Cloud system-resolving model simulations of aerosol indirect effects on tropical deep convection

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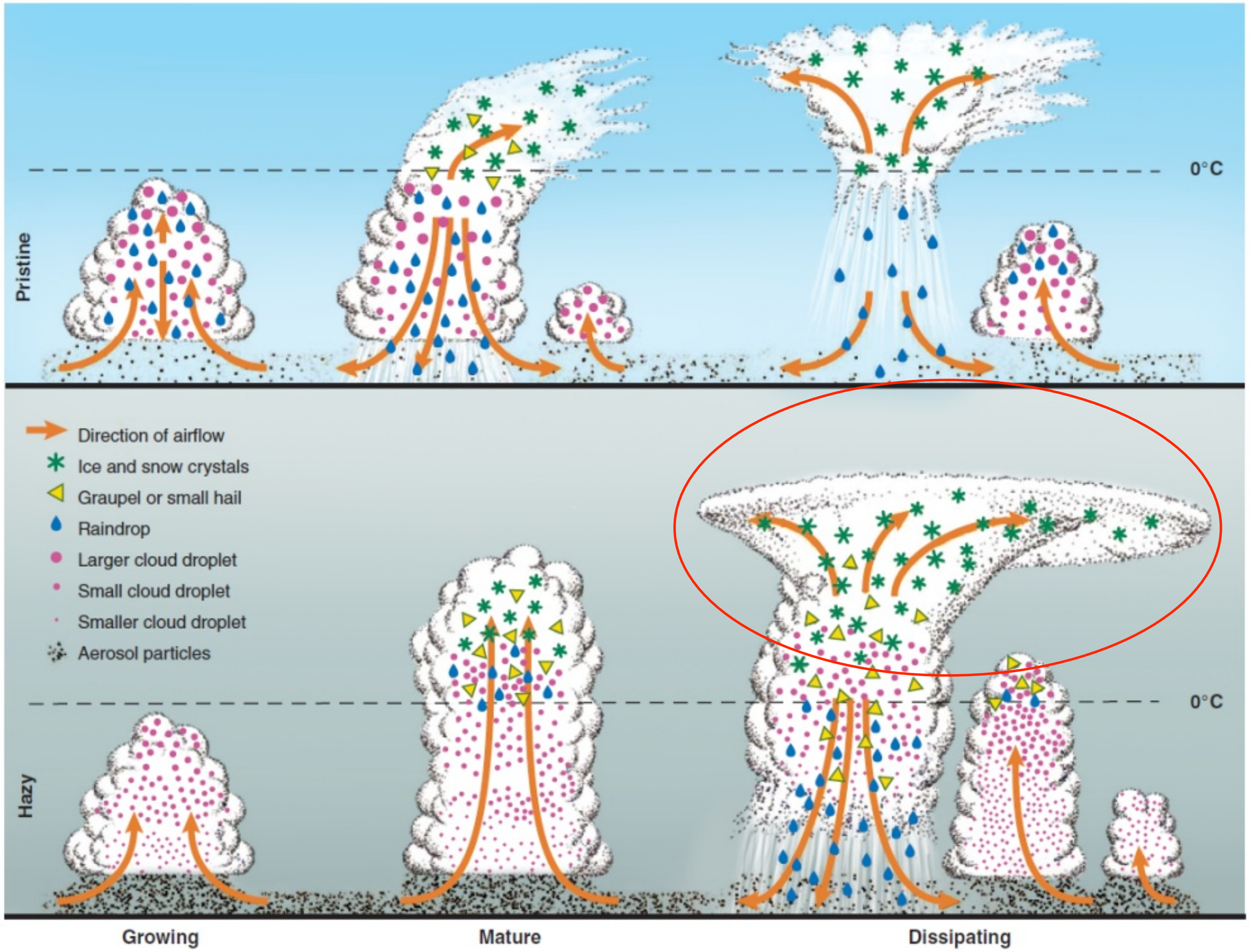
CMMAP meeting, Jan. 12, 2011

Rosenfeld et al.
Science, 2008

Koren et al. (2010)



