Response of tropical deep convection to convective-scale heating perturbations: Implications for aerosol-induced invigoration

Hugh Morrison and Wojciech Grabowski

NCAR* (MMM Division, NESL)

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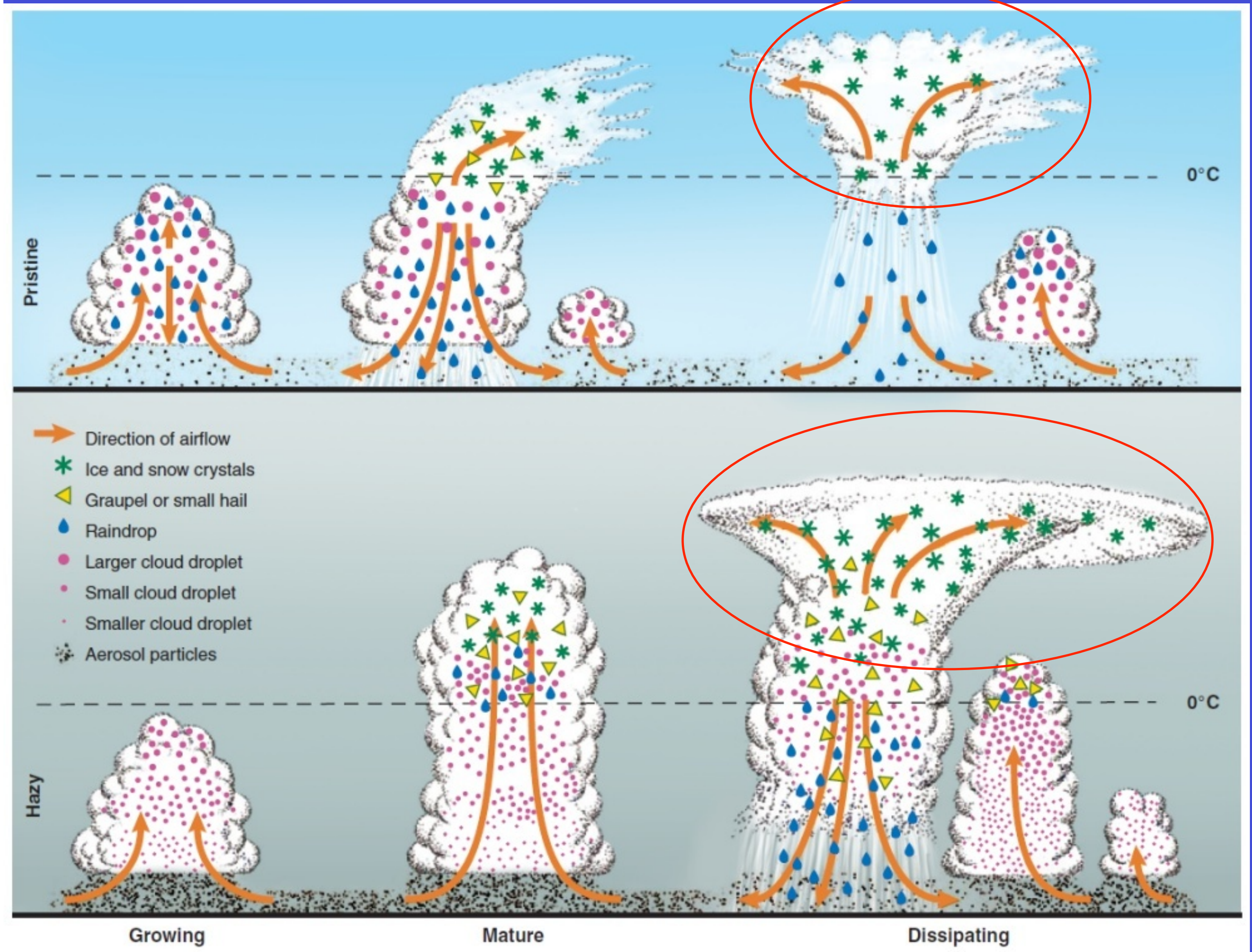
Rosenfeld et al.
Science, 2008

Koren et al. (2010)

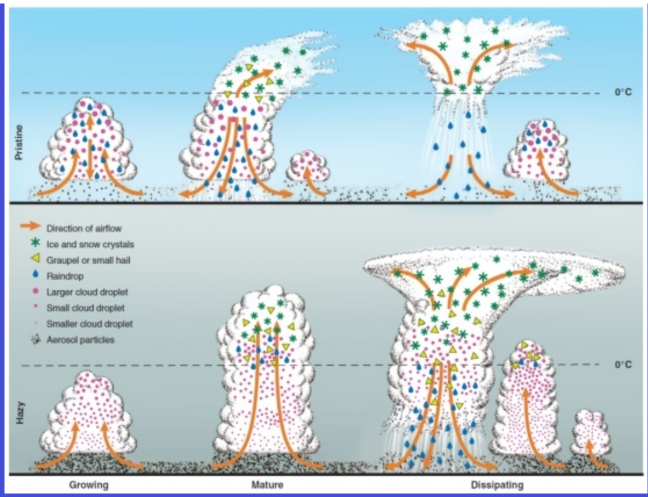


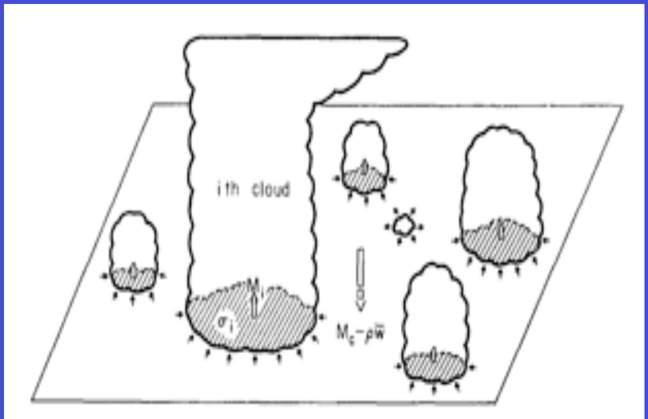
Example of aerosol-microphysics-dynamics interactions in deep convection

single-cloud reasoning

versus

cloud-ensemble reasoning





Another way to think about the problem: single-process reasoning (e.g., microphysics) versus the system-dynamics approach. Only the latter includes all the feedbacks and forcings in the system.

