Convective Transitions from Shallow Cumuli to Deep Cumulonimbi

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1. Introduction

Parameterization of clouds in coarse weather and climate models frequently include assumptions not supported by observations:

1) A trigger function that permits deep convection when environmental RH exceeds a certain value.

2) Lateral entrainment that is sensitive to environmental RH.

However, theoretical and modeling studies suggest that convection is sensitive in a non-negligible way not just to the atmospheric thermodynamic state, but also its dynamic structure (e.g., wind shear) as well as physical characteristics of the convection itself (e.g., updraft radii).

2. Updraft Vertical Accelerations During Convective Transitions

a) Background

Vertical momentum equation, without diffusion and mixing:

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

w: Vertical velocity
ρ: Fluid Density
p': Pressure perturbation from hydrostatic balance
B: Archimedean buoyancy

The vertical pressure gradient acceleration can be separated into two terms: One associated with a buoyancy pressure perturbation, and one associated with a dynamic pressure perturbation.

$$\frac{Dw}{Dt} = -\frac{1}{\rho}\left(\frac{\partial p_D}{\partial z} + \frac{\partial p_B}{\partial z}\right) + B$$

b) Simulations of Convective Transitions

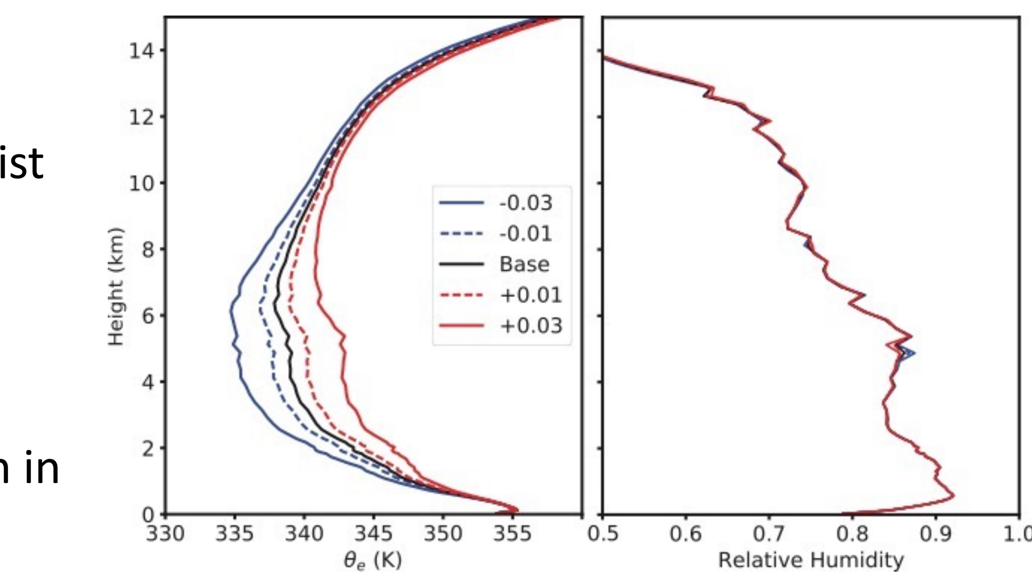
Run Cloud Model 1 (CM1) in LES configuration with moist tropical sounding.

