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# Multiscale Cloud-Aerosol Interactions


Steven Ghan, Jiwen Fan, and Minghuai Wang: PNNL
Yuan Wang: Jet Propulsion Laboratory
Renyi Zhang: Texas A&M University
Andrew Gettelman and Hugh Morrison: NCAR

# Outline

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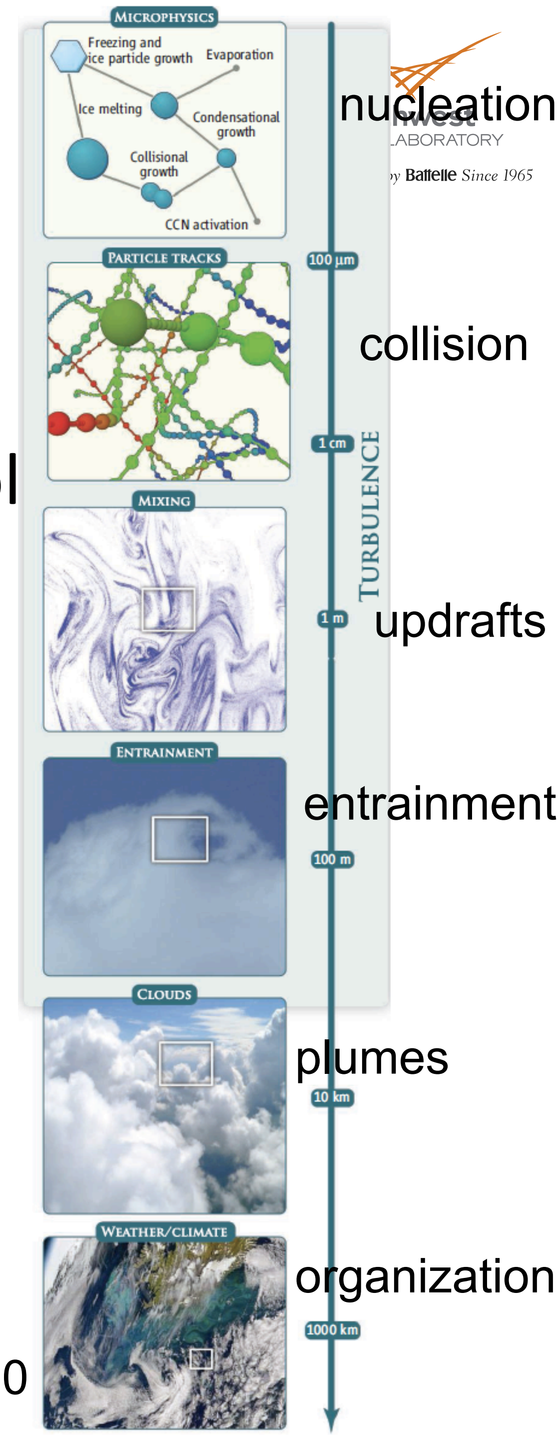
1. Challenges
2. Approaches
3. Understanding
4. A Path Forward

# 1. A Multiscale Challenge

- Cloud-aerosol interactions are intimately coupled with important cloud and aerosol processes.
- Improved representation of interactions depends on improved parameterizations of cloud microphysics and macrophysics.
- Creative methods are needed to represent processes across the wide range of spatial scales involved.




Bodenschatz et al., Science 2010

# Other Dimensions of Complexity: Phase, shape, composition

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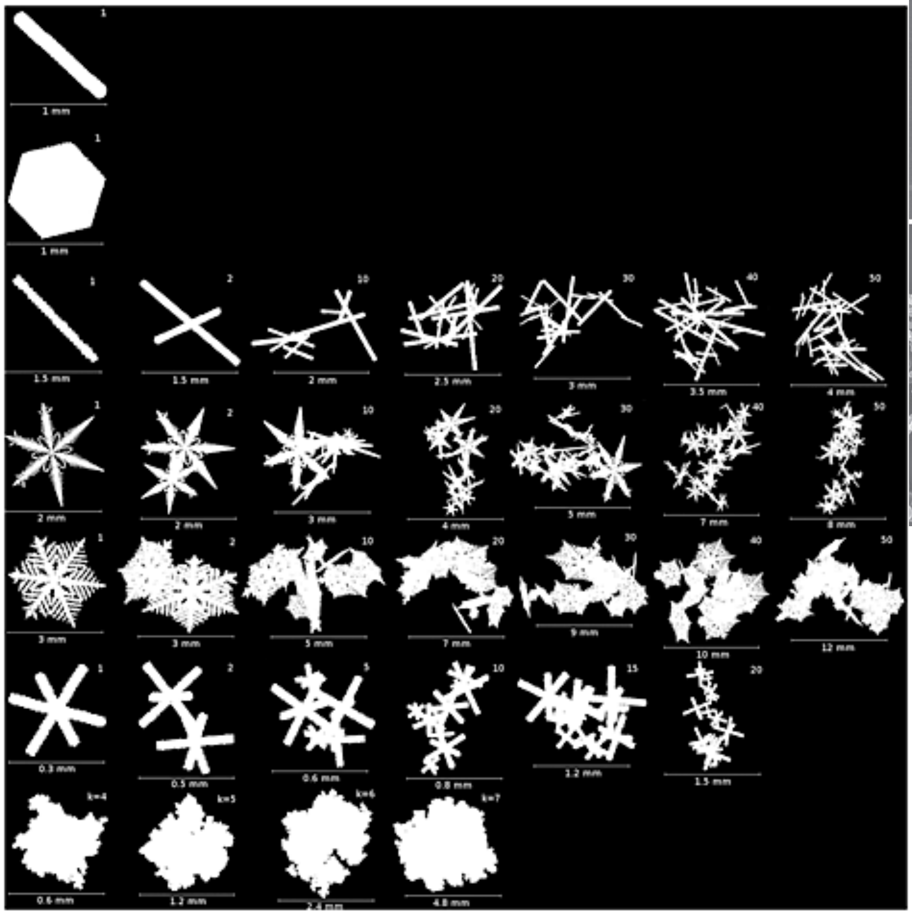
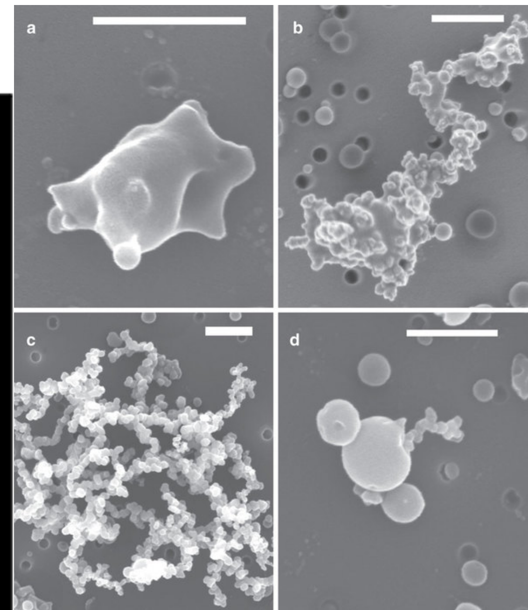
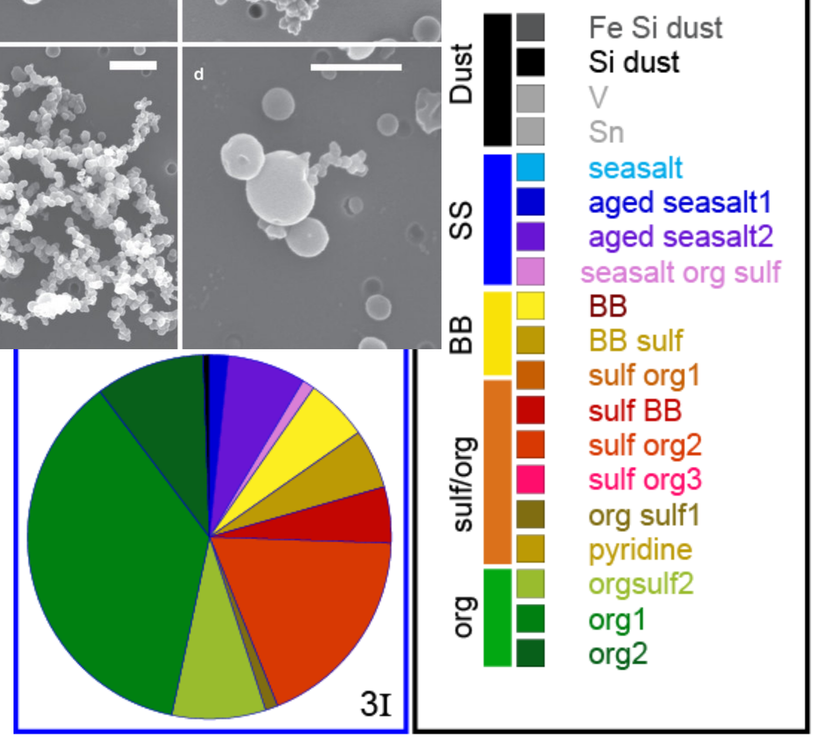
Ice particles