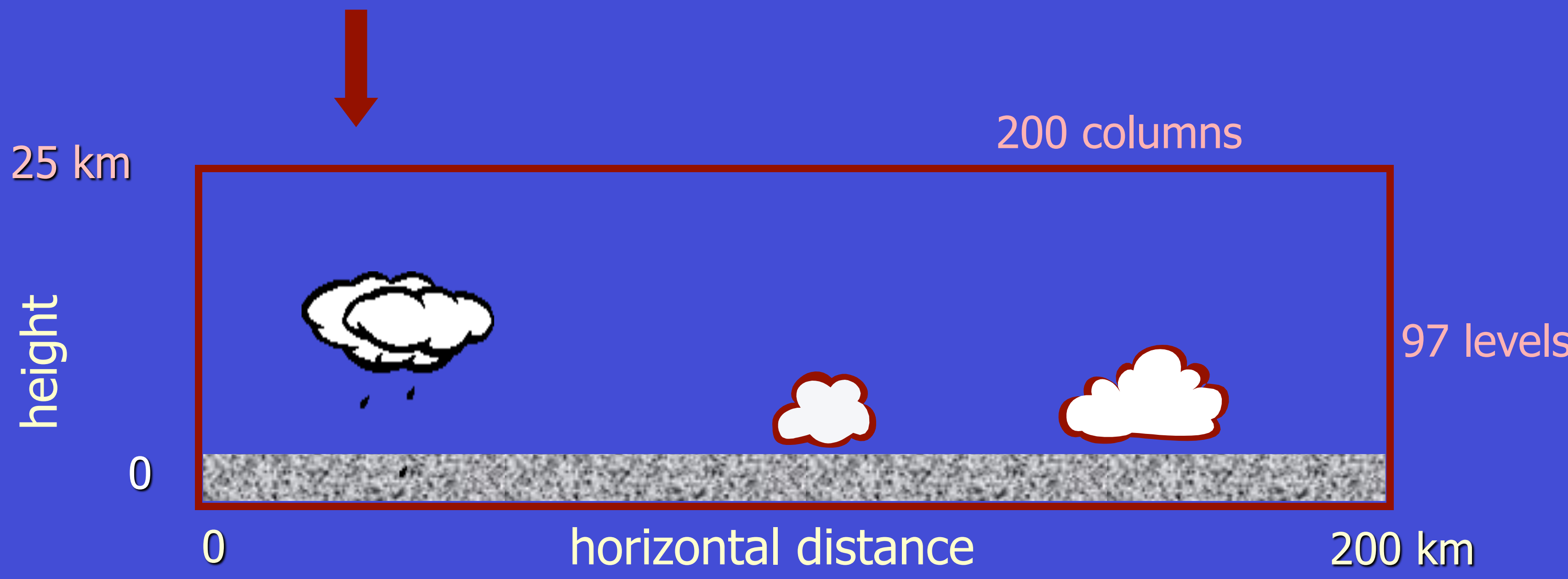
Example of hypothesized aerosol-microphysics-dynamics interactions in deep convection

What are impacts over longer timescales relevant to climate, where interactions between clouds and their environment are key?

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

- **similar setup to ARM/GCSS intercomparison**

Prescribed large-scale forcing of T, qv, 6 hr nudging of u to observations



horizontal grid spacing of order 1 km

Surface temperature = 29° C

Numerical model:

Dynamics: 2D super-parameterization model (Grabowski 2001)

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

Radiation: NCAR's Community Climate System Model (CCSM) (Kiehl et al 1994) in the Independent Column Approximation (ICA) mode

