Mesoscale thermodynamic and dynamic controls on aerosol-induced invigoration of tropical deep convection

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Overview

Studies have suggested that pollution can invigorate convection by delaying warm-rain production and increasing latent heat release by freezing of liquid water and enhanced ice processes (Rosenfeld et al. 2008).

Previous studies have generally looked at the impact of aerosols of individual convective clouds, neglecting feedback with the larger-scale environment.

Satellite studies have examined correlations between cloud height, cloud fraction, and aerosols to infer that convection is invigorated in polluted conditions (Koren et al. 2010). However, observations of aerosol impacts are confounded by issues related to causation versus correlation and confounding meteorological factors.

The goal of this study is to examine aerosol impacts on tropical deep convection using multi-day simulations in a large domain that includes feedback with the larger-scale thermodynamic and dynamical environment.

Model Setup

Simulations of the Tropical Warm Pool – International Cloud Experiment (TWP-ICE) have been conducted with a version of the anelastic Eulerian-Lagrangian (EULAG) cloud model (Grabowski and Smolarkiewicz 1999)

Similar setup as TWP-ICE cloud model intercomparison (Fridlind et al. 2012):

- Simulation period: Jan 18 to Jan 25, 2006, 10 mb V2 ARM forcing/initial dataset
- 2D, 97 vertical levels with stretched vertical coordinate, 1000 x 25 km domain, 1 km horizontal grid spacing, periodic lateral boundaries, fixed surface fluxes

Due to large convective variability, we use an ensemble approach with 120-240 members. Different members are generated by applying different random number seed to small, random perturbations of the low-level potential temperature field (Morrison and Grabowski 2011).

Pristine aerosols based on measurements from TWP-ICE are assumed except as indicated. For simulations with perturbed aerosols, an idealized urban-type aerosol is assumed. Ice nuclei concentrations are not modified in any simulations.

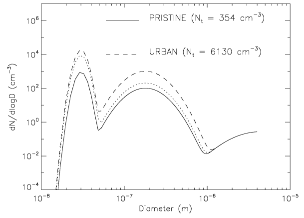


Fig. 1. Specified pristine and perturbed (URBAN) aerosol size distribution. A 3-mode lognormal distribution is assumed.

Simulations with perturbed heating

To investigate the hypothesis that aerosols invigorate convection through enhanced latent heating in updrafts above the freezing level *in the context of feedback with larger-scale thermodynamics and dynamics*, we run large-domain 7.5 day simulations with perturbed heating applied to updrafts.

Latent heating is enhanced by a factor of 1.2 between 6 and 8 km. Corresponding cooling is applied in downdrafts at these levels such that there is no net forcing of static energy. Overall results are insensitive to details of the heating perturbations.

Simulations are tested with (PERT) and without (BASE) perturbed heating.

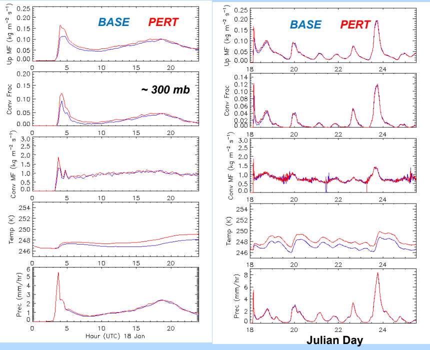
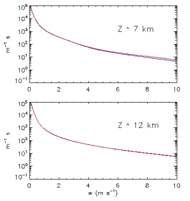


Fig. 2. a) Ensemble-mean timeseries of various quantities at a height of ~ 300 mb over the first 24 hours. b) as in a), but for the full 8.5 day simulation.

Fig. 3. PDFs of updraft velocity averaged from day 19-25.5.



There is an initial convective invigoration with perturbed heating, but the environment subsequently adjusts by warming. This limits the impact of perturbed heating on convection after ~ 1 day. We propose that the adjustment timescale is controlled by a rapid initial phase (~ few h) corresponding to initial convective overturning and gravity wave adjustment, followed by slower adjustment related to vertical mixing by convective drafts (~ 1 day).