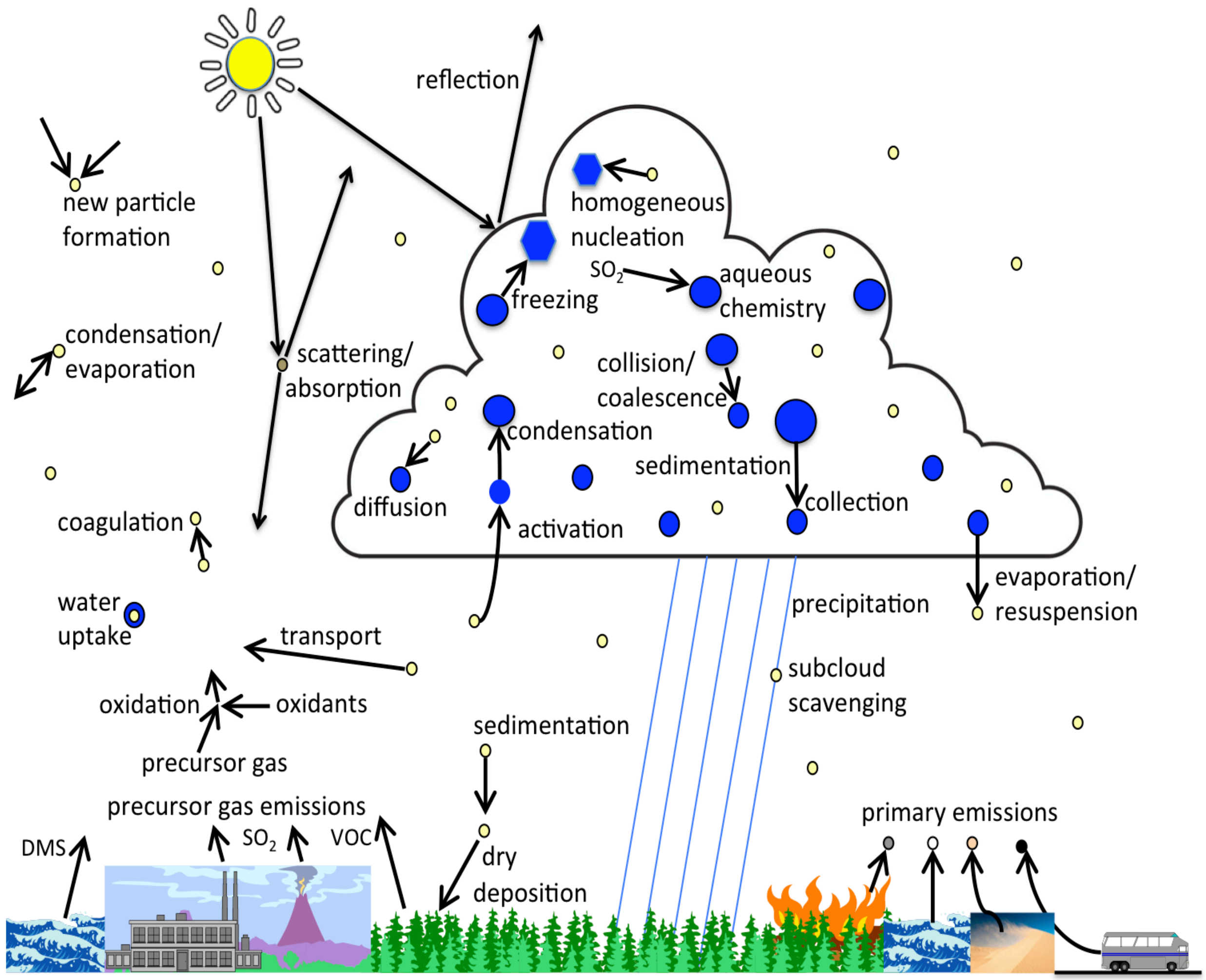


Aerosol particles



# Complexity of Microphysical Processes




**For the whole Atmosphere!**

# 2. Approaches



- Aerosol Microphysics
- Cloud Macrophysics
- Cloud Microphysics
- Interactions

# Aerosol Microphysics

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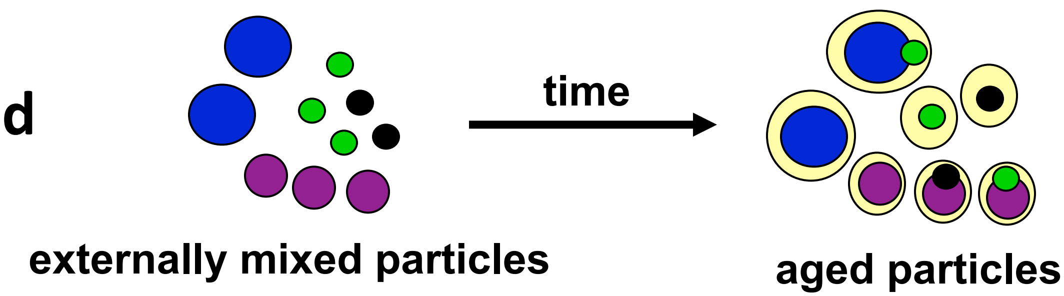
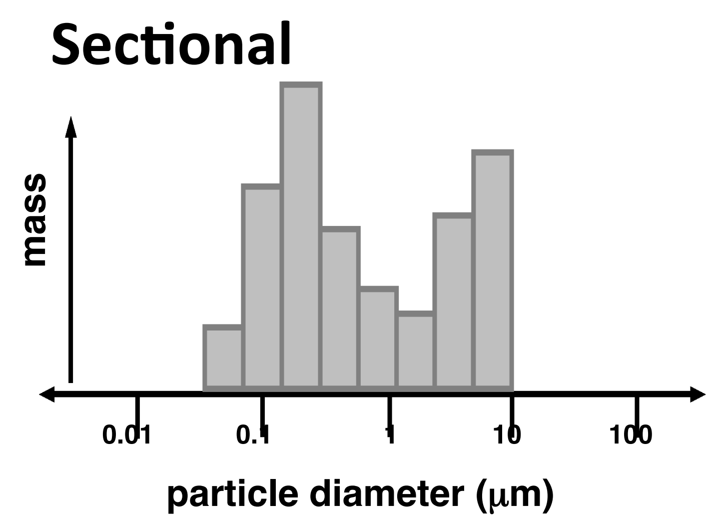
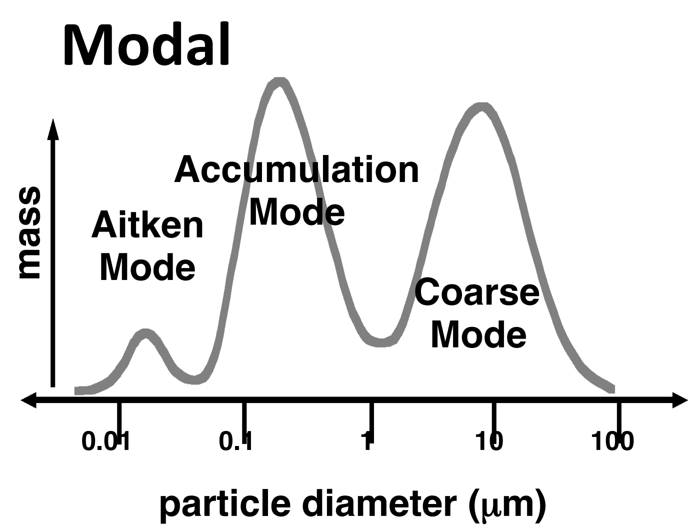
Particle-Resolved