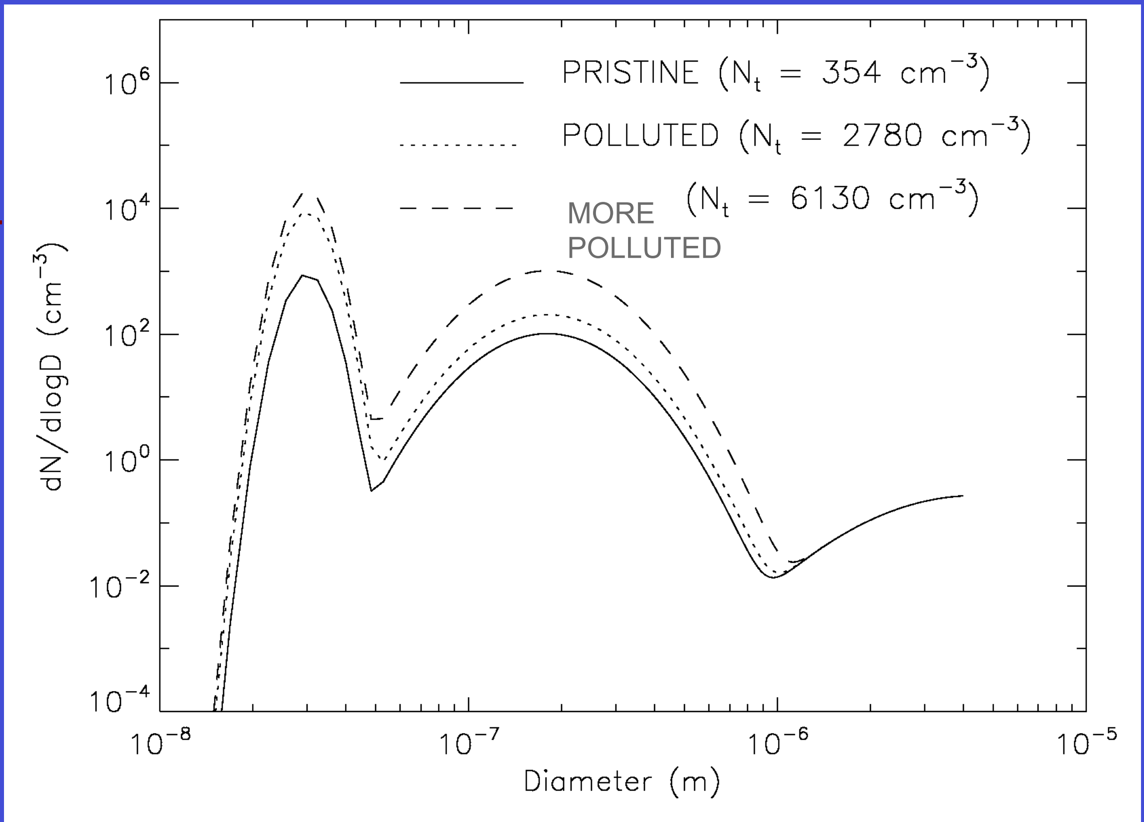
200 x 25 km domain and 97 stretched levels

• **BASE** → Baseline configuration (Morrison and Grabowski 2007; 2008a,b)

• **FRZ** → Heterogeneous droplet freezing of Bigg (1953) replaced by Barklie and Gokhale (1959), ~ factor of 100 reduction in freezing rate