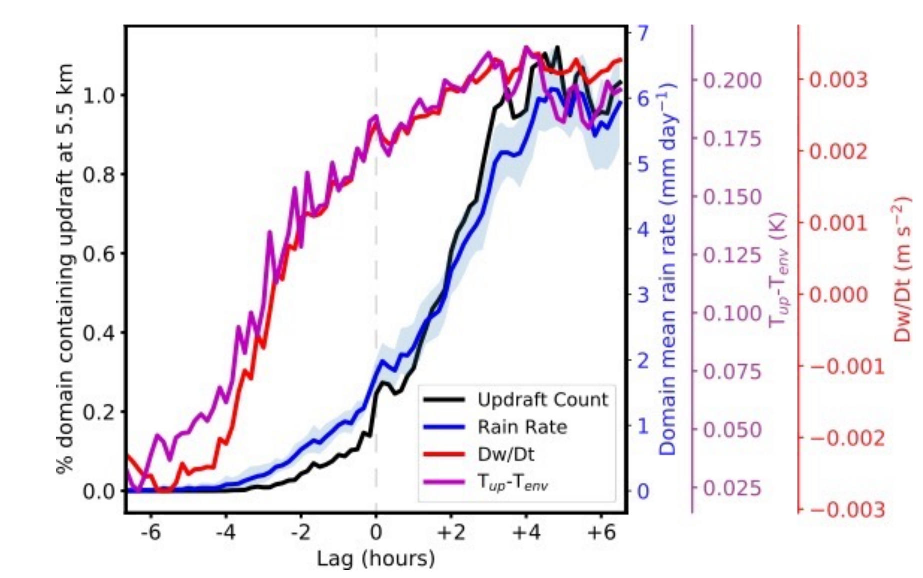
Domain size: 64 km x 64 km x 20 km

Grid spacing: 100 m horizontal, 50m stretched to 250 m in vertical

Initial perturbation: Random potential temperature perturbations in lowest 500 m up to 0.25K.

Upper right*:* Initial temperature and RH profiles
Lower right: Timeseries of rain rate (blue), updraft fractional areal coverage at 5.5 km (black), difference between updraft and environmental temperature (magenta), and updraft Dw/Dt (red) relative to a time (t=0) when deep convection reaching the tropopause first occurred.