# Particle-Resolved Modeling

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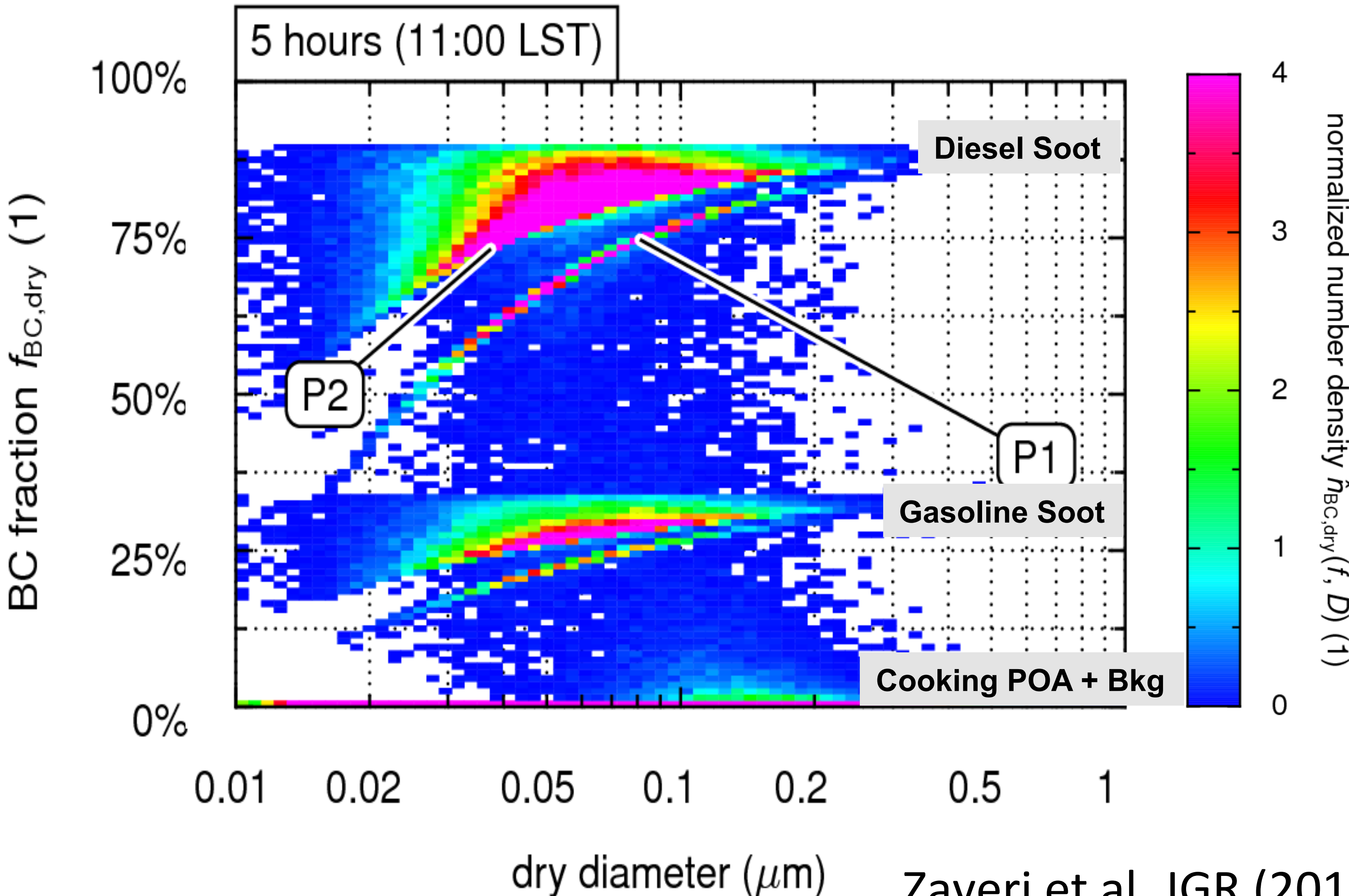
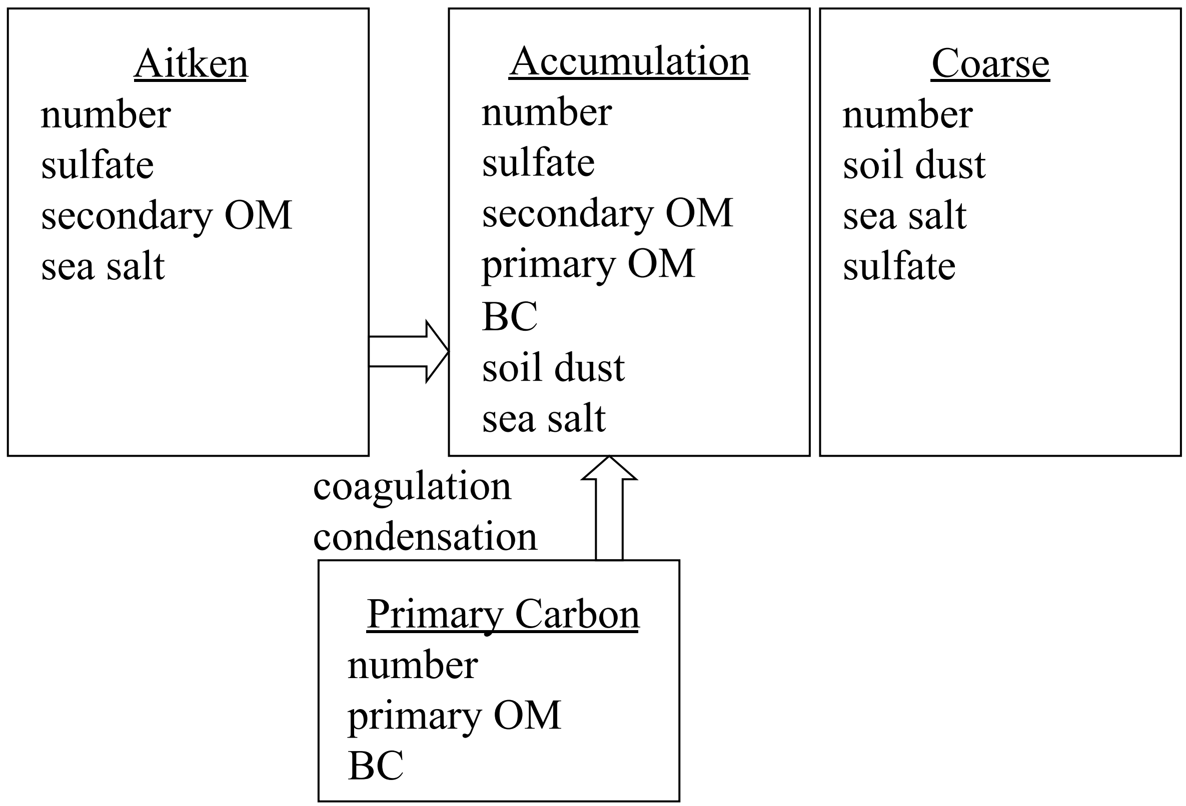



Zaveri et al. JGR (2010)

