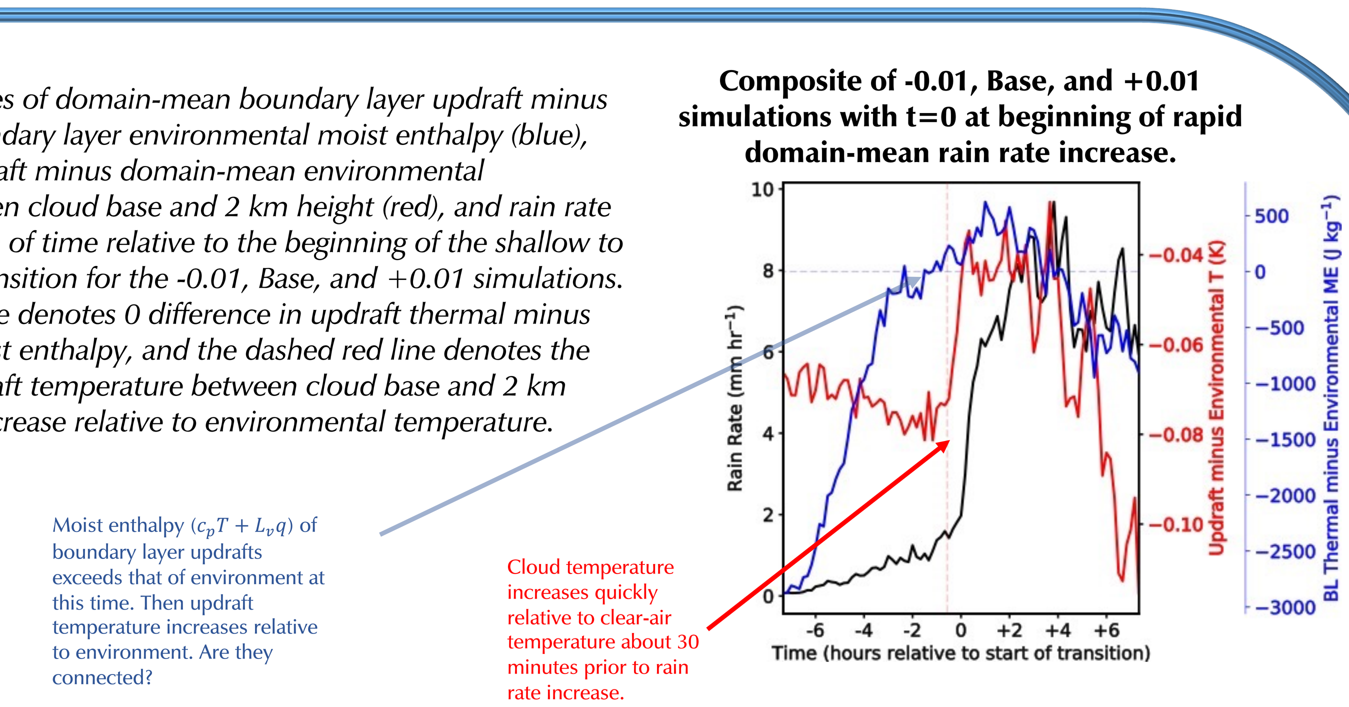


Figure 7: *As in Fig. 6, but for domain-mean updraft vertical velocity. The lighter colors in top right denote upward motion in broad stratiform regions that develop after rain rate rapidly increases and are connected to convective updrafts.*

5. Rain Rate Dependence upon Environment and Updraft Characteristics

Figure 8: *Time series of domain-mean boundary layer updraft minus domain-mean boundary layer environmental moist enthalpy (blue), domain-mean updraft minus domain-mean environmental temperature between cloud base and 2 km height (red), and rain rate (black) as a function of time relative to the beginning of the shallow to deep convective transition for the -0.01, Base, and +0.01 simulations. The dashed blue line denotes 0 difference in updraft thermal minus environmental moist enthalpy, and the dashed red line denotes the time at which updraft temperature between cloud base and 2 km begins to rapidly increase relative to environmental temperature.*