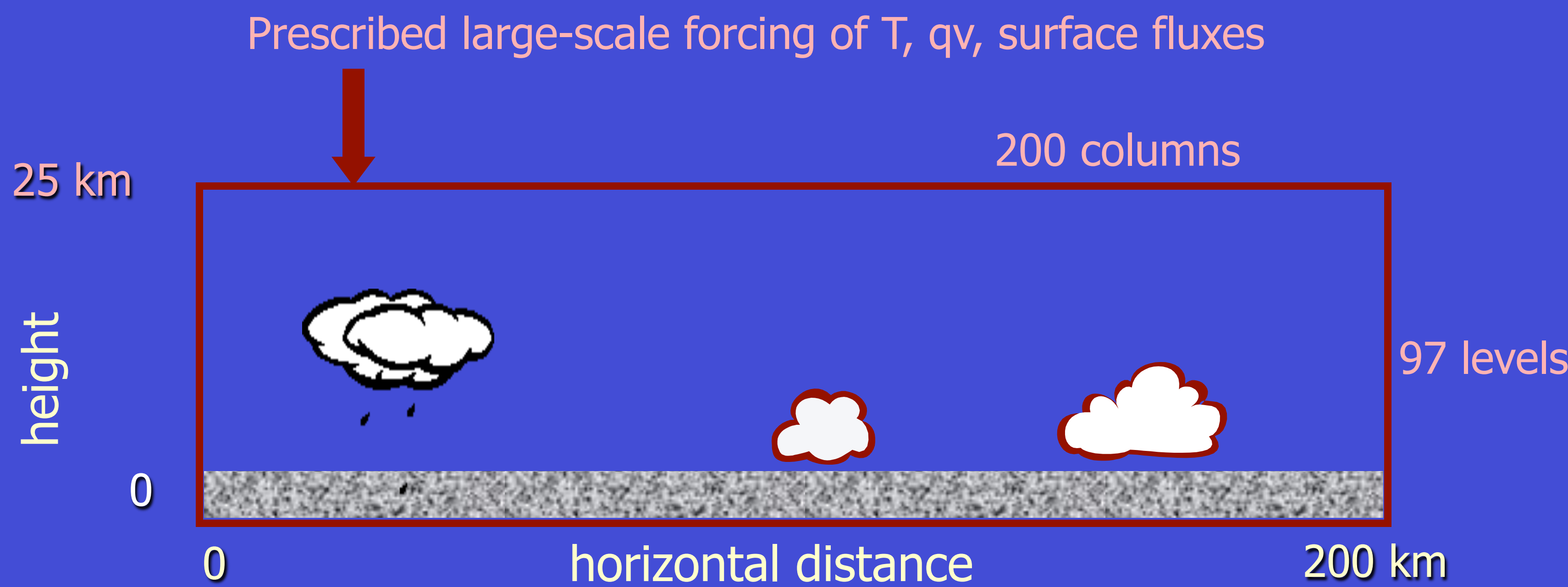
Let's take as a given that aerosol loading causes enhanced heating in convective updrafts…

The key question we then want to ask is: what are impacts of convective-scale heating perturbations in the context of feedback with the larger-scale environment?

7.5-day, 2D simulations of TWP-ICE, using observed large-scale forcing

(Morrison and Grabowski, 2011, ACP)

- **similar setup to ARM/GCSS CRM intercomparison (Fridlind et al., 2012)**



horizontal grid spacing of 1 km

Surface temperature = 29° C

Numerical model:

Dynamics: 2D super-parameterization model (Grabowski 2001), periodic lateral boundaries.

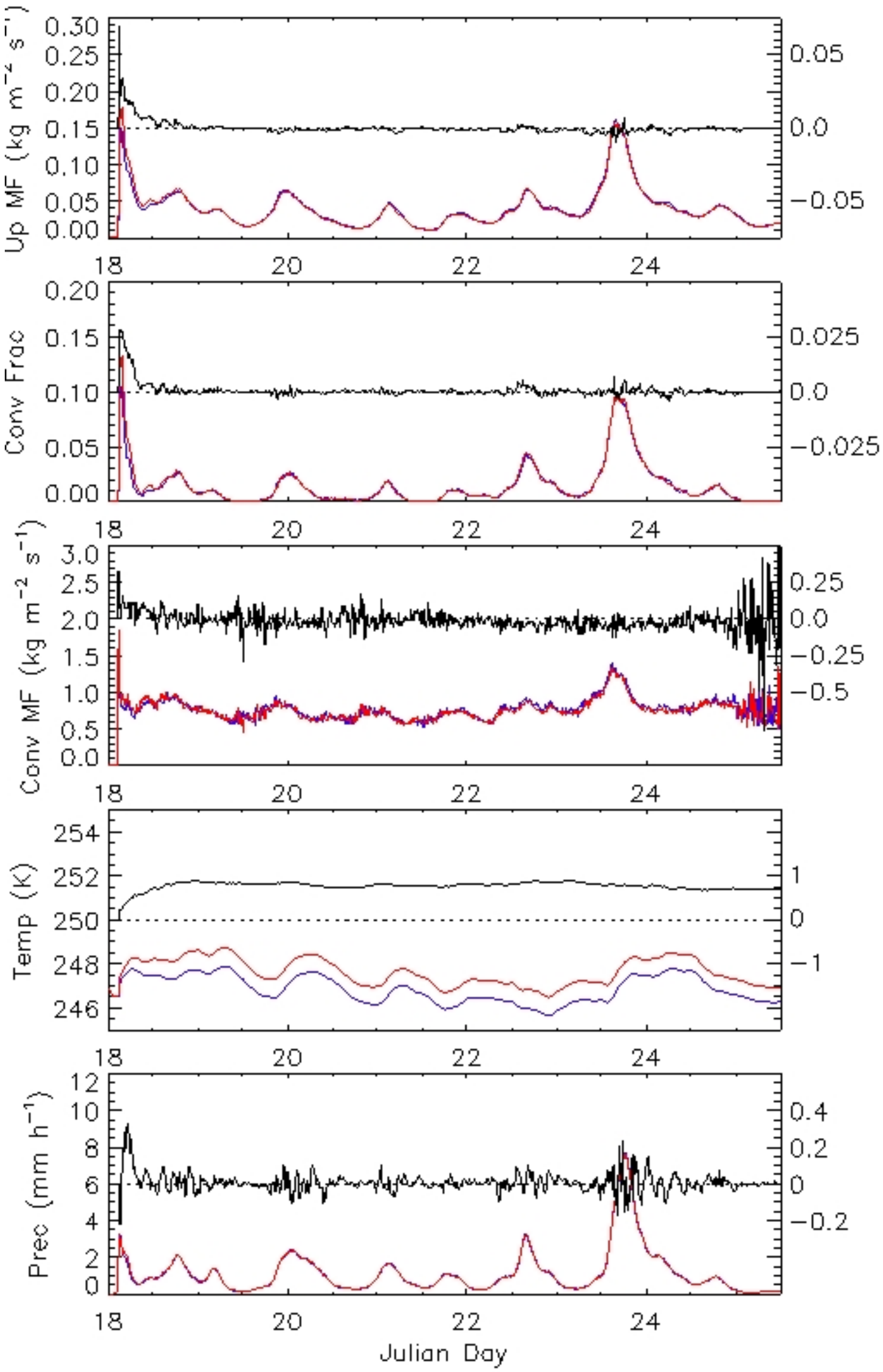
Microphysics: two-moment bulk scheme (Morrison and Grabowski 2007; 2008a, 2008b).