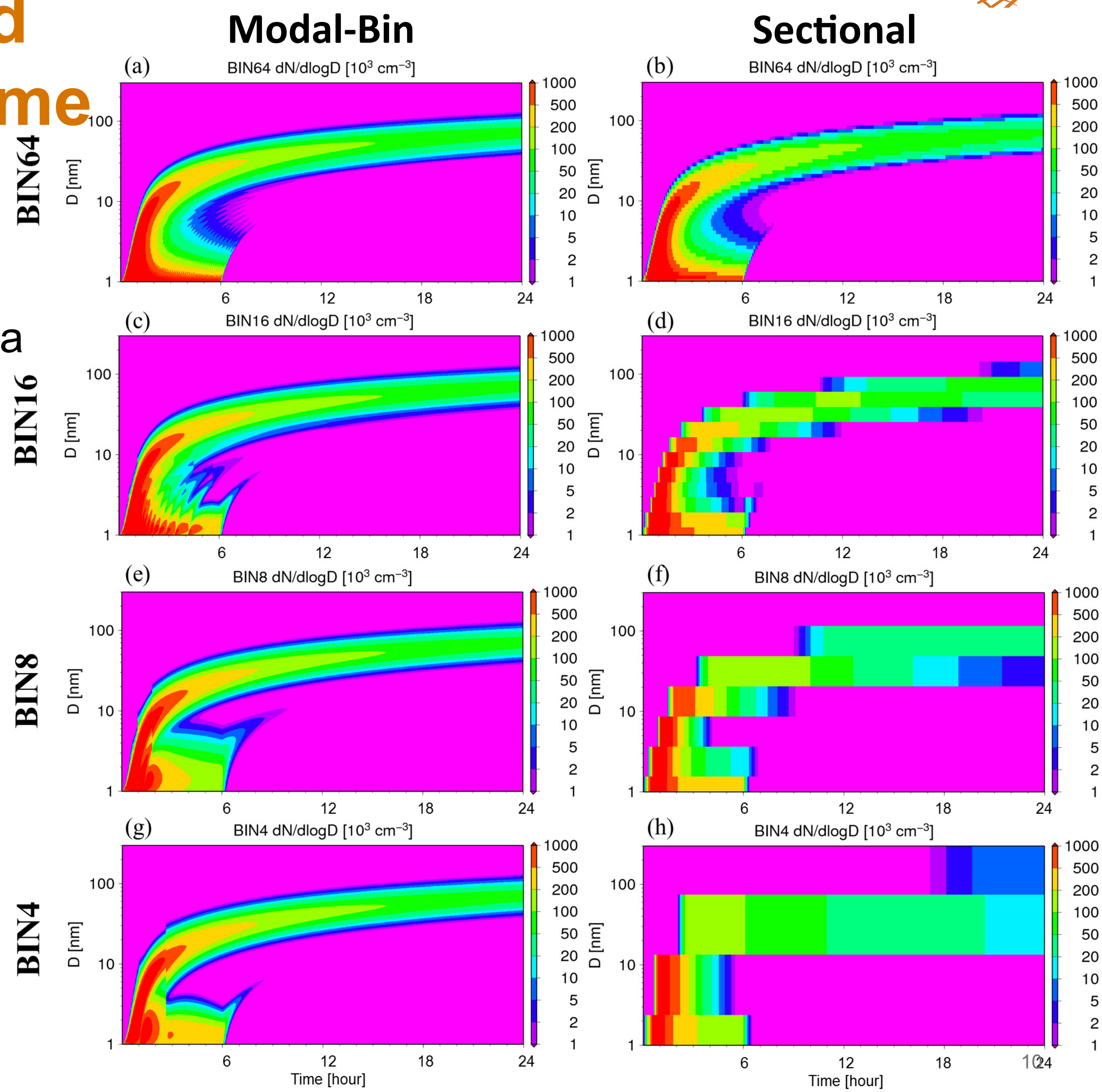
# Four-Mode Aerosol Model in CAM





# An Advanced Hybrid Scheme

- Superior performance of a triple-moment hybrid aerosol scheme

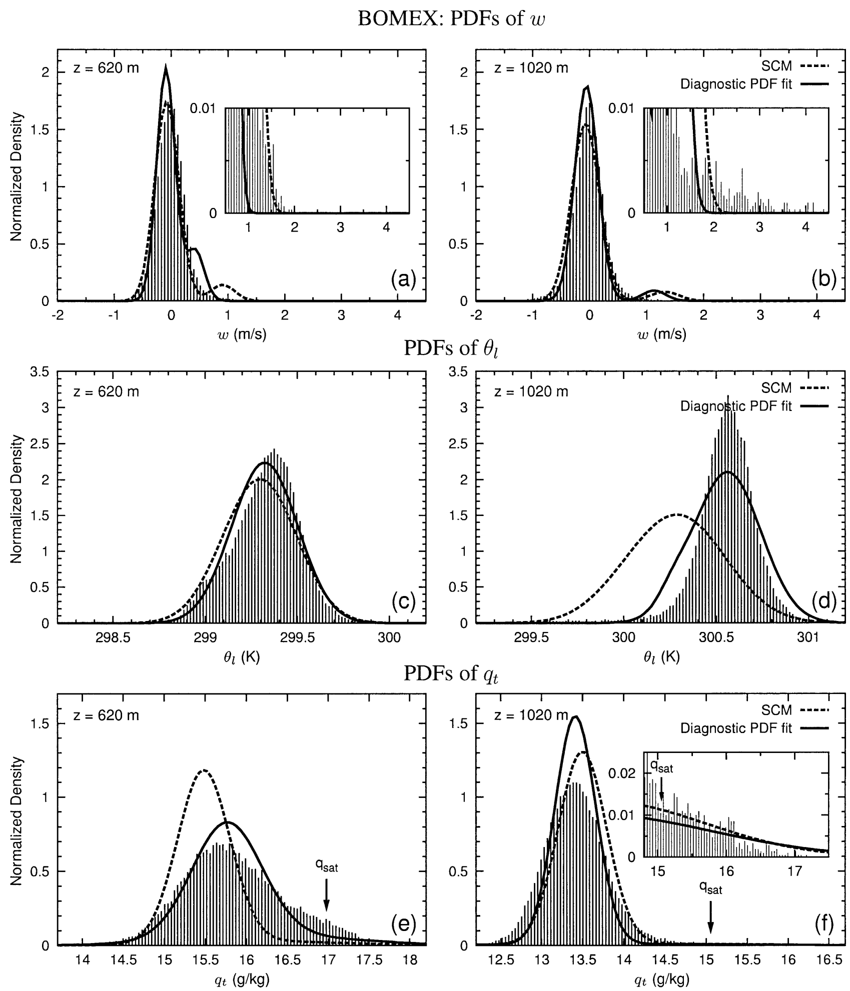



Kajino et al., JGR 2013

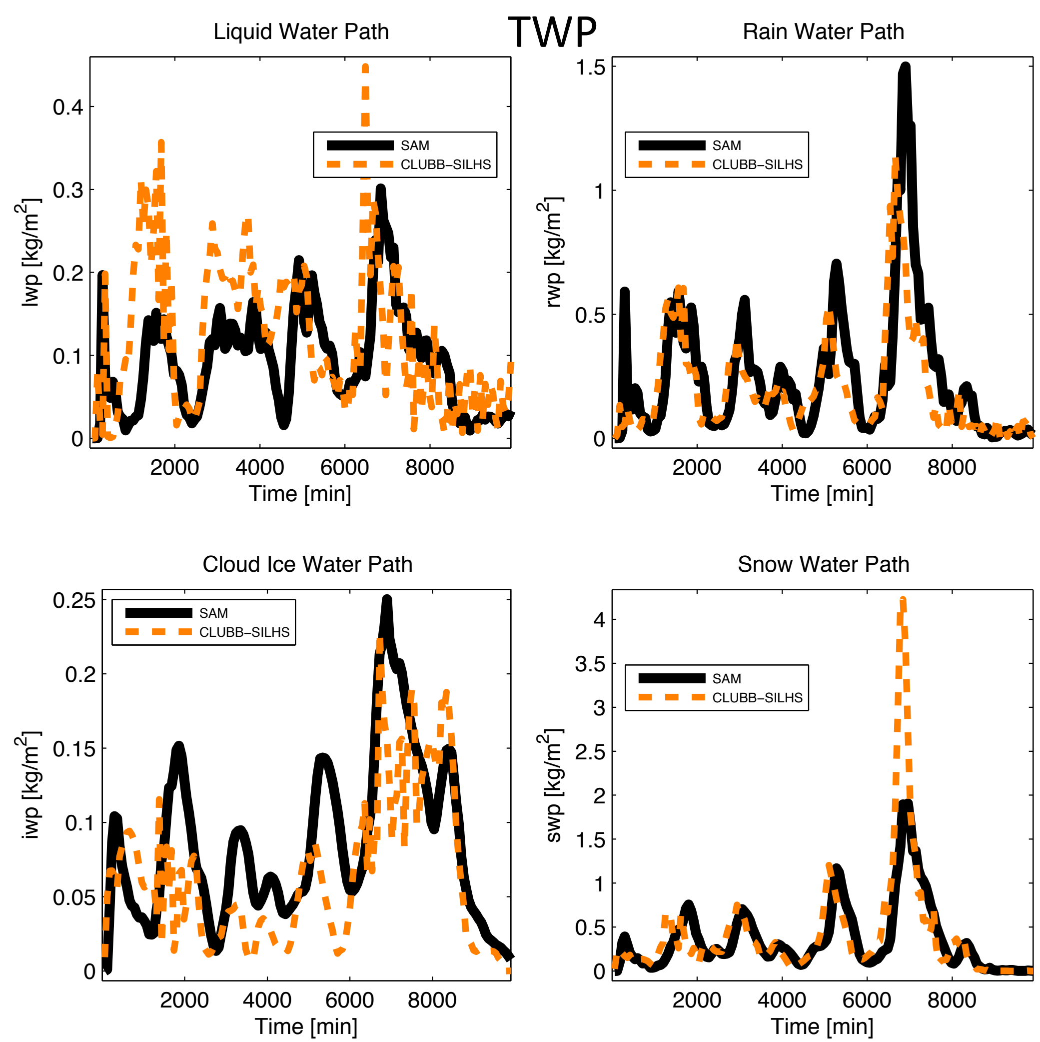
# Cloud Macrophysics



- Double Gaussian PDF
- Superparameterization




Golaz et al. JAS (2002)




Storer et al., GMDD (2014)

# Cloud Microphysics



- Bin microphysics
  - Explicit condensation
  - Ice nucleation a source of uncertainty
- Bulk microphysics
  - Saturation adjustment
  - Prescribed size distribution for cloud water, rain, ice, snow, graupel
  - Temperature-dependent phase and hybrid saturation vapor pressure
- Double-moment microphysics
  - Number and mass for each hydrometeor class
  - Particle phase depends on ice nucleation
  - Saturation adjustment for liquid
  - Explicit vapor deposition to ice
  - Precipitating species often diagnosed rather than predicted.