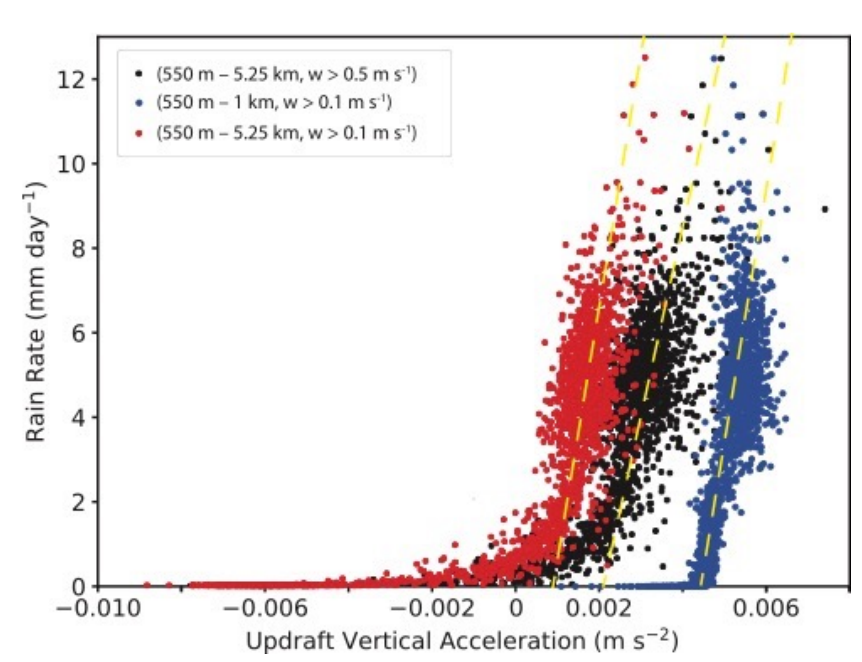




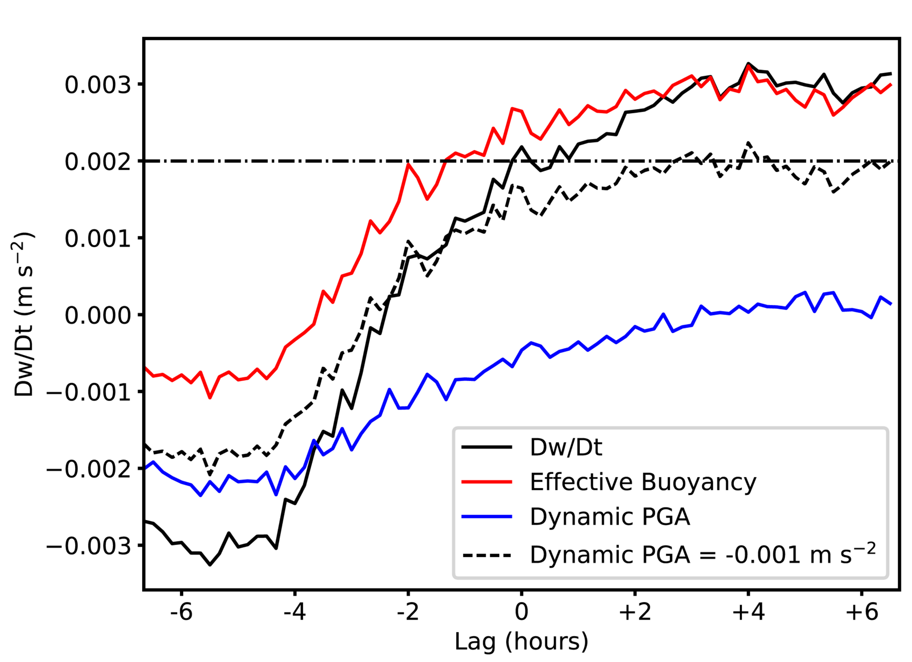
3. Modeled Criticality in Vertical Accelerations

The modeled tropical convection was forced using the soundings shown in Section 2b. 15 different simulations were run—3 each with the different temperature profiles shown. Most of the simulations showed an increase in rainfall over a 4-hour period at about the same time after initialization.

Top: Domain-mean updraft Dw/Dt versus model domain-averaged rain rate for different definitions of updrafts and averaged over different layers. All simulations are composited together. For example, the black dots show updraft Dw/Dt for updrafts with w > 0.5 m/s and averaged within the 550 m – 5.25 km layer, between approximately cloud base and the 0°C level. The yellow dashed line drawn through each set of dots intersects the abscissa at an approximate "critical" layer-mean acceleration above which domain-mean rainfall increases approximately linearly as Dw/Dt increases.

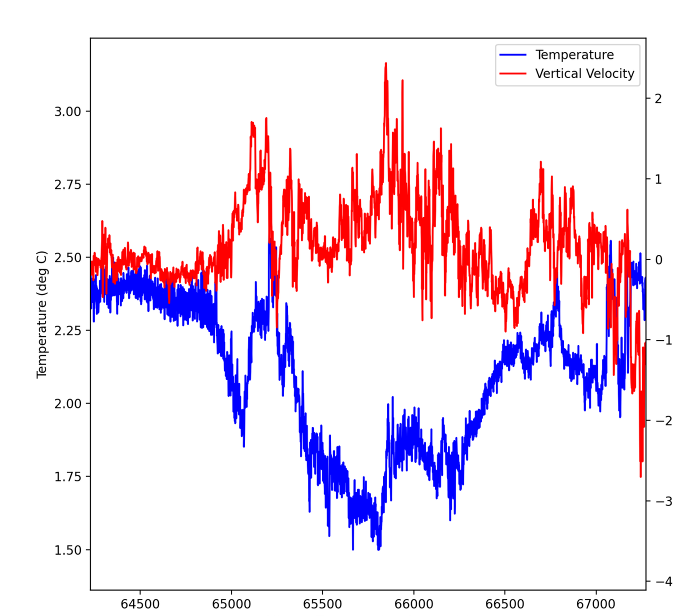


Bottom: For w > 0.5 m/s and averaged in the 500 m – 5.25 km layer: Domain-mean updraft Dw/Dt broken down into components for effective buoyancy $\left(-\frac{1}{\rho}\frac{\partial p_B}{\partial z} + B\right)$ (red), $-\frac{1}{\rho}\frac{\partial p_D}{\partial z}$ (blue), and Dw/Dt (black), composited around the same t=0 from Section 2b. The dashed black line is Dw/Dt if $-\frac{1}{\rho}\frac{\partial p_D}{\partial z}$ were simply considered to be a constant -0.001 m/s^2. The horizontal dashed black line is the critical Dw/Dt needed for deep convection.