An ensemble approach is used given large variability, with ensembles generated by applying different random number seeds for random, low-level theta perturbations (120 or 240 ensemble members).

We specifically test the Rosenfeld et al. mechanism of invigoration above the freezing level by perturbing the convective-scale buoyancy field → latent heating added to updrafts with cooling in downdrafts such that net moist static energy is unchanged.

Heating is increased by a factor of 1.2 in updrafts from 6 to 8 km, which is broadly similar to enhancement of heating in previous bin model studies of aerosol-induced convective invigoration (e.g., Khain et al. 2004; Lebo and Seinfeld 2011). Other magnitudes and functional forms for heating perturbations were tested and give similar results.

The perturbed and unperturbed simulations otherwise apply identical conditions (large-scale forcing, microphysics, etc.).



Convective-scale heating perturbations cause an initial invigoration of convection, but it returns to its unperturbed state after ~ 1 day. This occurs because of adjustment of the larger-scale environment (~ 1 K).

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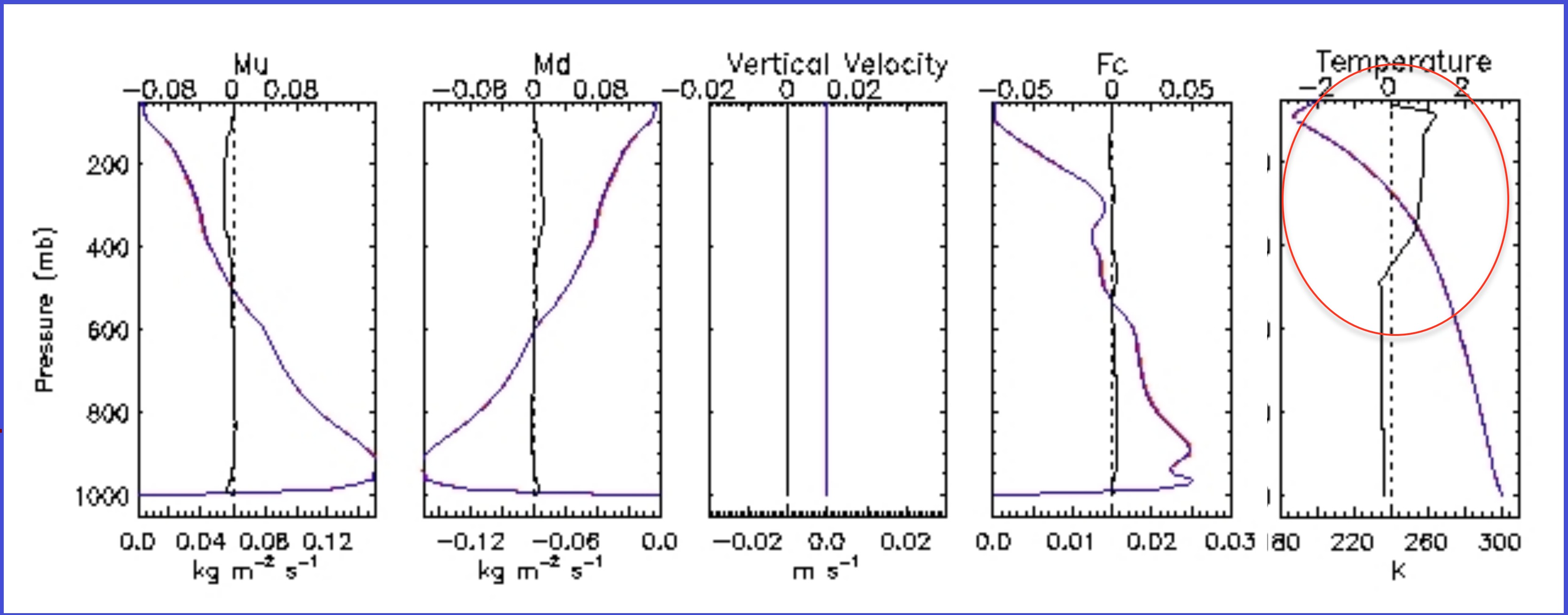
After the initial invigoration, convective characteristics are nearly unchanged for the remainder of the simulation.



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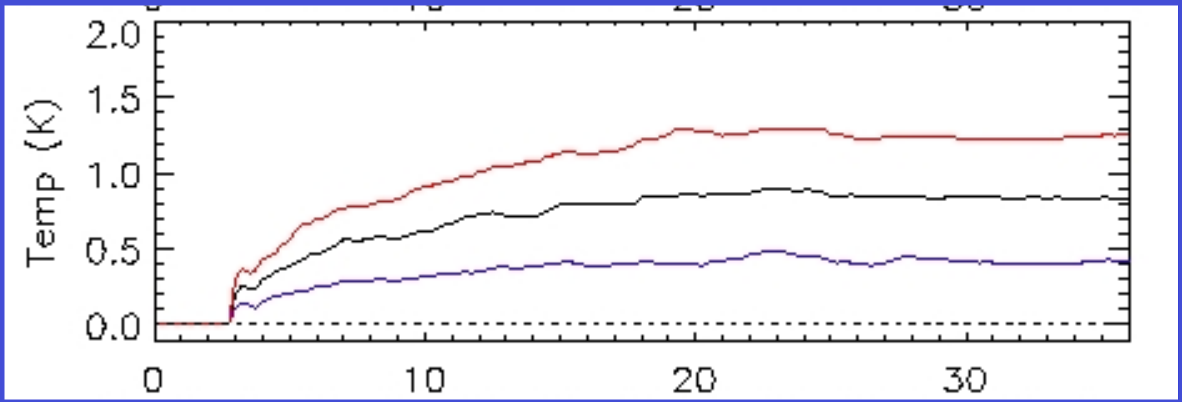
Vertical profiles of various quantities, averaged over the last 6 days.

Adjustment of the environment is controlled by two processes:

1. Gravity wave dynamics (adjustment timescale ~ 1 h, depends on static stability and half-width distance between convective cells)