# Cloud Microphysics

Morrison and Gettelman, JGR 2008

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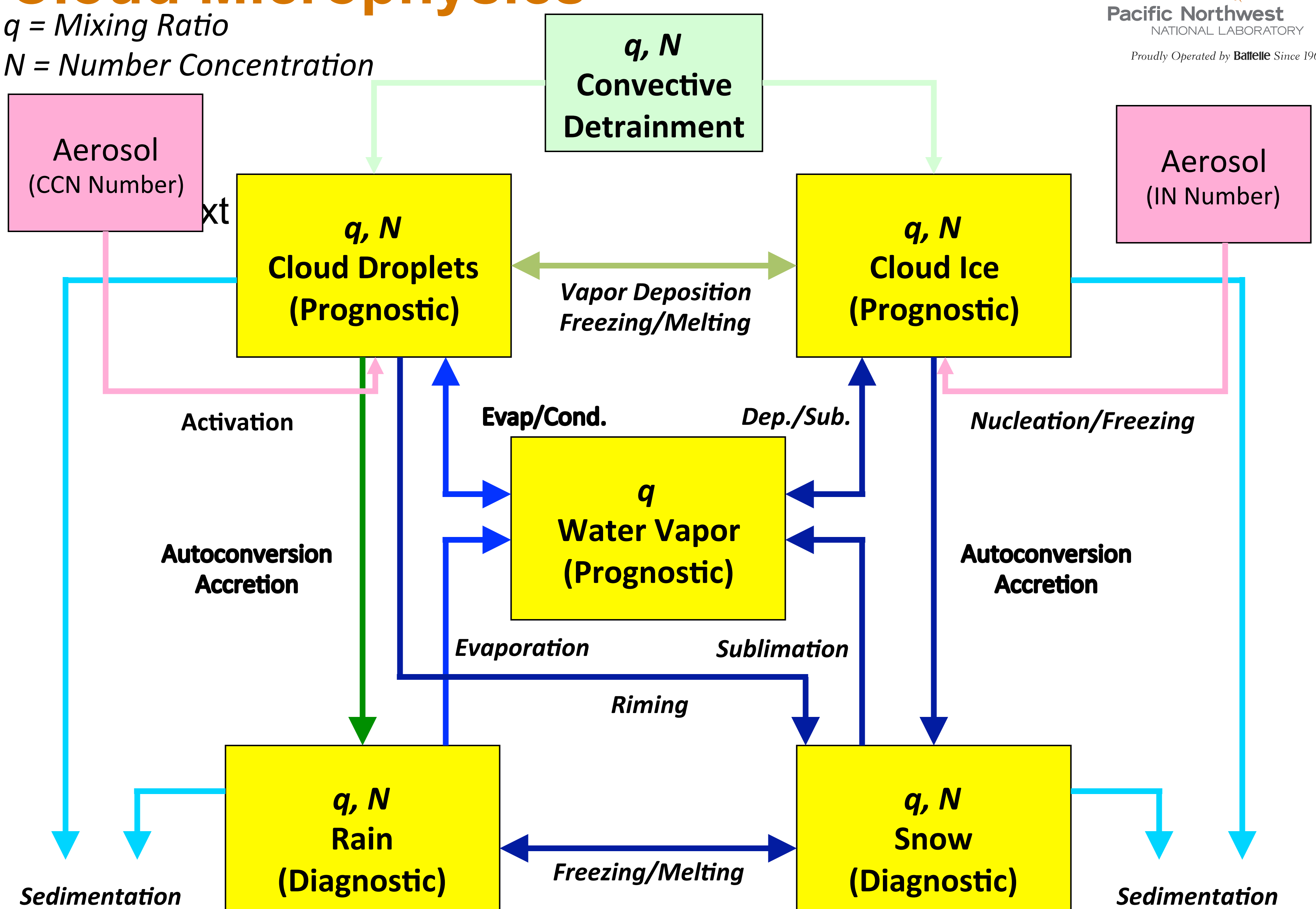

# Interactions



- Aerosol effects on clouds
- Cloud effects on aerosol

# Aerosol Effects on Clouds

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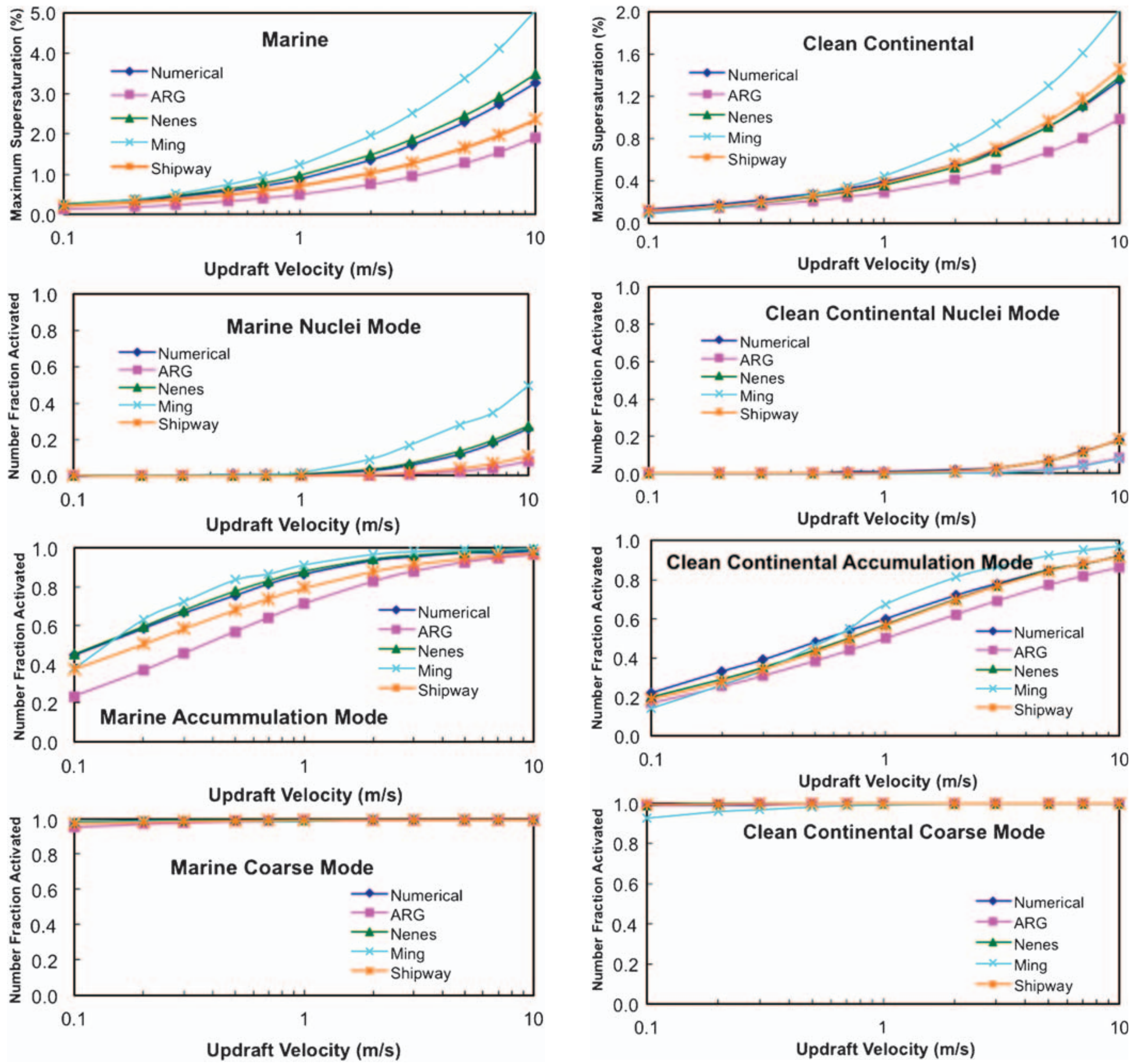
- Explicit prediction of supersaturation in resolved updrafts
- Parameterization of maximum supersaturation at cloud base

$$N_c = \int_0^\infty N_{act}(w)\,p(w)\,dw$$




Ghan et al., JAMES (2011)

