Why does deep convection have different sensitivities to temperature perturbations in the lower and upper troposphere?

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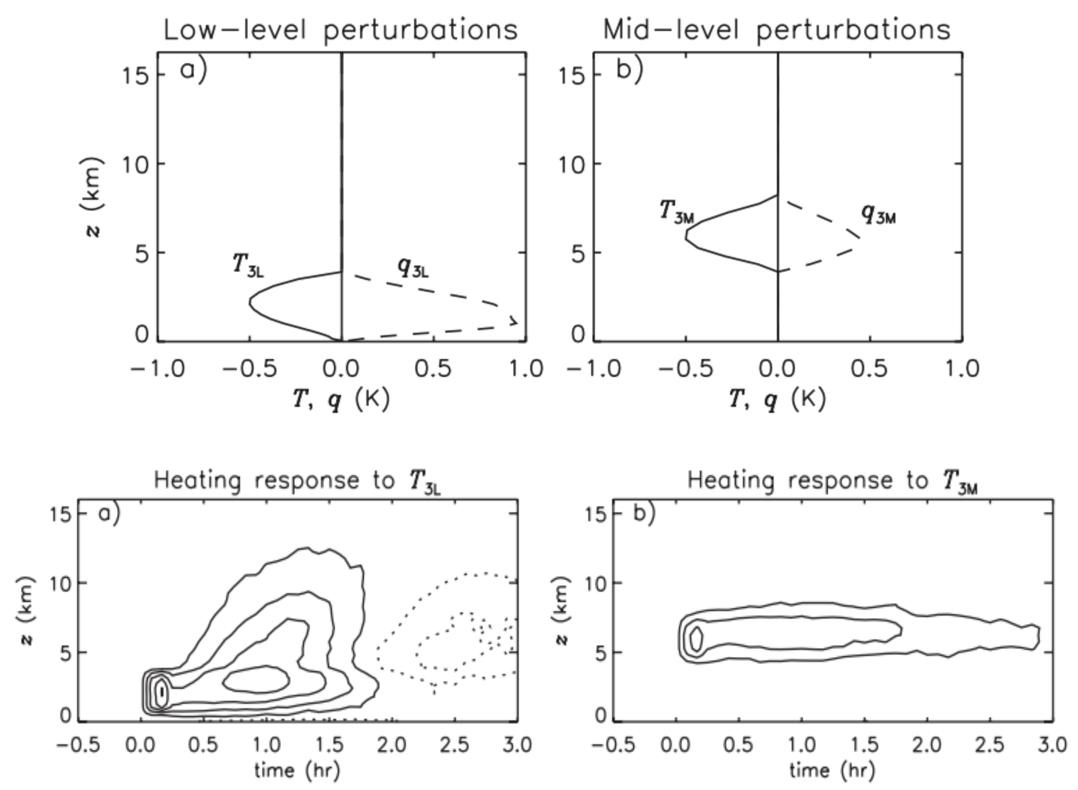
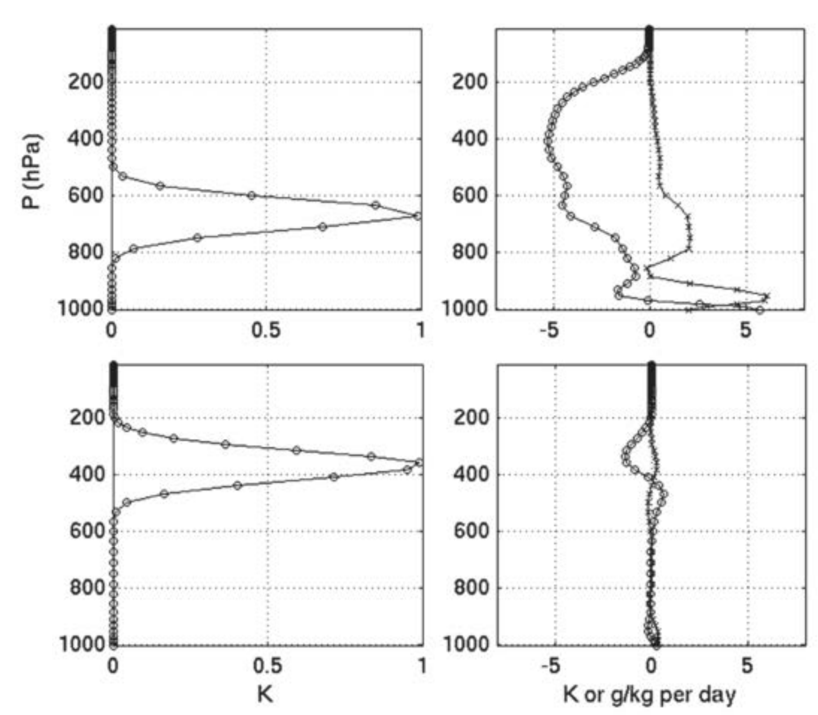
Introduction

Motivation

Previous studies have documented that deep convection responds more strongly to above-the-cloud-base temperature perturbations in the lower troposphere than to those in the upper troposphere (Tulich and Mapes 2010, Kuang 2010).