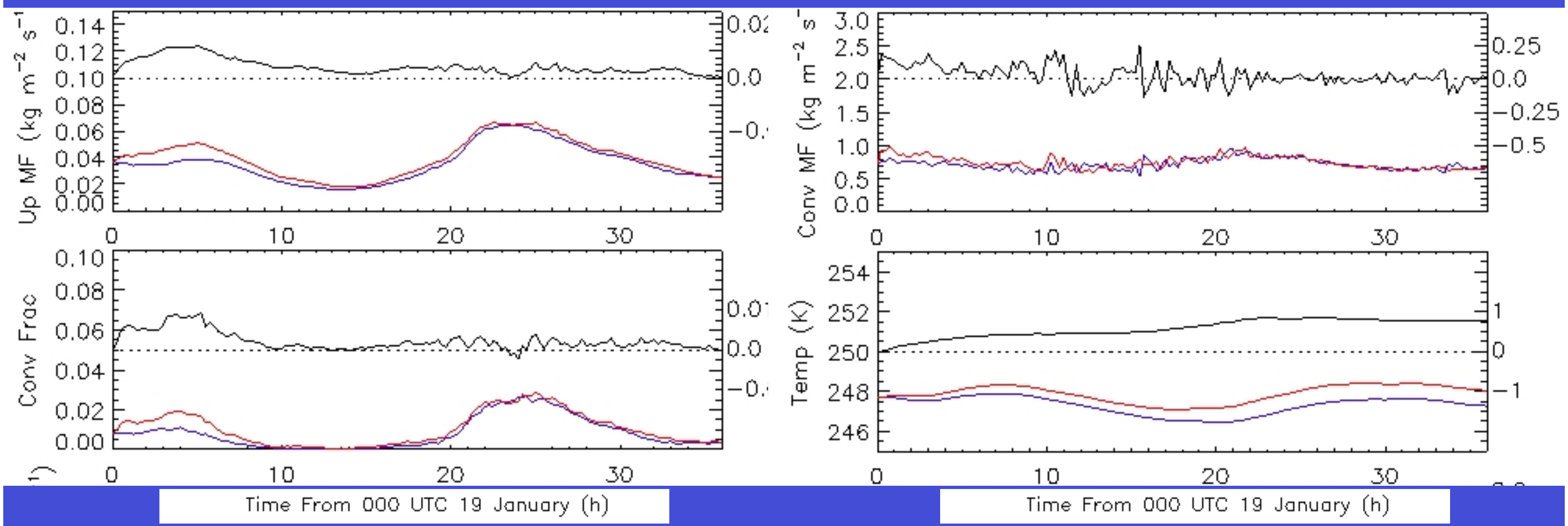
2. Convective overturning (adjustment timescale ~ 1 day, depends on total mass of domain divided by total convective mass flux)

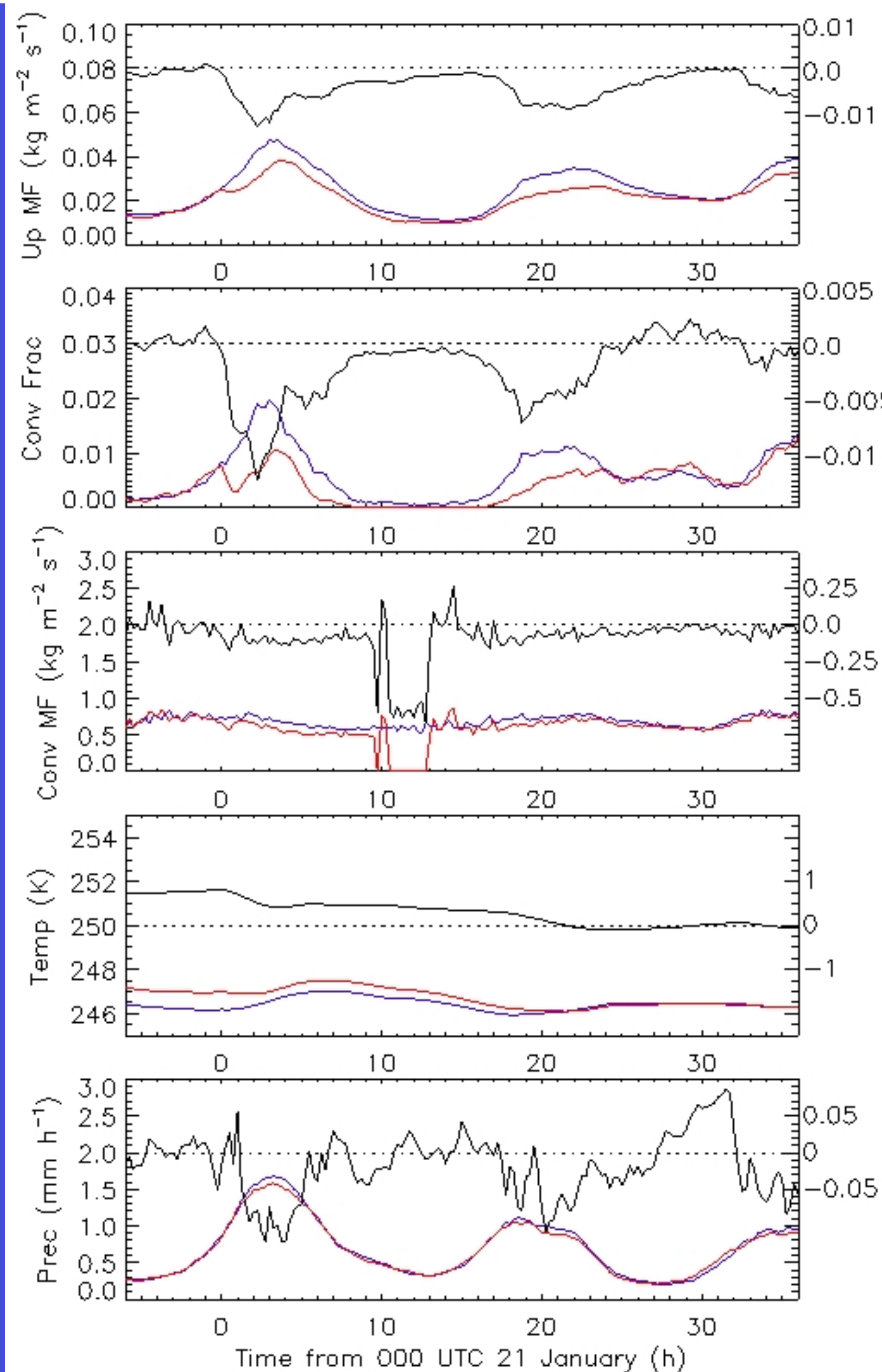
Since both processes depend mostly on initial conditions and large-scale forcing, the adjustment timescale has little dependence on magnitude of the applied heating perturbations. The adjustment is also nearly linear with respect to perturbation magnitude (including for negative perturbations).



1.1 x latent heating
1.2 x latent heating
1.3 x latent heating

Initially, the system is in a strongly non-equilibrium state and CAPE is rapidly consumed. However, results are qualitatively similar when heating perturbations are only applied 24 hours into the simulations, when convection is in a quasi-balance with the large-scale forcing.





The opposite adjustment processes occur when perturbations are removed.

Large differences in the environmental temperature (~ 1 K) after adjustment imply that mesoscale circulations can develop if perturbed conditions are applied in only a portion of the domain.

To test this, we increase the domain size to 1000 km and apply perturbed conditions only to the inner 250 km (in the spirit of Lee 2012, JAS).