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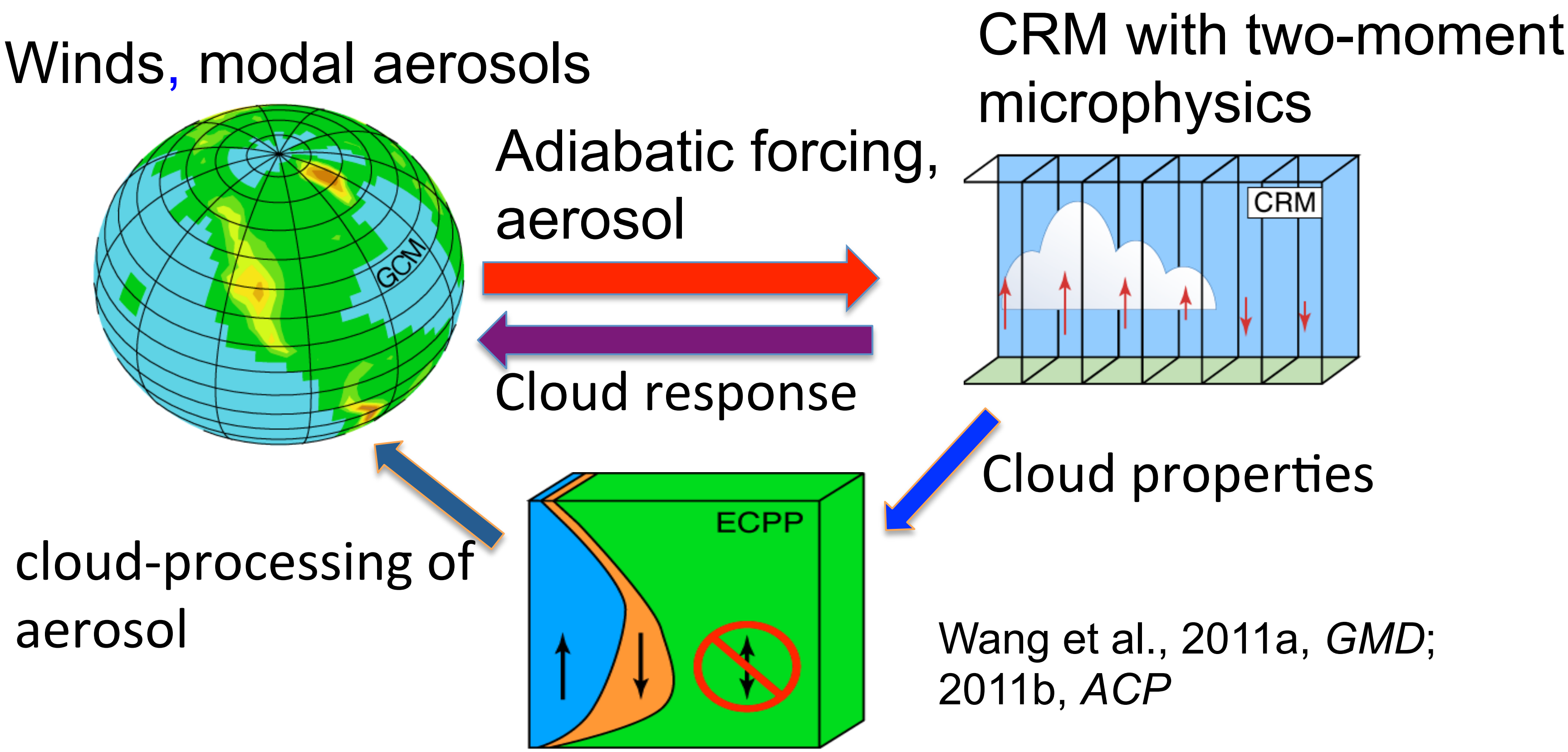
# Cloud Effects on the Aerosol in the Multiscale Modeling Framework

ECPP: Explicit Clouds – Parameterized Pollutants




CRM cloud/precipitation statistics used for cloud processing of aerosols

# 3. Understanding the Coupled Cloud-Aerosol System

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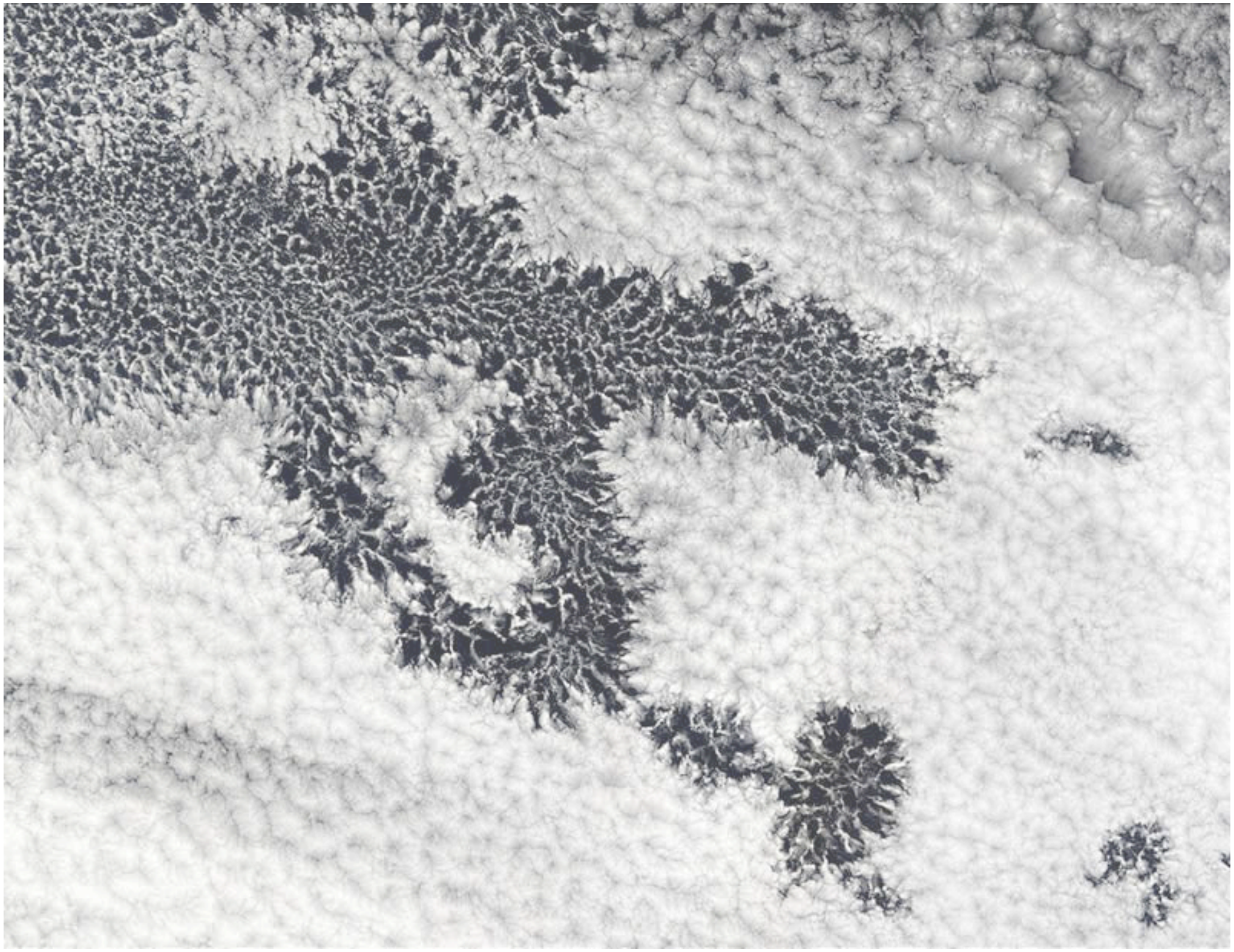
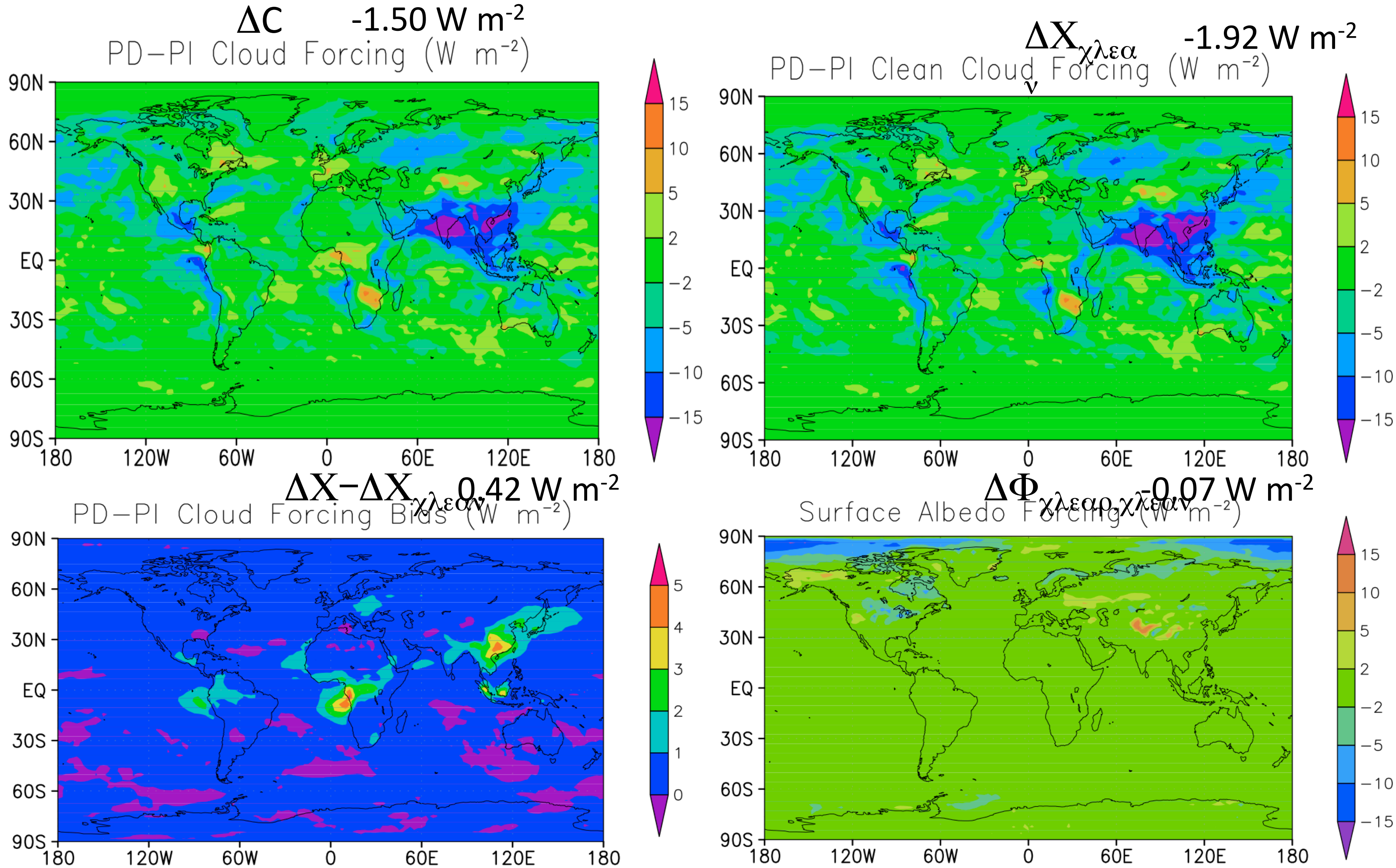