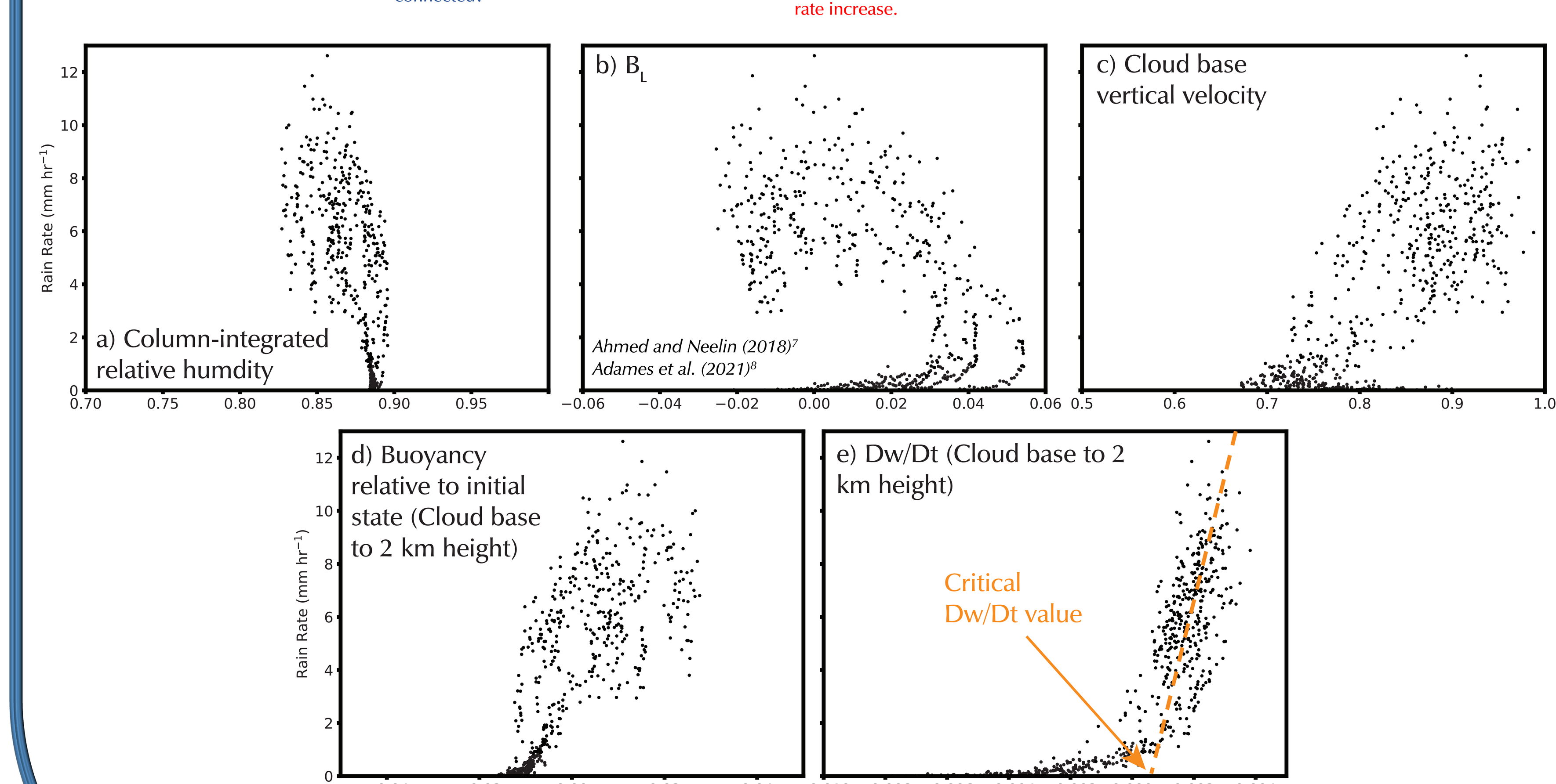
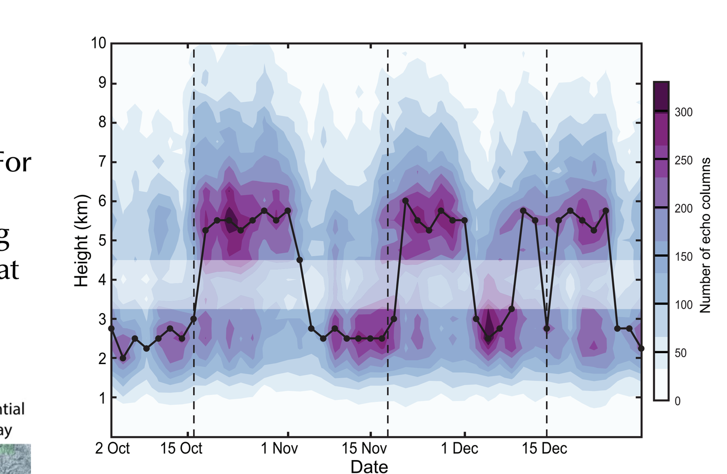