Tulich and Mapes (2010)



Kuang (2010)

Implications

- Results in a "shallower" convective quasi-equilibrium rather than a full tropospheric quasi-equilibrium
- A stronger lower/middle troposphere convective response leads to wave potential energy generation and wave growth

A mechanistic understanding of what contributes to different sensitivities can help model convectively coupled waves better

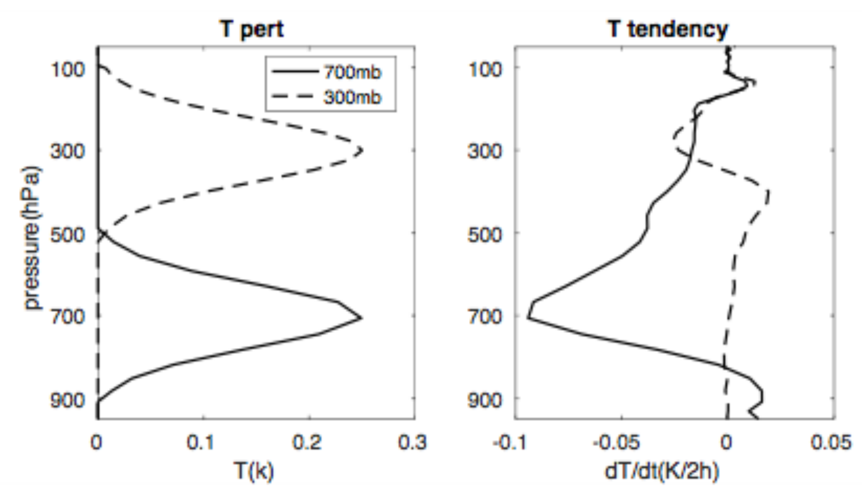
Model setup

Hypotheses

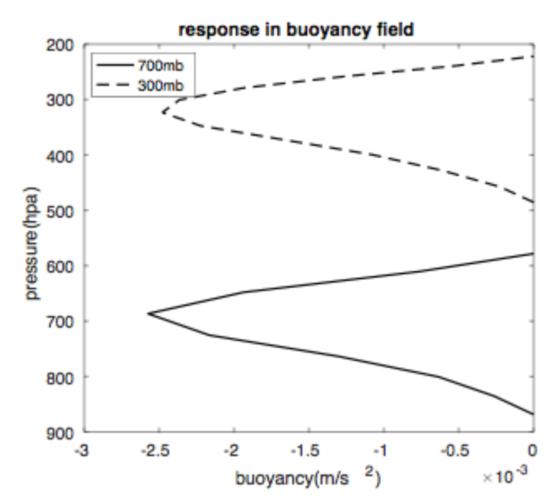
- Liquid water content is limited in the upper troposphere, so is evaporative cooling
- Near-neutral buoyancy in the lower troposphere
- Vertical velocity inertia, velocity increases with height

Model Configurations

- RCE: Radiative Convective Equilibrium
- SAM: 500m horizontal resolution (128 x 128 km), 10s temporal resolution (2 hours)
- Introduce temperature perturbations at 700 hPa (lower tropo) and 300 hPa (upper tropo): +0.25 K Gaussian-shaped temperature perturbation with 75mb half width
- 100 ensemble runs, each has 8 particle per grid box(~30 million **Lagrangian** particles)



Test Hypothesis 1: The amount of liquid water content



$$B = -g(\rho'/\rho) \approx g(T'/T - q_l)$$

T' is the same at the peak perturbation!

Peak buoyancy reduction between 700 hPa(-0.0027) and 300 hPa(-0.0026) is similar, whereas the difference in response is more than 3 times, **condensed water content should not be a controlling factor**

Results

Test Hypothesis 2 & 3: Relative importance between vertical velocity and buoyancy acceleration through "swapping"