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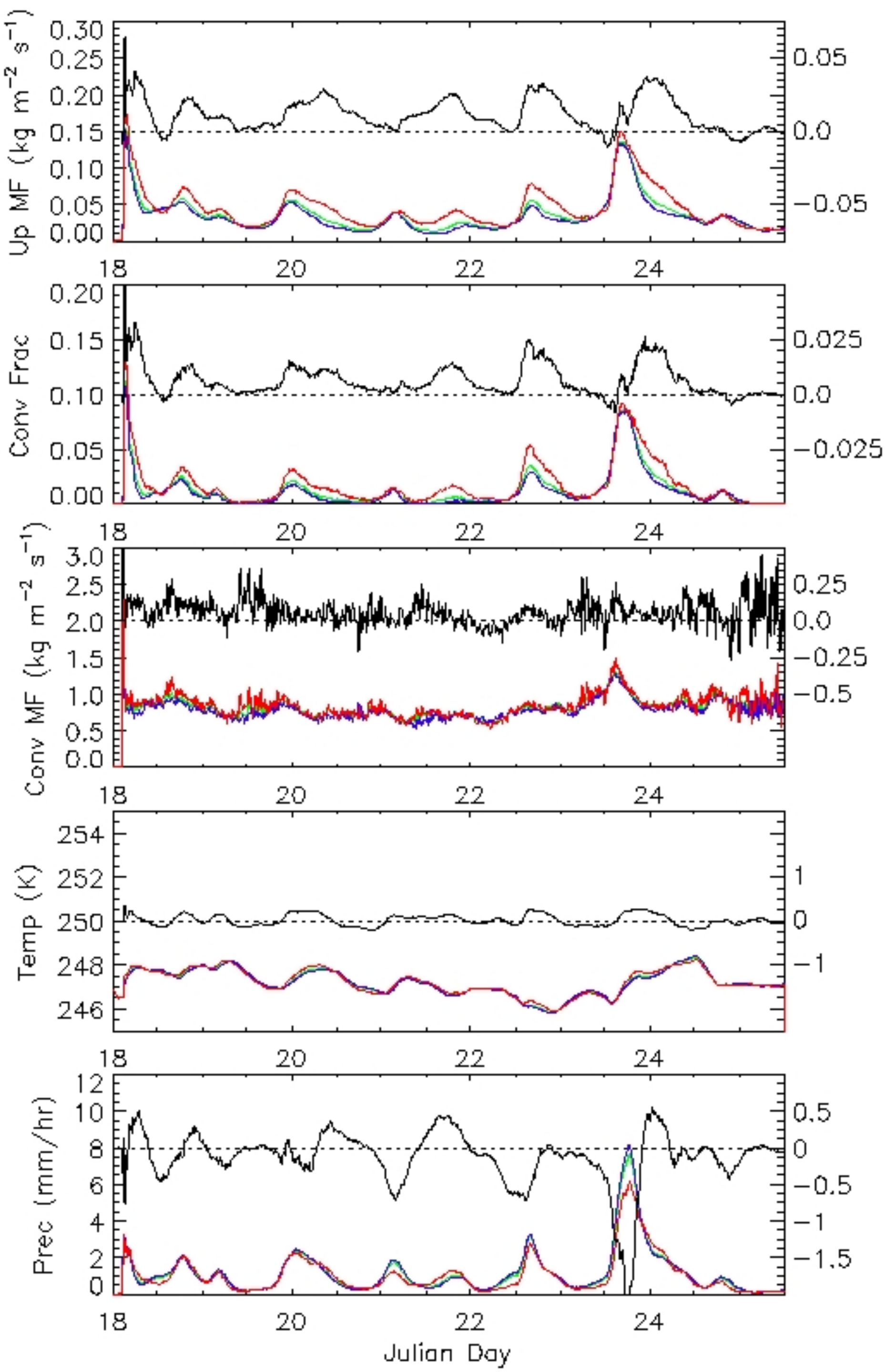

In contrast to simulations w/ perturbed conditions throughout the domain, perturbed convection is maintained when heating perturbations are only applied in the inner 250 km.

This occurs because of mesoscale circulations between the perturbed and unperturbed parts of the domain, driven by heating gradients.

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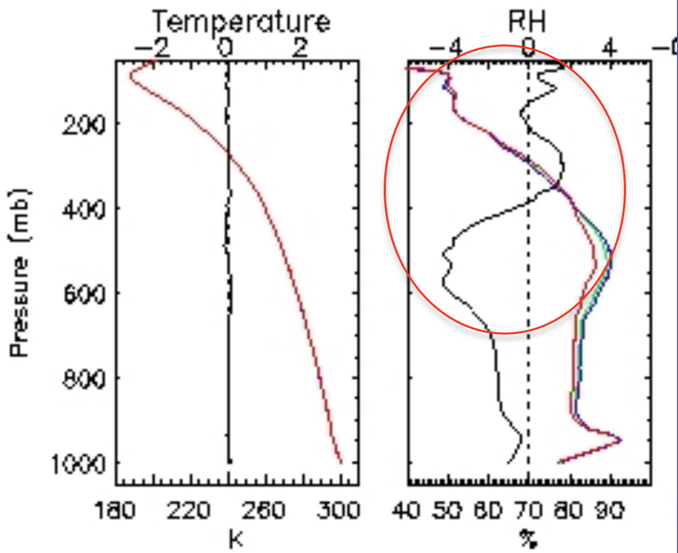
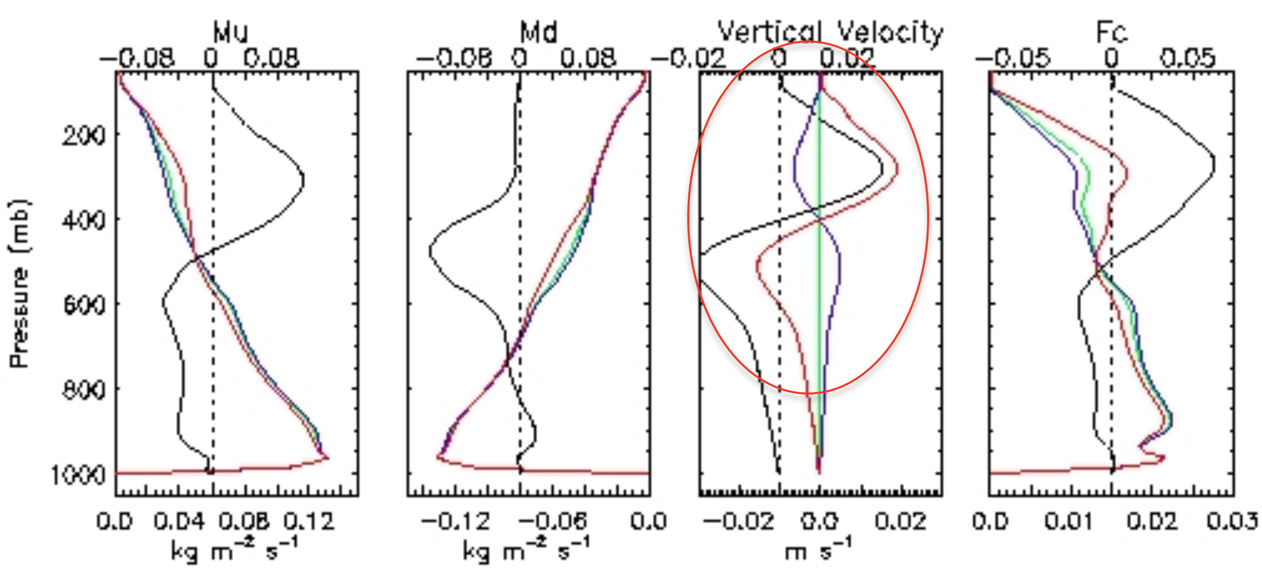
Since the timescale for mesoscale circulation (~ few days) is much longer than timescale for gravity wave adjustment (~ 1 h), there are large horizontal gradients in water vapor and moist static energy, but not temperature.