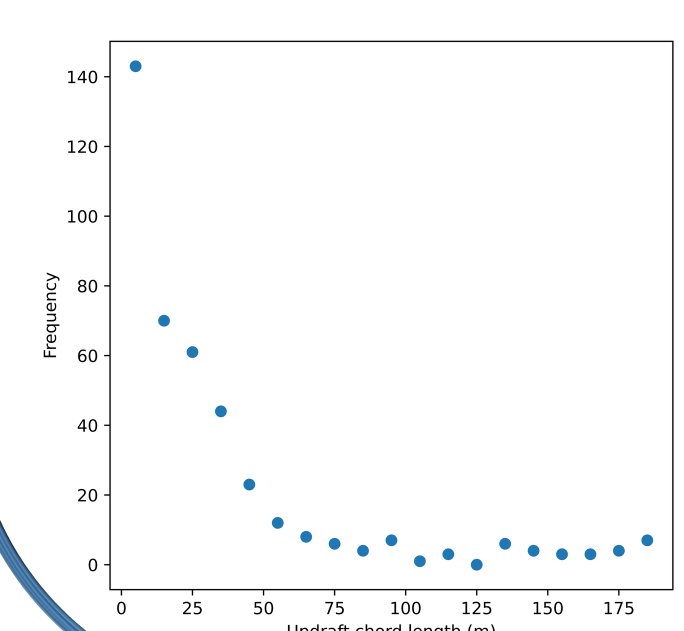


4. Observing Convective Growth (CALICO)

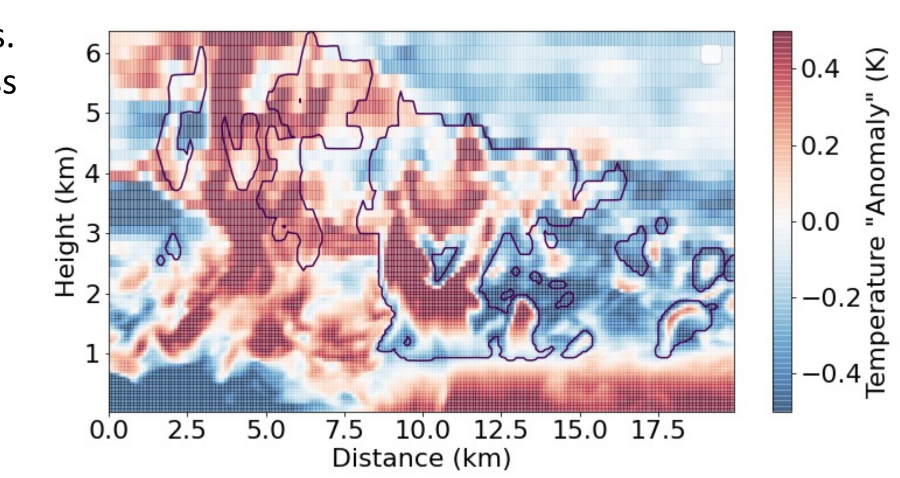
The CALifornia Investigation of Convection over Ocean (CALICO) took place in February–March 2022 in the Monterey Bay area. Postfrontal cumuliform convection driven by cold pools was sampled directly using the NPS Twin Otter out of Marina, CA, and various remote sensing instruments located on the coast at Monterey Bay Academy in La Selva Beach, CA. Regular weather balloon launches from Monterey and Big Sur during flights provided information about the vertical kinematic and thermodynamic structure of the atmosphere during the convective events. Observational analysis and numerical simulations of observed convection are underway.