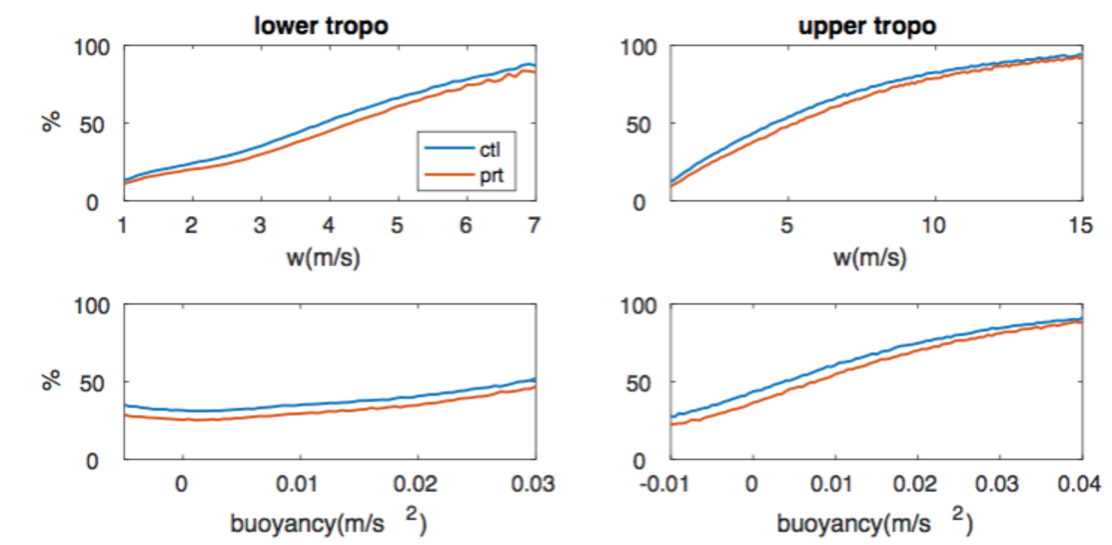
Lagrangian representation of updraft mass flux: counting the number of cloudy parcels that cross a particular interface within a certain time interval.

$$M = \frac{n\delta m}{XY\Delta t} \qquad \delta m = \frac{1}{N}\sum_{k=1}^{N_z} \rho_k \Delta z XY$$

Selected two levels instead of a single interface, mass flux is calculated over the entire perturbation.

Upper level: 3000 m (700 hPa); 9400 m (300 hPa)
Lower level: 1400 m (700 hPa); 7300 m (300 hPa)

From here we can calculate the percentage of particles that can successfully cross the perturbation layer, defined as crossing percentage.



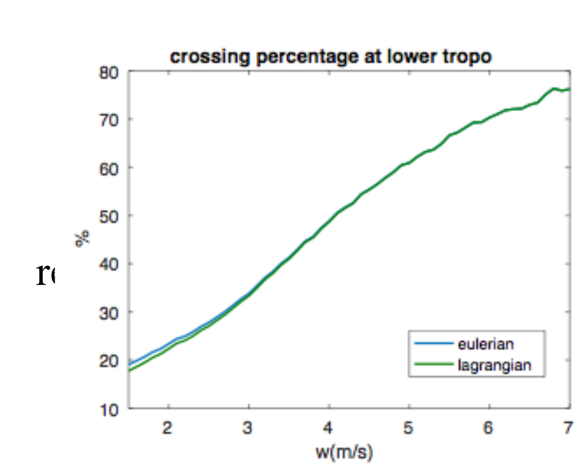
Weaker dependence on initial buoyancy in the lower troposphere

Sub-grid scale diffusion term is small in the height range we consider, we can accurately compute how a parcel's vertical velocity and position evolve using buoyancy and vertical pressure gradient accelerations.

$$z(t) = z_{bottom} + \int_{t_{bottom}}^{t} w(t')dt' \quad (1)$$

$$\frac{1}{2}w^2(z) = \frac{1}{2}w^2(z_{bottom}) + \int_{z_{bottom}}^{z} F(x(z'), y(z'), z')dz' \quad (2)$$

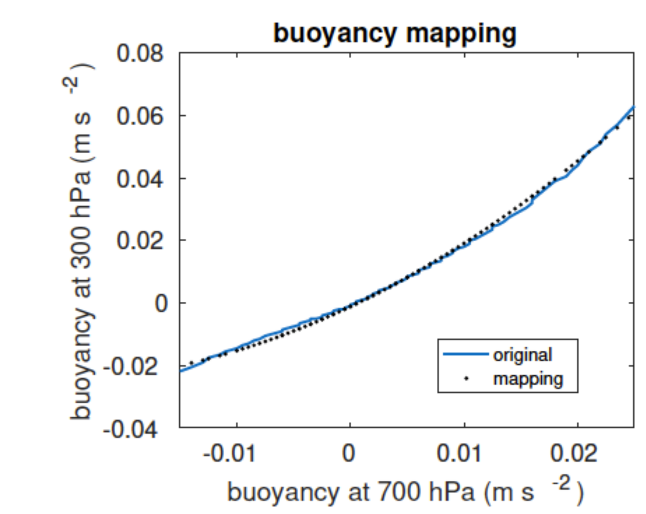
$$F(x(z), y(z), z) = B(x(z), y(z), z) - \frac{dp'_b}{\rho dz}(x(z), y(z), z) - \frac{dp'_m}{\rho dz}(x(z), y(z), z) \quad (3)$$