A lower-level mesoscale downdraft leads to drying and reduces surface precipitation in the perturbed region.





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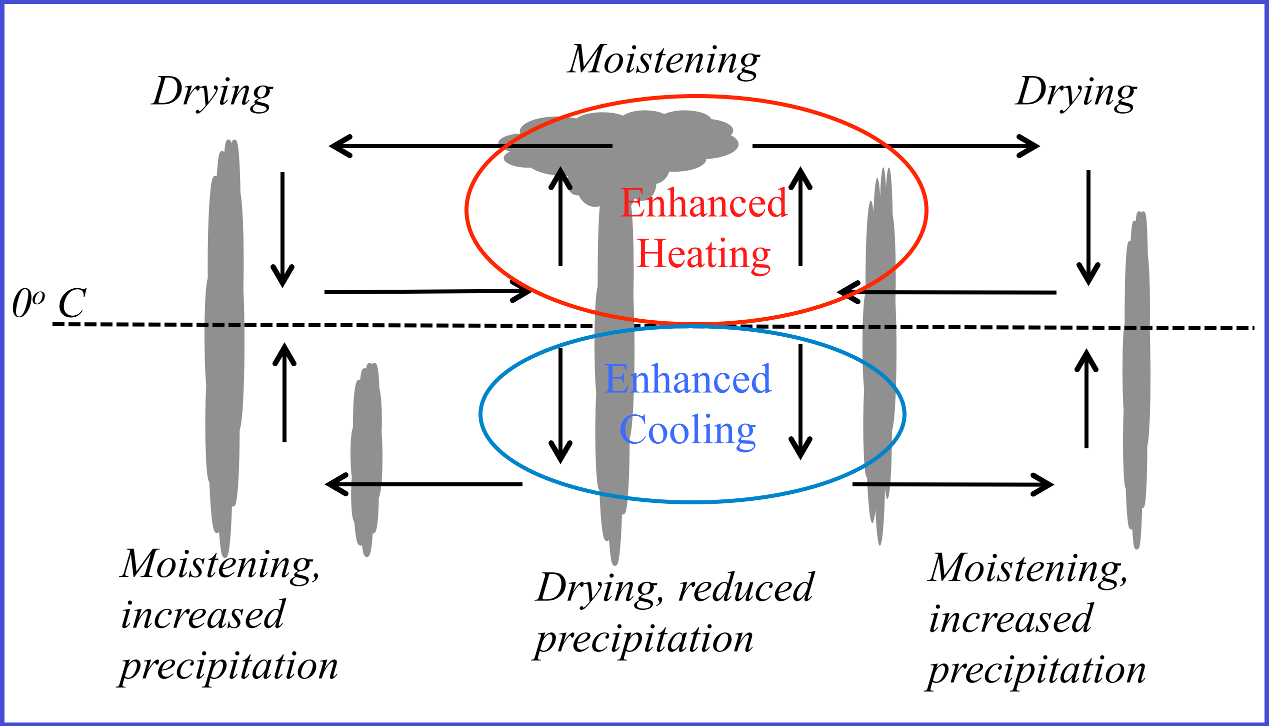
Schematic of mesoscale circulation associated with perturbed conditions applied to part of domain



Conclusions

- **In a uniform environment, convective-scale heating perturbations cause an initial invigoration of convection, but overall effects are limited because of rapid adjustment of the environment through gravity waves and convective overturning.**

- **If perturbations are only applied to part of the domain, mesoscale circulations develop that maintain invigoration.**

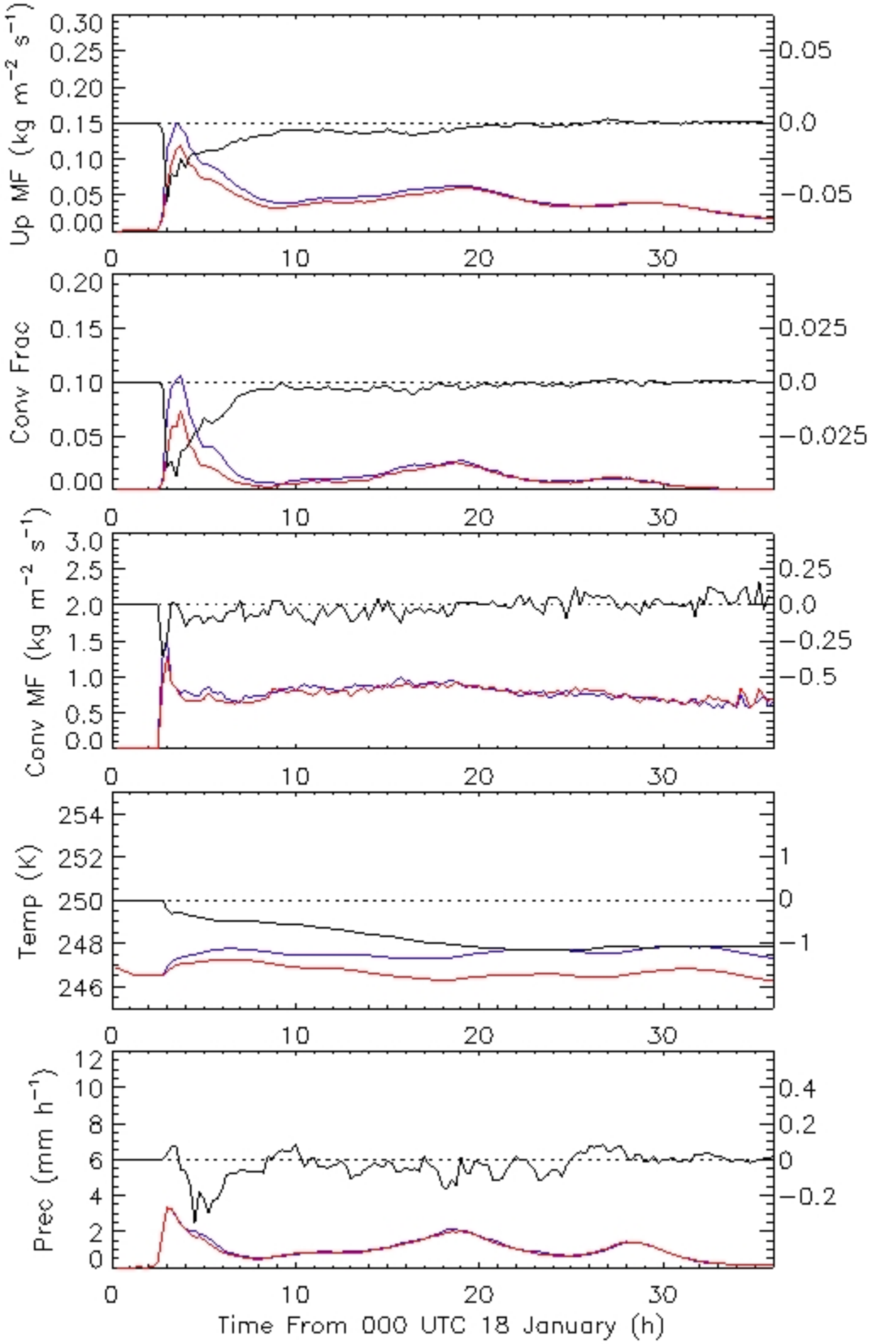
- **These results suggest that the timescale and spatial scale of the perturbed region is critical.**