Figure 9: *Scatter plots of various domain-mean various vs. domain-mean rain rate. All five simulations are combined into each panel. While weak relationships between cloud base vertical velocity or buoyancy relative to the initial sounding are found with respect to rain rate, domain-mean in-cloud total vertical acceleration appears to most closely relate to domain-mean rain rate.*

6. Conclusions

- For a moist environment, rain rate prior to shallow-to-deep convective transition is at least partially dependent upon the atmospheric temperature profile (lapse rate). This has been documented before (Wu et al. 200X)[9].
- Some simulations include rapid increases in domain-mean rain rate (doubling or tripling within an hour), although the most unstable sounding exhibits a steady increase in rain rate.
- Regardless of the initial sounding, all simulations evolve to apparently similar states after their maximum rain rates are achieved.
- When averaged over entire 64 km x 64 km model domain, rain rate is more closely related to total vertical acceleration (neglecting friction, drag) than to buoyancy relative to initial state or environmental B_L (as defined previously[7,8]). In fact, for this setup, a critical D*w*/D*t* between cloud base and 2 km altitude of about 0.0005 m s^{-2} was found. Regardless of the initial sounding used, rain rate increased as D*w*/D*t* in this layer increased above the critical value.

Figure 10: Are the rapid transitions seen in these simulations similar to transitions that have been observed on longer time scales? For example, to the right is a time series of echo top heights derived from TRMM radar during DYNAMO, which indicated that convection at MJO onset of the MJO rapidly increased in depth over just 2–3 days[10].



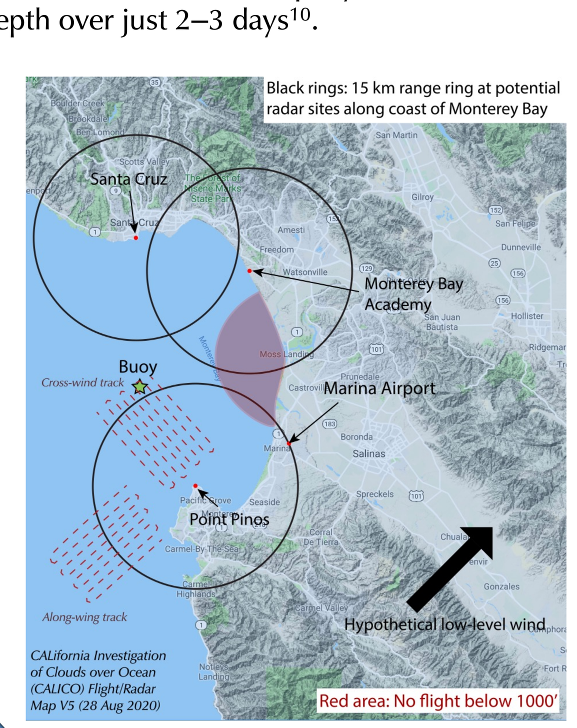


Figure 11: CALifornia Investigation of Convection over Ocean (CALICO; planned for Early 2022): Small ONR-sponsored joint aircraft/Ka-band radar observational field effort to investigate the properties of clouds and their environment during postfrontal convective events along the US West Coast.

Not tropical! But the dynamics of convective growth are quite similar. Goals include investigating relative importance of boundary layer and free tropospheric thermodynamic properties as well as properties of clouds themselves to shallow convective growth. Please reach out if you find this interesting!

7. References

[1] Powell (2016), *JAS*, **73**, 2913–2934
[2] Powell and Houze (2015), *JGR-Atmos.*, **120**, 4783–4805
[3] Peters and Neelin (2006), *Nature Phys.*, **2**, 393–396
[4] Davies-Jones (2003), *JAS*, **60**, 2922–2925
[5] Jevanjee and Romps (2016), *QJRMS*, **142**, 811–820
[6] Nugent and Smith (2014), *JAS*, **71**, 991–1007
[7] Ahmed and Neelin (2018), *JAS*, **75**, 1587–1608.
[8] Adames et al. (2021), *JAS*, **78**, 509–528.
[9] Wu et al. (2009), *JAS.*, **66**, 1793–1806
[10] Powell and Houze (2015), *JGR-Atmos.*, **120**, 3906–3919

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