• **GRPL** → Graupel density decreased by ~ factor of 3

• **Resolution** → Horizontal gridlength varied from 2 km to 500 m

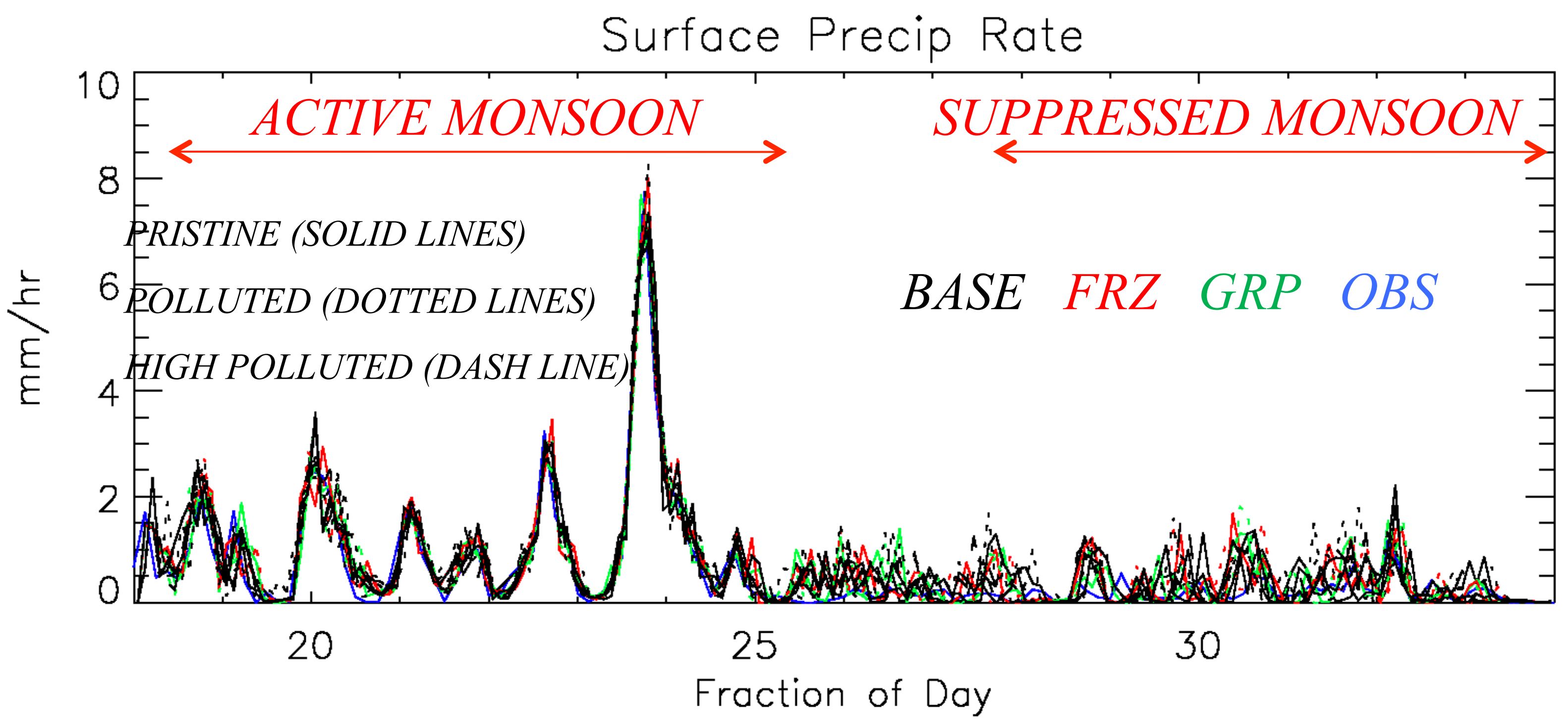


Aerosol specification, similar to Fridlind et al. (2010, in prep)

No impact of aerosol on heterogeneous IN, no direct aerosol effect

• **Impact on surface precipitation**

- limited impact on forcing terms in the bulk moist static energy budget (tropospheric radiative cooling, surface fluxes) and rapid convective adjustment lead to mean surface precipitation rates → constrained by prescribed large-scale forcing and SST



Budget thinking…

Rapid convective adjustment maintains consistency between s and q through Q_c / Q_{pre}

$$\frac{\partial[s]}{\partial t} + l.s.adv/div([s]) - RAD - SH = Q_c$$

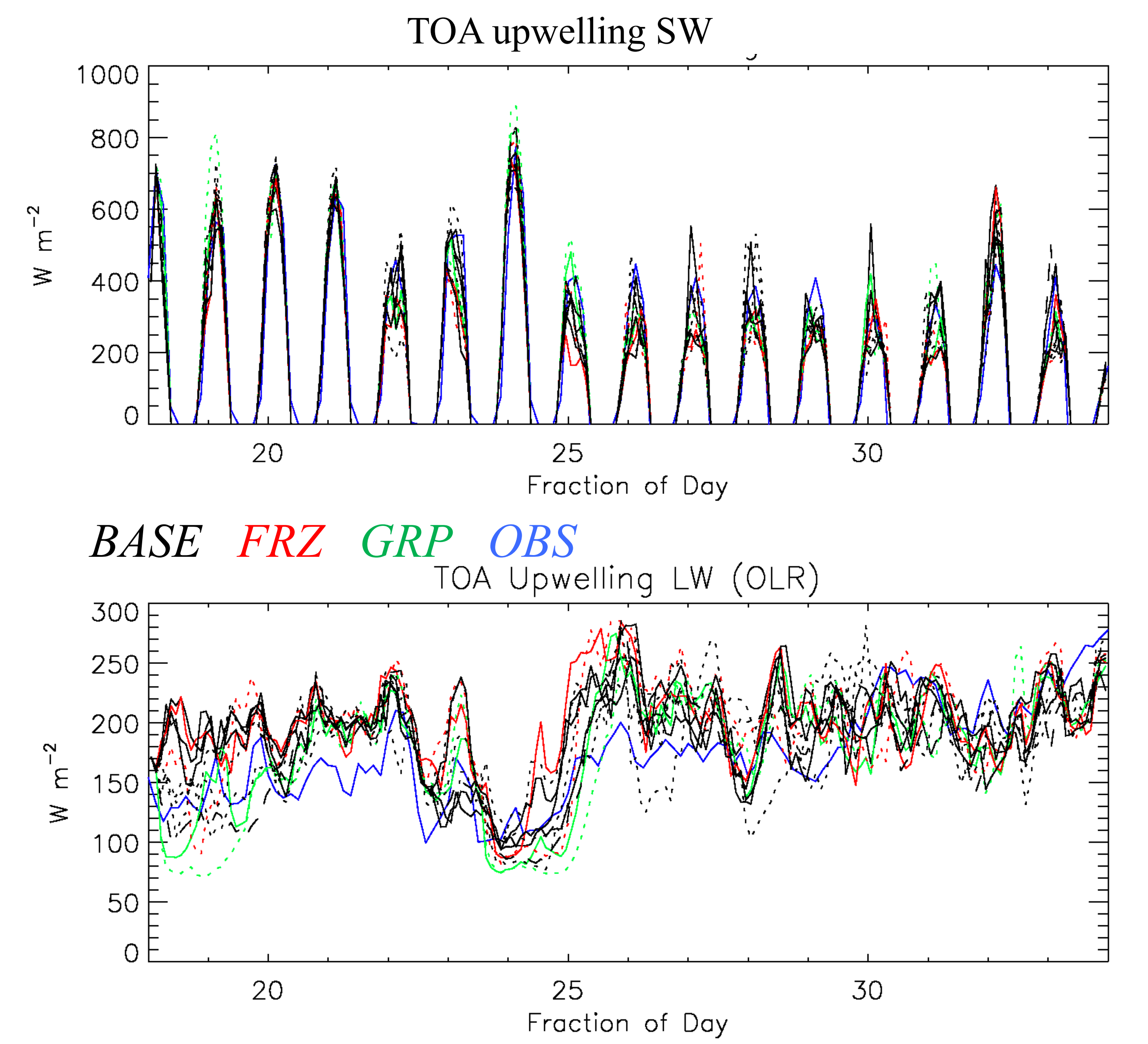
$$= -\left(\frac{\partial[q]}{\partial t} + l.s.adv/div([q]) - LH\right) = -Q_{pre}$$