- **Similar results occur for convective-scale perturbations to condensate loading.**

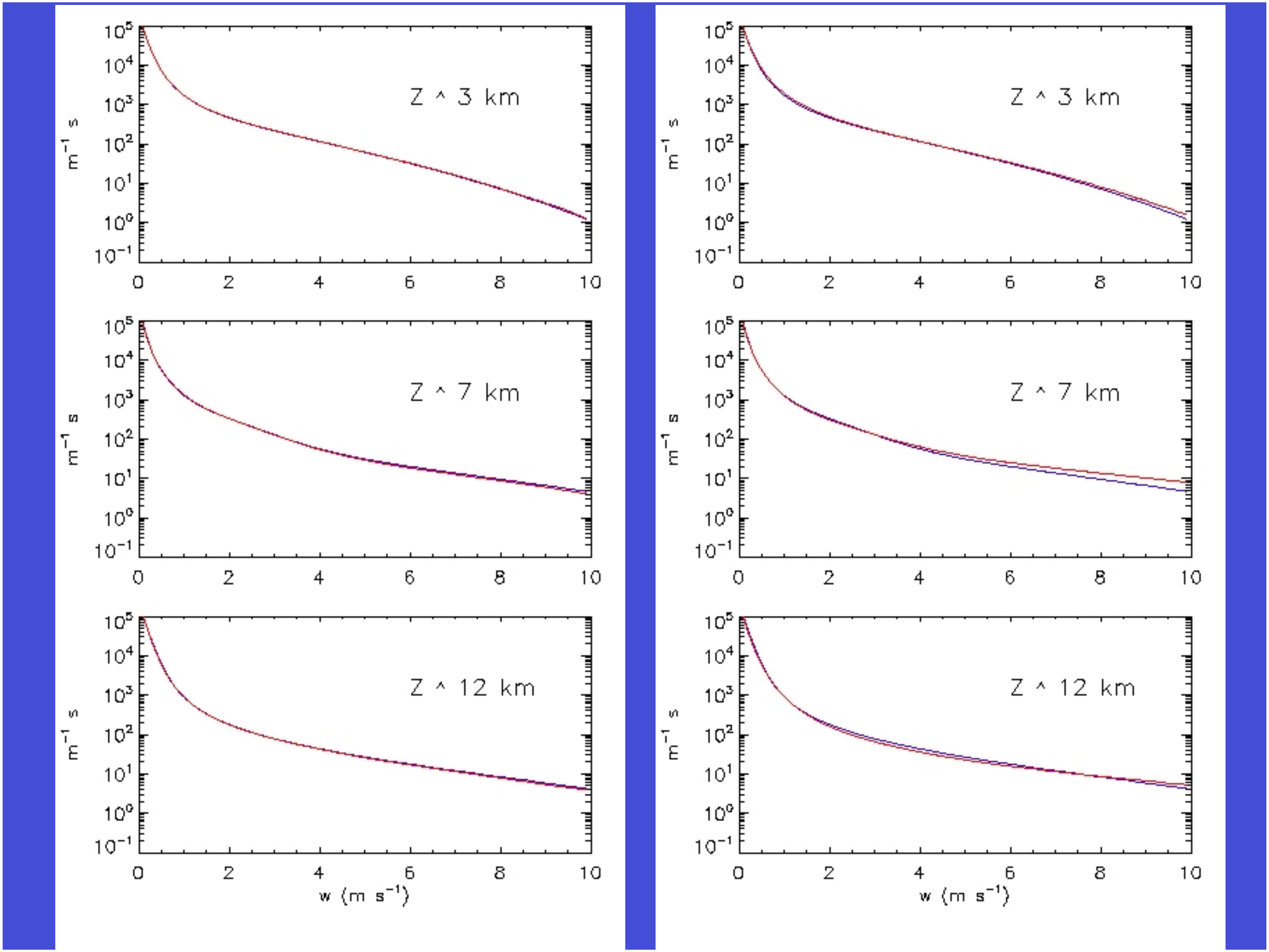
- **Take home message: Over timescales longer ~ 1 day, aerosol effects on deep convection are driven by larger-scale circulations rather than directly by convective-scale buoyancy perturbations, and require larger-scale gradients in heating (aerosols).**

Thank you!