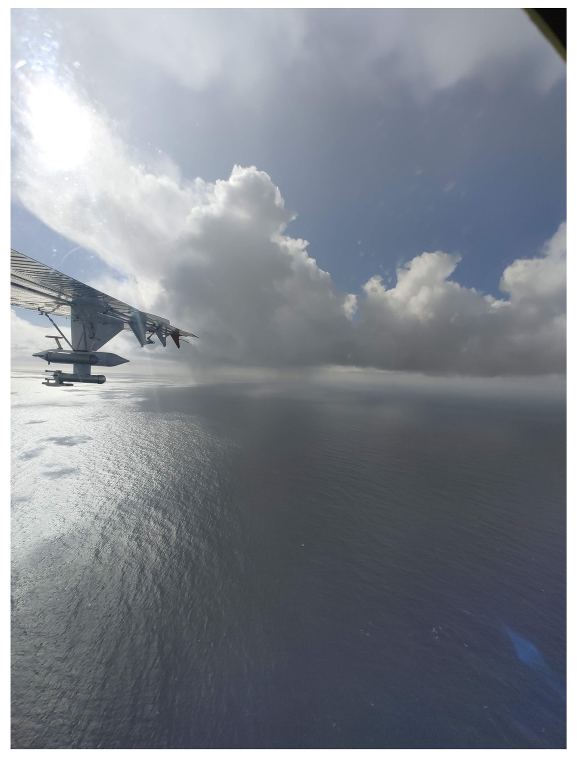
Top Left: The aircraft observed kinematic and thermodynamic properties of updrafts. Shown at left are cross sections of vertical velocity (red) and temperature (blue) through an in-cloud updraft. Several such "cold" updrafts were observed.



Bottom Left: Cockpit video has been analyzed so far to determine when the aircraft was in cloud. We can then determine the distribution of updraft "chord lengths" observed, which will soon be converted into 2D size distribution estimates. One key question: How does updraft radius/width relate to vertical wind shear magnitude?

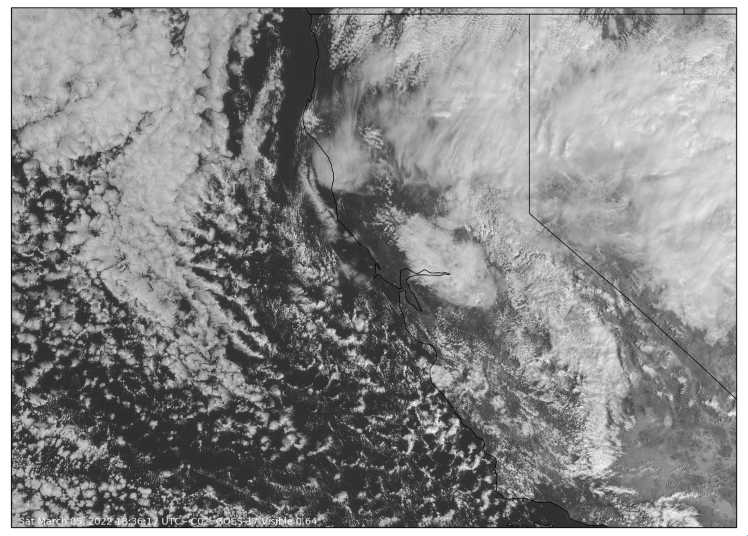


Center: CM1 2D cross section through cold pool driven convection with clouds outlined in black. The base of the cloud shown was colder than the surrounding environment although an updraft (not shown) was present.



Top Right: Photo of cumulonimbus cloud from Twin Otter during CALICO. Most flights were conducted near cloud base height (about 800 meters), where temperature was 1–2°C, to prevent icing of instruments.

Bottom Right: GOES-17 640 nm imagery illustrating cold pool driven convection on 5 March 2022.



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