In convective-radiative equilibrium

(Grabowski 2006; Grabowski and Morrison 2010):

$$\frac{\partial[h]}{\partial t} + l.s.adv/div([h]) - RAD - SH - LH = 0$$

• Impact on TOA radiative fluxes



PRISTINE (SOLID LINES)

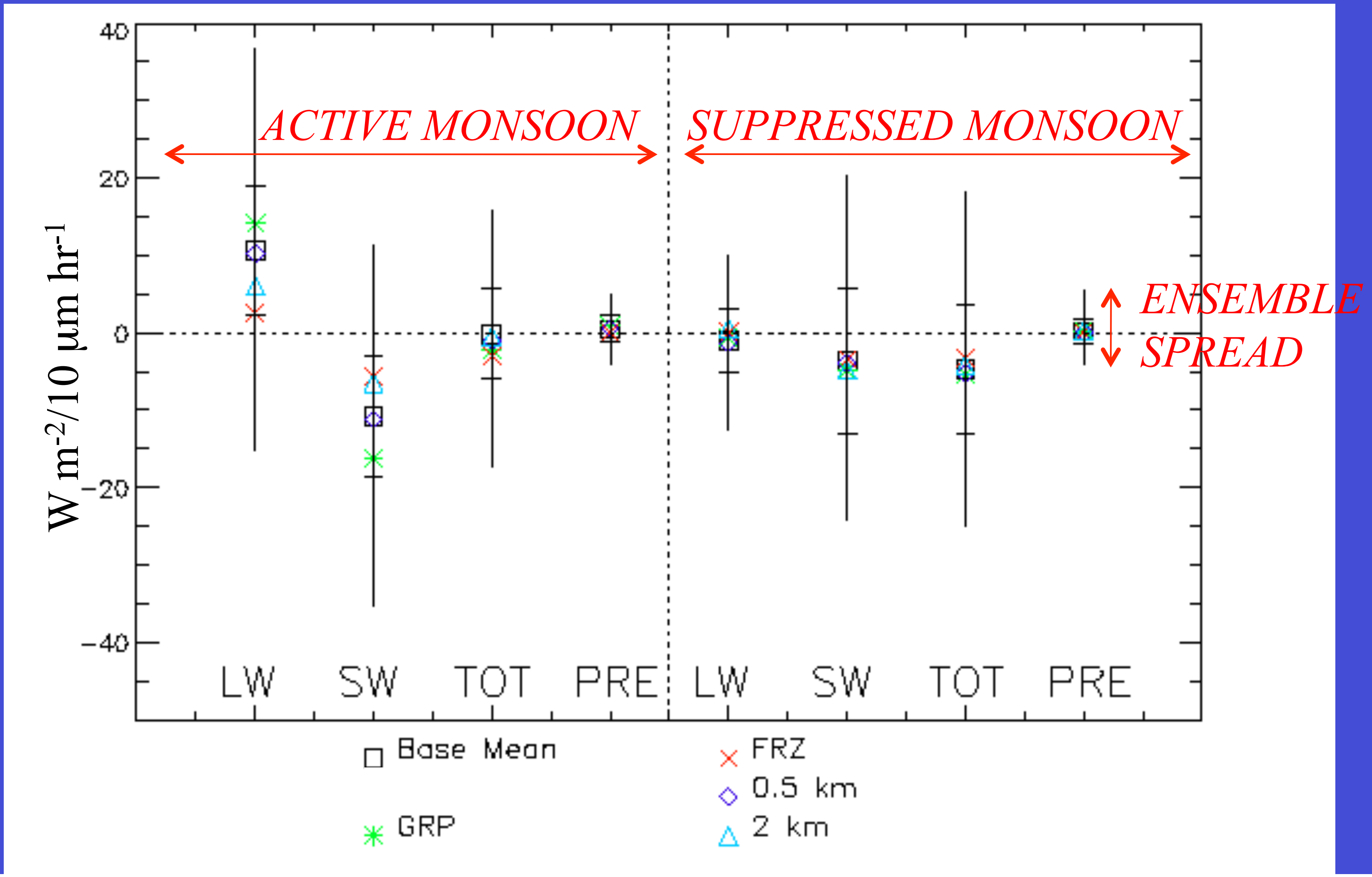
POLLUTED (DOTTED LINES)