Baker and Charlson (1990) multiple equilibria and POCs

# Quantifying Cloud-Aerosol Interactions

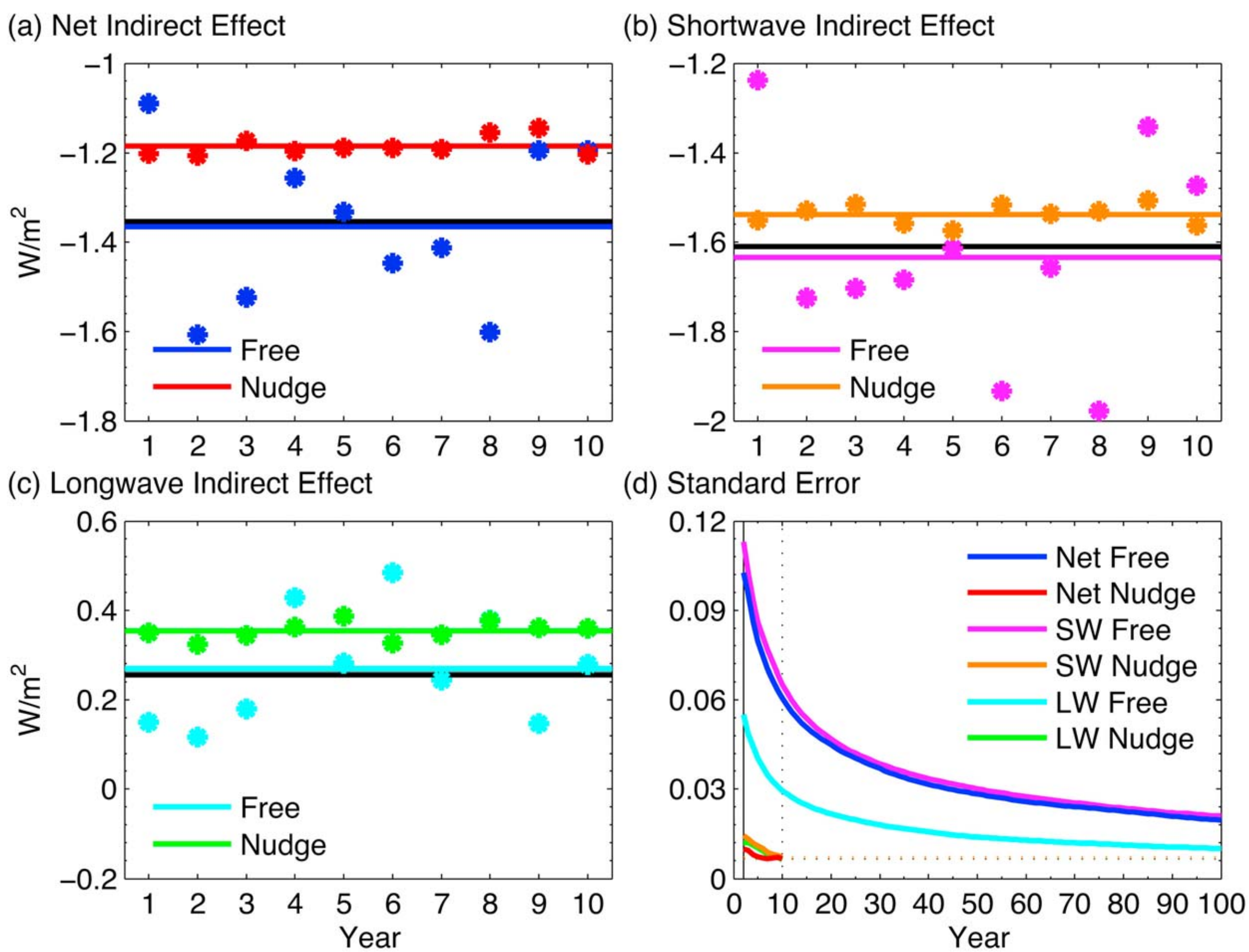



Ghan, S., 2013: *Atmos. Chem Phys.*

# Suppressing Natural Variability



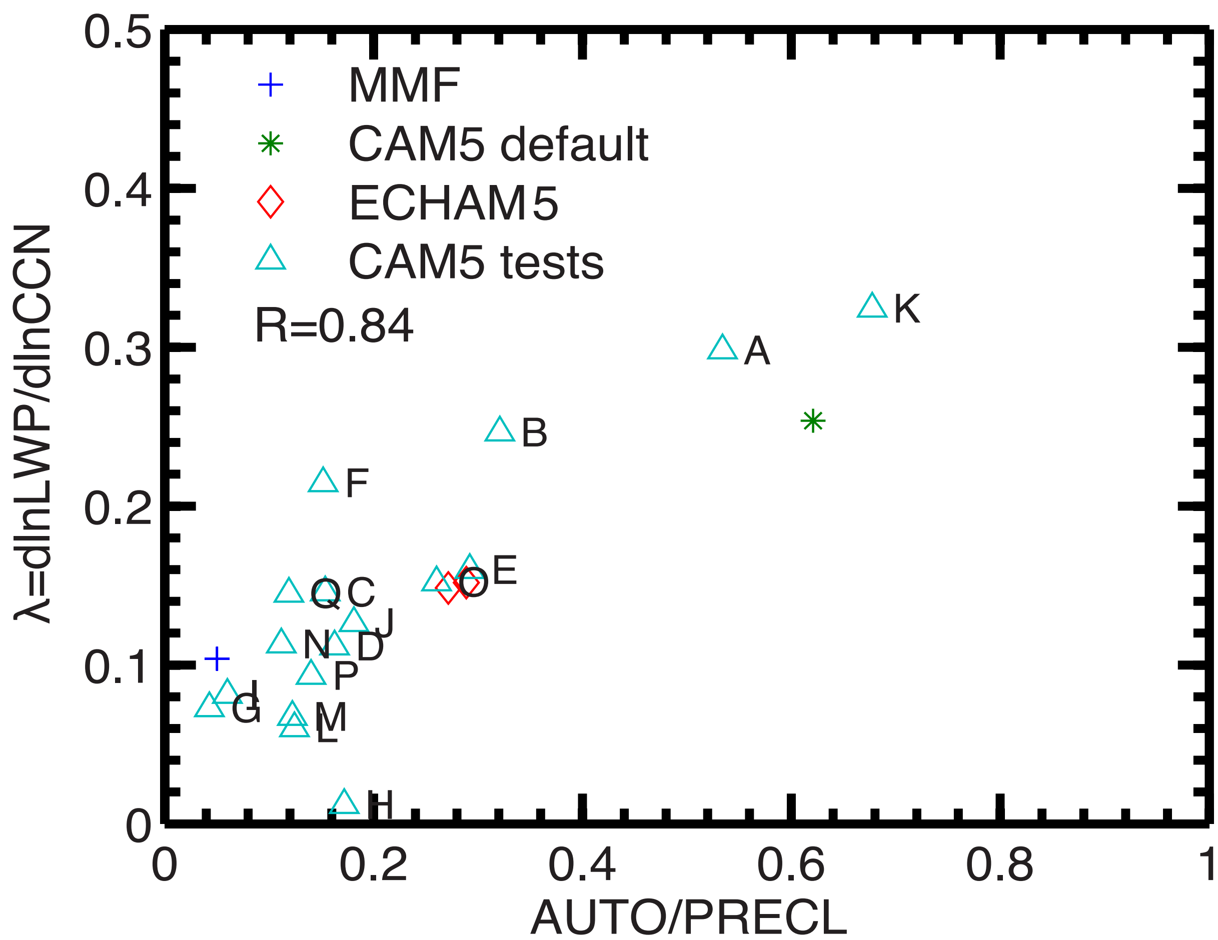
- Nudge simulations toward the same winds