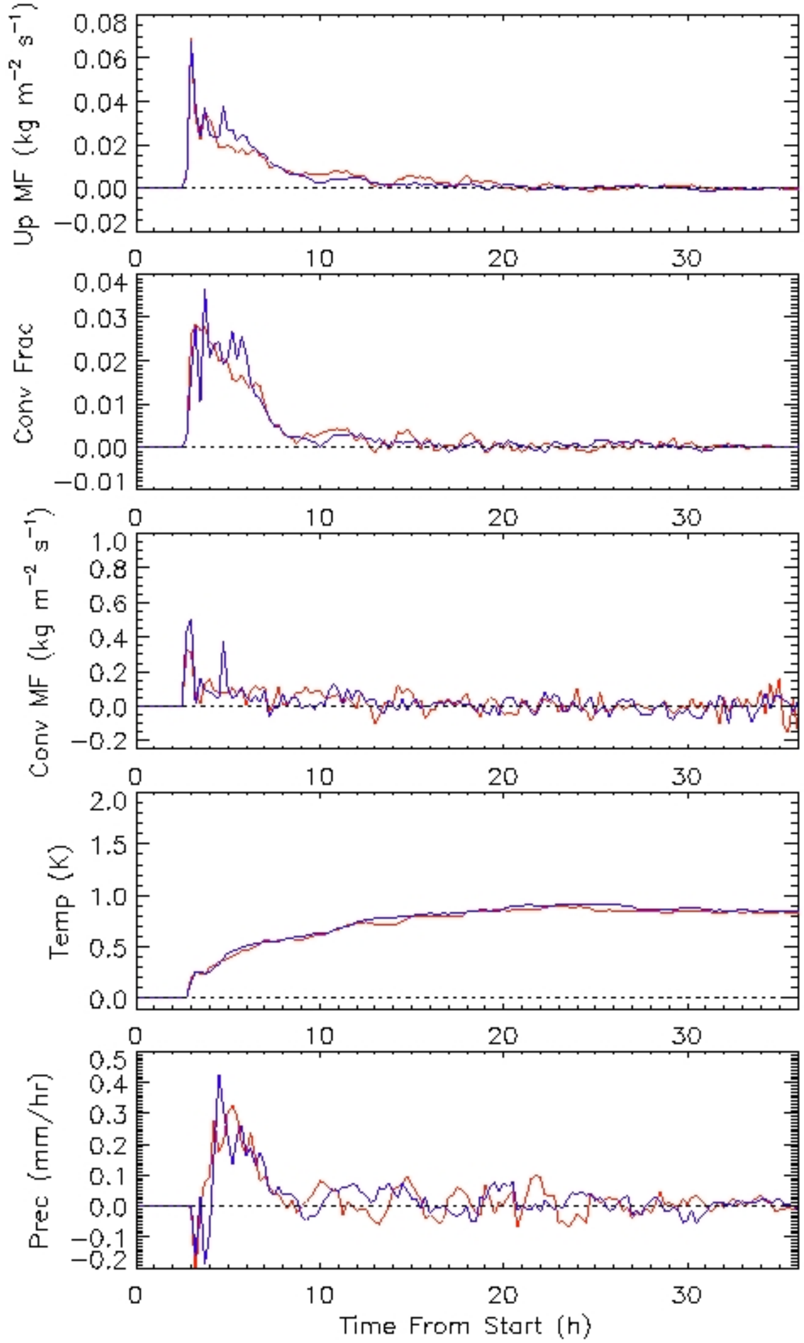
Questions???



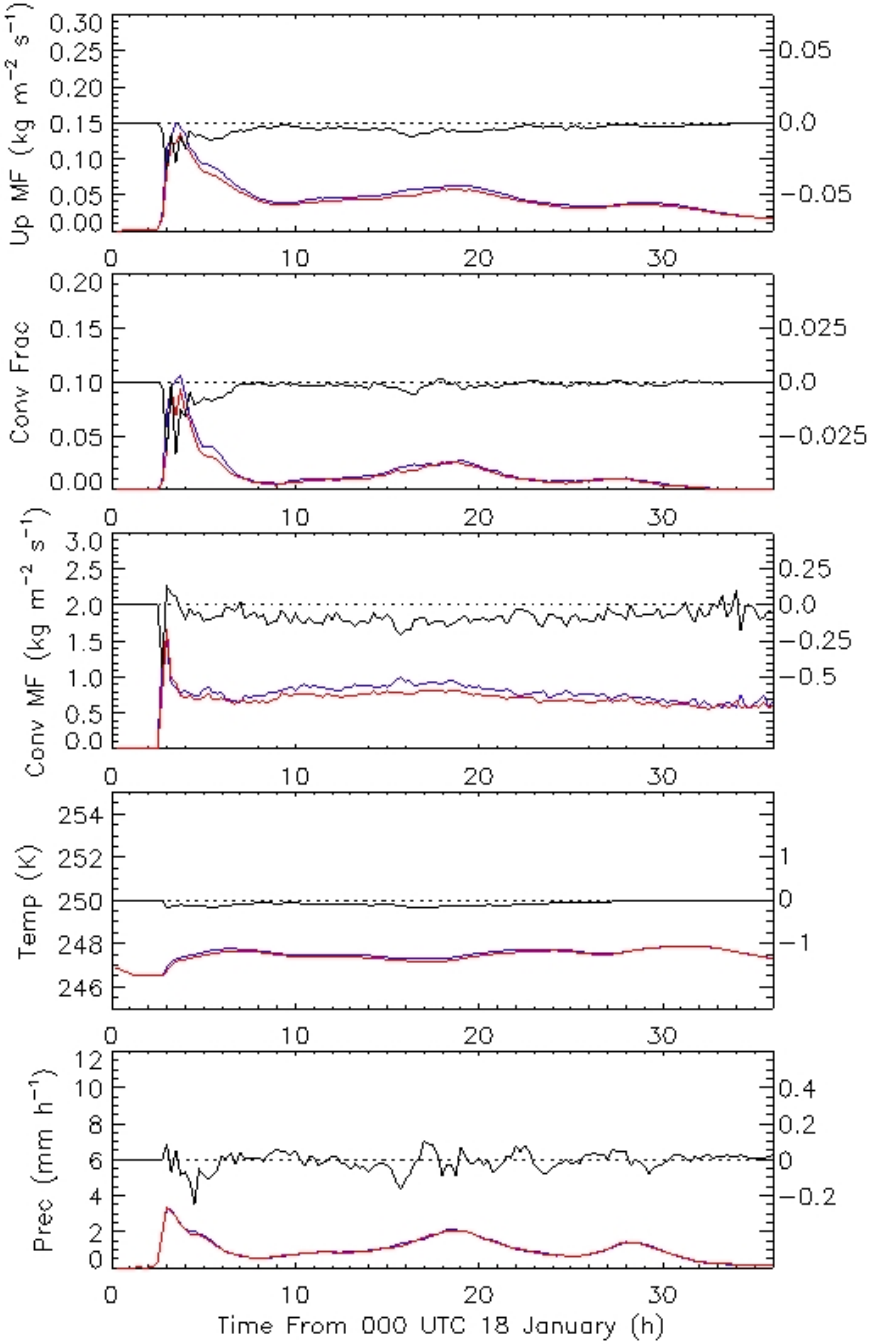
Up MF (kg m^{-2} s^{-1})
0.30 0.25 0.20 0.15 0.10 0.05 0.00
0.05 0.0 −0.05
Conv Frac
0.20 0.15 0.10 0.05 0.00
0.025 0.0 −0.025
Conv MF (kg m^{-2} s^{-1})
3.0 2.5 2.0 1.5 1.0 0.5 0.0
0.25 0.0 −0.25 −0.5
Temp (K)
254 252 250 248 246
1 0 −1
Prec (mm h^{-1})
12 10 8 6 4 2 0
0.4 0.2 0 −0.2
0 10 20 30
Time From 000 UTC 18 January (h)



Z ^ 3 km
Z ^ 7 km
Z ^ 12 km
m⁻¹ s
w (m s⁻¹)
10⁵
10⁴
10³
10²
10¹
10⁰
10⁻¹
0 2 4 6 8 10



Up MF (kg m^{-2} s^{-1})
Conv Frac
Conv MF (kg m^{-2} s^{-1})
Temp (K)
Prec (mm/hr)
Time From Start (h)


Up MF (kg m^{-2} s^{-1})
Conv Frac
Conv MF (kg m^{-2} s^{-1})
Temp (K)
Prec (mm h^{-1})
Time From 000 UTC 18 January (h)