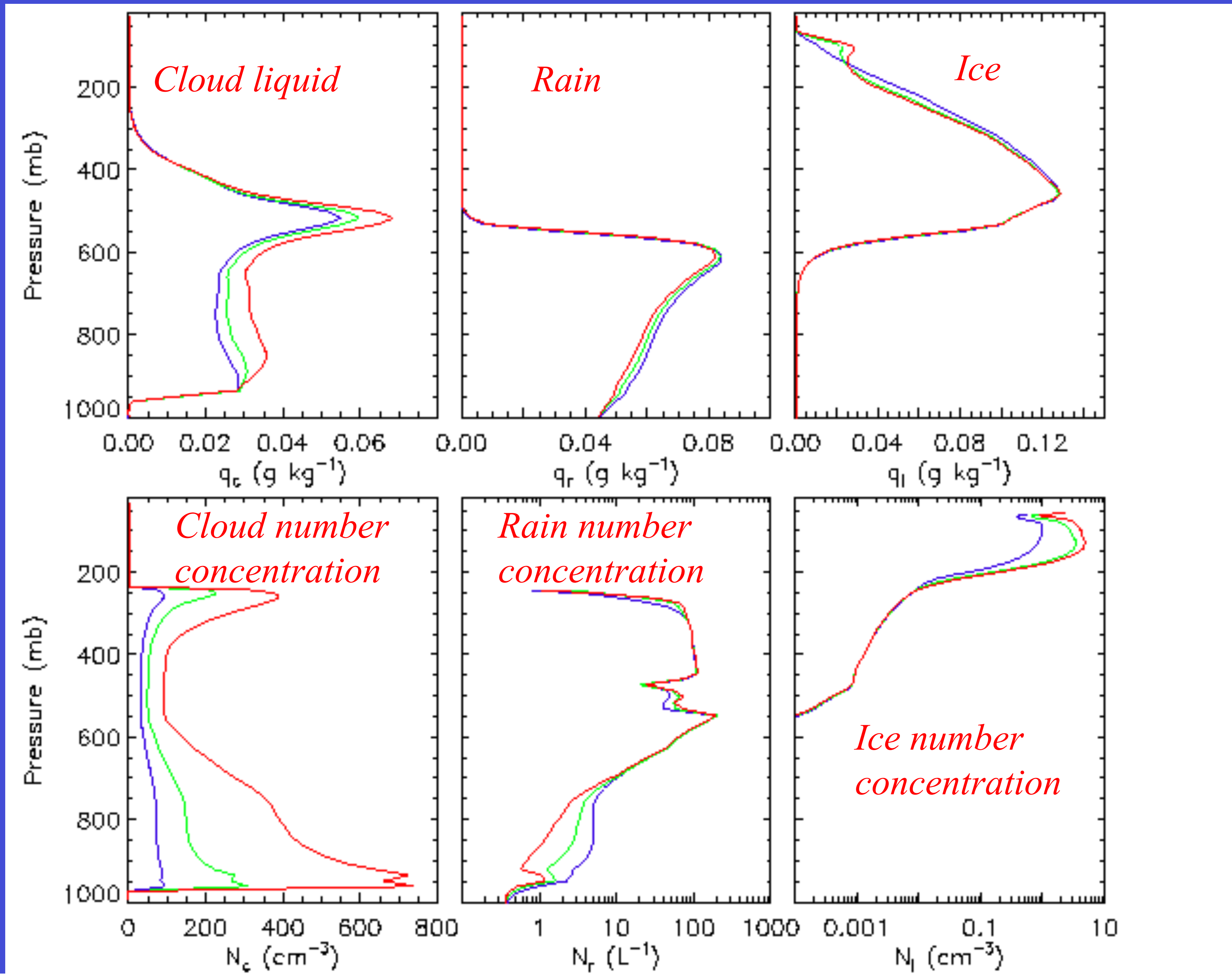
What is the role of internal variability in explaining these differences?