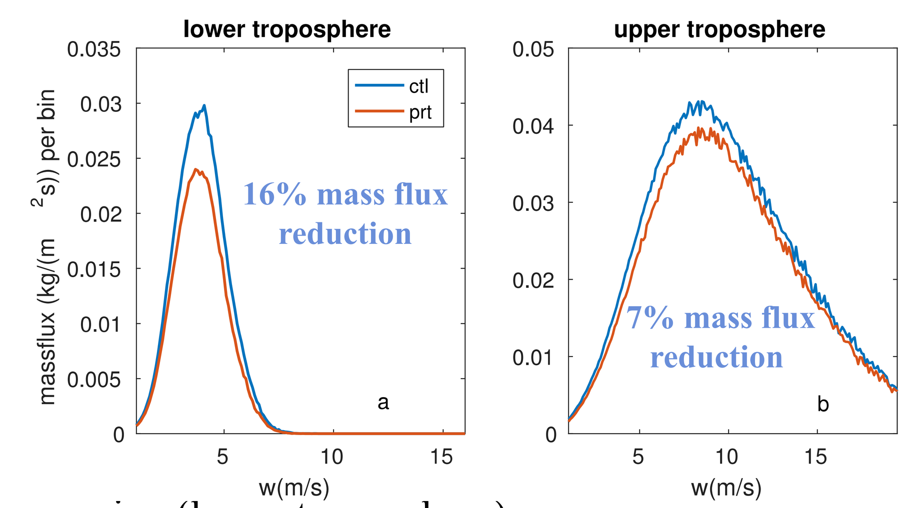
Using Eq. (1)-(3) to

crossing percentage, agrees well with model direct output.

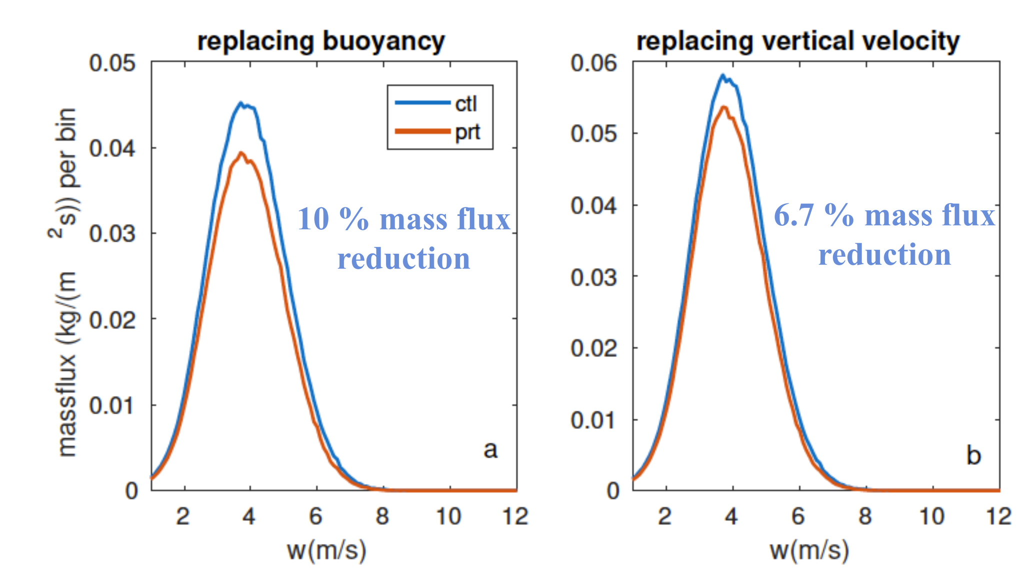
To quantify the effect of the initial vertical velocity, we can, for example, solve Eqs. (1-3) for the 700 hPa case, but with the initial vertical velocity from the 300 hPa case. This is done through non-linear mapping:



Before swapping:



After swapping (lower troposphere):



Conclusions

- Total water content difference plays a secondary role
- Both vertical velocity and buoyancy play important roles in determining the different convective sensitivity, but velocity is a bit more important than the buoyancy
- Vertical velocity should be included for parameterization to account for correct convective sensitivity

1. **Kuang, Z. (2010), Linear response functions of a cumulus ensemble to temperature and moisture perturbations and implication to the dynamics of convectively coupled waves., J. Atmos. Sci., 67, 941-962.**
2. **Tulich, S. and B. E. Mapes, Transient environmental sensitivities of explicitly simulated tropical convection. J. Atmos. Sci, 697, 923-940.**