Large differences in tropospheric temperature between PERT and BASE suggest that larger-scale circulations can develop if perturbed conditions are limited in area (inducing mesoscale heating gradients). To test this idea, we ran perturbed simulations with perturbed heating only applied to the inner 250 km of the domain (in the spirit of Lee 2012).

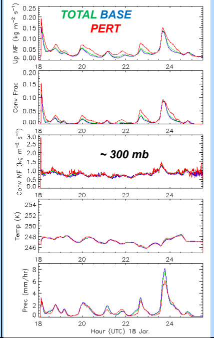
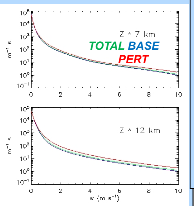


Fig. 4. Ensemble-mean timeseries of various quantities at a height of ~ 300 mb. PERT is the average in region with perturbed heating, BASE is the unperturbed region, and total is the domain-average.

Fig. 5. PDFs of updraft velocity for TOTAL, BASE, and PERT.



With perturbed heating only applied to part of the domain, there is a net mesoscale heating gradient. The associated gravity waves and mesoscale circulation sustains convective invigoration in the perturbed region over time.

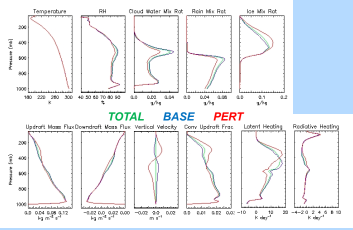


Fig. 6. Ensemble- and time-averaged profiles for simulations with perturbed heating in part of the domain.

Mesoscale circulation consists of upper-tropospheric upward motion and lower-tropospheric downward motion in the perturbed region to compensate for the applied warming/cooling. The opposite occurs in the unperturbed region.

Net upward motion results in moistening of the upper-troposphere in the perturbed region and drying in the unperturbed region. At lower levels, net downward motion produces drying and a *reduction of surface precipitation in the perturbed region*, with the opposite for the unperturbed region.

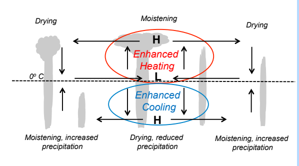


Fig. 7. Schematic of the relationship between convection, heating, cooling, and mesoscale circulations.

Simulations with perturbed aerosols

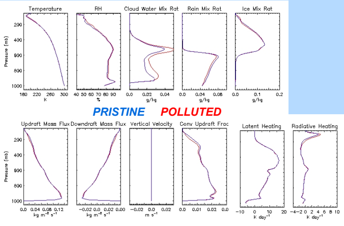


Fig. 8. Ensemble- and time-averaged profiles for simulations with pristine and polluted aerosols applied throughout the domain.

With perturbed aerosols applied to the entire domain, there is a slight *weakening* of convection in polluted conditions due to enhanced radiative heating of the upper troposphere (caused by microphysical changes in anvil ice clouds). We speculate that radiative heating gradients resulting from perturbed aerosols applied to only part of the domain could result in mesoscale circulation and drive convective invigoration.

Conclusions

- In the absence of larger-scale heating gradients and circulations, *aerosol-induced convective invigoration cannot be sustained* because the larger-scale thermodynamic environment rapidly adjusts. This is true even when perturbed heating is directly applied to convective updrafts. If perturbed heating is applied to only part of the domain, mesoscale circulations develop that sustain convective invigoration over time.

- If perturbed aerosols are applied to the entire domain, there are no mesoscale heating gradients and hence no convective invigoration. We speculate that if aerosols are applied to part of the domain, radiative heating gradients could drive mesoscale circulations and invigorate convection. Testing of this hypothesis is underway.

- *These results suggest that aerosol-induced convective invigoration is primarily controlled by feedback with the environment*, via the development of larger-scale heating gradients. This presents a much different picture of convective invigoration than previous studies focusing on convective-scale buoyancy perturbations.

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