- **Tests w/ vanishingly small perturbations to initial/ boundary conditions or tiny random noise indicate large internal variability for parameters like TOA radiative fluxes, *even when averaged over 16-days.***

- **Need to run large-member ensembles to determine statistical significance of aerosol effects!**

• **240-member ensembles of simulations (pristine and polluted) with different initial seed for random noise**




Cloud liquid
Rain
Ice
Pressure (mb)
200
400
600
800
1000
0.00
0.02
0.04
0.06
q_c (g kg^-1)
0.00
0.04
0.08
q_r (g kg^-1)
0.00
0.04
0.08
0.12
q_I (g kg^-1)
Cloud number concentration
Rain number concentration
Ice number concentration
Pressure (mb)
0
200
400
600
800
N_c (cm^-3)
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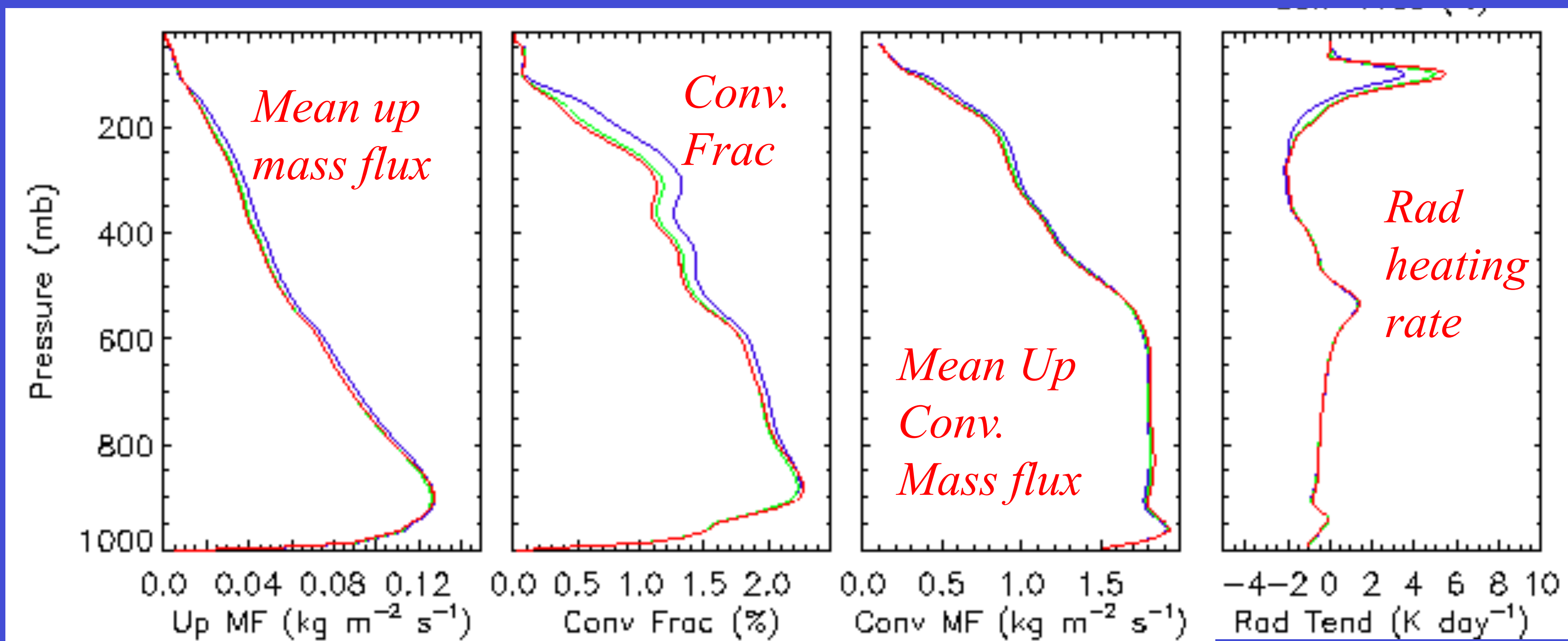
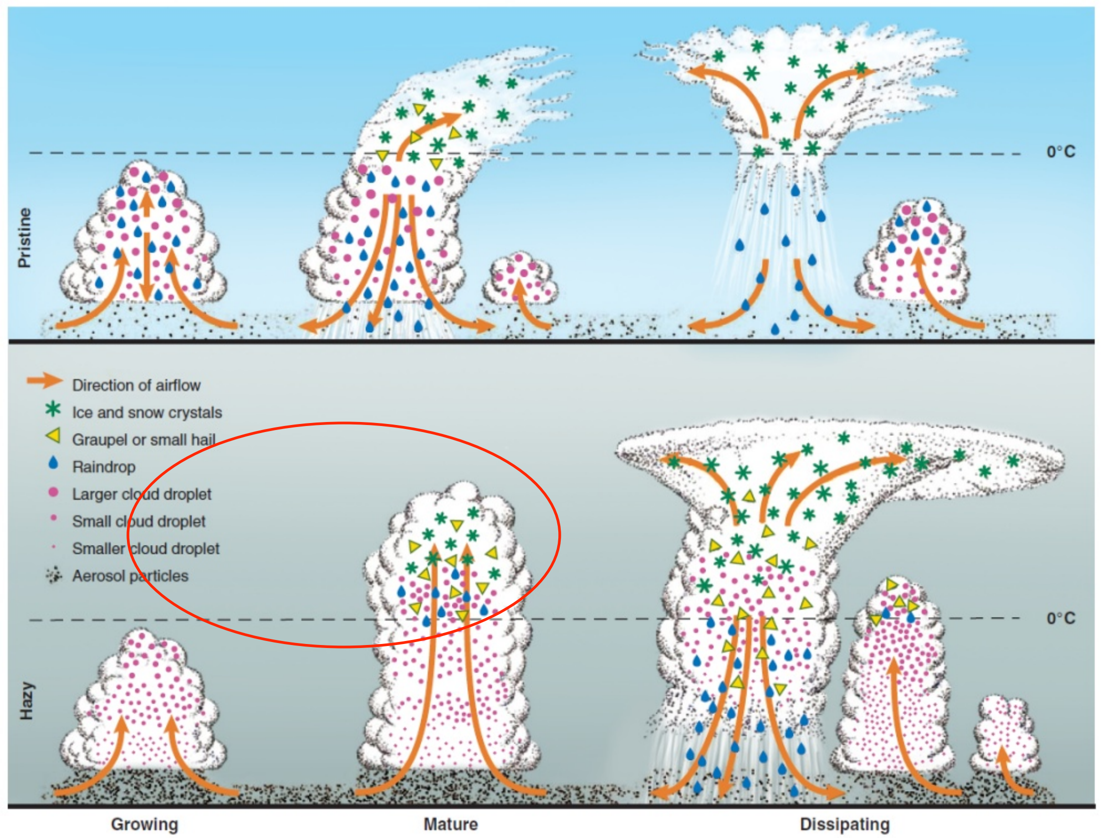
10
100
1000
N_r (L^-1)
0.001
0.1
10
N_I (cm^-3)


Mean up
mass flux
Conv.
Frac
Mean Up
Conv.
Mass flux
Rad
heating
rate
Pressure (mb)
200
400
600
800
1000
0.0 0.04 0.08 0.12
Up MF (kg m−2 s−1)
0.0 0.5 1.0 1.5 2.0
Conv Frac (%)
0.0 0.5 1.0 1.5
Conv MF (kg m−2 s−1)
−4−2 0 2 4 6 8 10
Rad Tend (K day−1)

• Model produces increase in anvil thickness/height with increased aerosol consistent with some observations (Koren et al. 2010).

• However, this does NOT occur due to convective invigoration, but appears to result from direct impact of changes in ice number concentration (due to droplet freezing).



Conclusions

• There is limited impact of aerosol on forcing terms in the moist static energy budget, and hence not much change in the mean surface precipitation rate and updraft mass flux → strongly constrained by prescribed large-scale forcing and SST. Overall there is a small net upper tropospheric radiative heating with increased aerosols which slightly weakens convection.

• Changes induced by aerosol may feed back to surface/large-scale dynamics and thus impact surface precipitation (an effect not considered in this study).

• This study did not consider how plumes of aerosols might affect precipitation locally.

Conclusions

• **SW and LW fluxes are less constrained than precipitation by MSE budget terms and are therefore more sensitive in this framework, but these quantities are also subject to large internal model variability (less problematic in 3D?).**

• **Statistically-significant aerosol effects on net TOA flux:**

- active monsoon ~ 0 W m^{-2} (LW and SW effects approximately cancel)
- suppressed monsoon ~ -5 W m^{-2} (SW effects dominate)

• **Sensitivity to microphysics and resolution: means from all tests lie within the baseline ensemble standard deviation, but statistically significant differences are apparent for active monsoon.**

- also sensitivity tests to domain size and other microphysics parameters