Kooperman et al., JGR (2012)

# Liquid Water Path response to Aerosol

- Role of autoconversion




M. Wang et al. GRL (2002)

# Diagnostic vs Prognostic Precipitation

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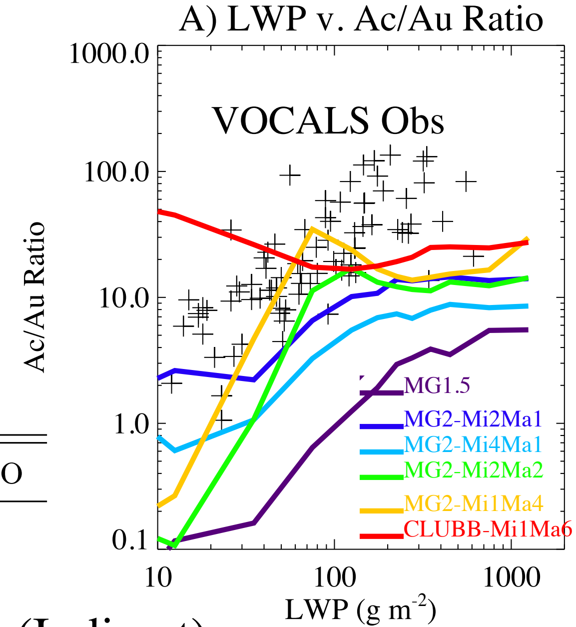
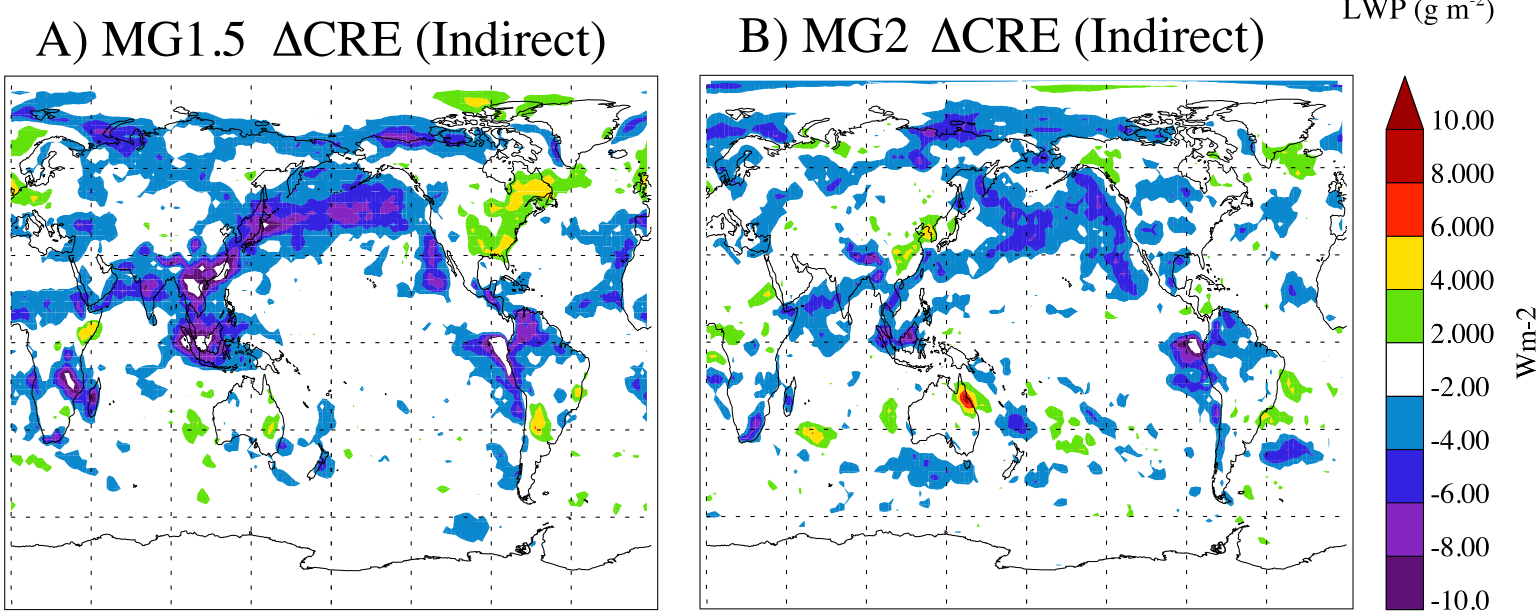



Gettelman et al., in revision.

| Run | ΔR | ΔDE | ΔACI | ΔAlbedo |
|---|---|---|---|---|
| MG1.5 | -1.22 | -0.09 | -1.25 | -0.09 |
| MG2-Mi2Ma1 | -1.08 | -0.07 | -0.98 | -0.10 |



# Improved Turbulence Reduces Liquid Water Path Response

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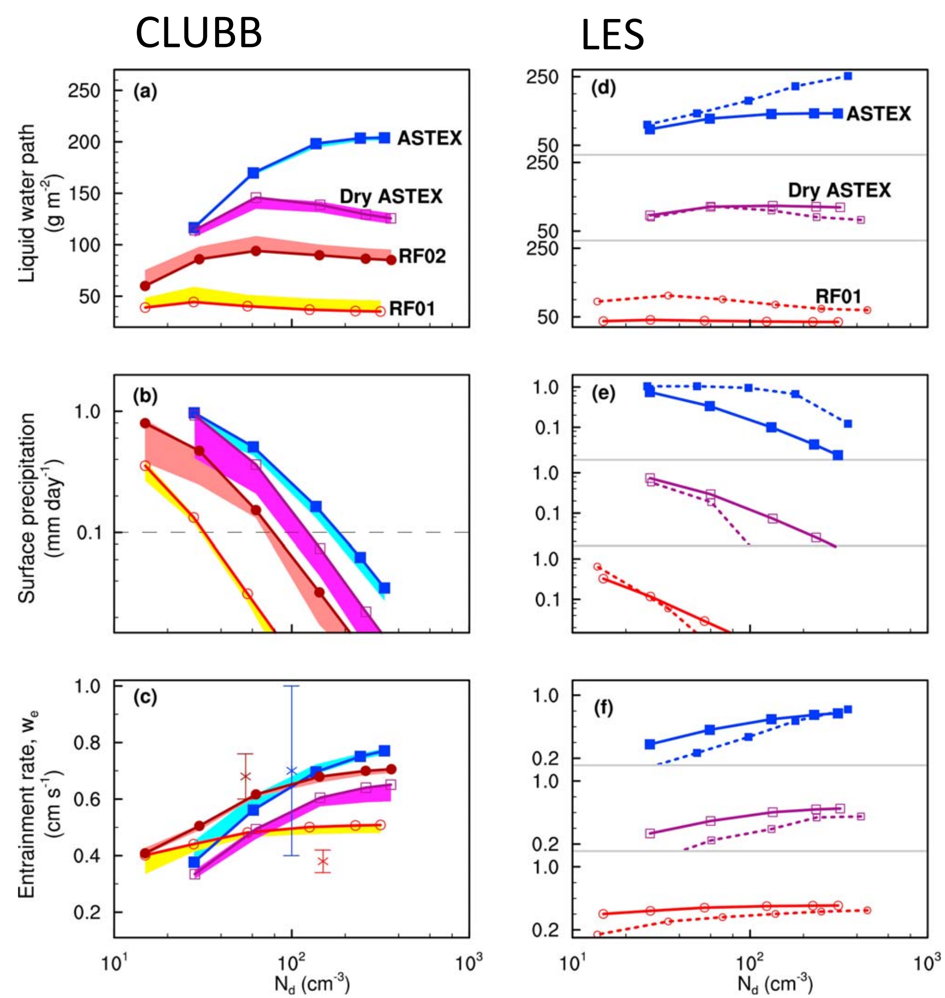
- LES finds LWP reduction due to droplet number – sedimentation – entrainment feedback under dry conditions
- GCMs fail to produce this result
- CLUBB in a single column model succeeds




Guo et al., GRL (2011)

# Diversity in Global Estimates of Cloud-Aerosol Interactions

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$$\Delta C = C \frac{d\ln C}{d\ln \tau} \frac{d\ln \tau}{d\ln N_d} \frac{d\ln N_d}{d\ln CCN} \frac{d\ln CCN}{d\ln E} \Delta \ln E$$

$\Delta C$: aerosol-cloud interactions $C$: clean-sky shortwave cloud forcing
$\tau$: cloud optical depth $N_d$: cloud droplet number
$CCN$: cloud condensation nuclei concentration $E$: emissions

Cloud lifetime effect Cloud albedo effect

$$\frac{d\ln \tau}{d\ln N_d} = \frac{\partial \ln \tau}{\partial \ln L} \frac{\partial \ln L}{\partial \ln N_d} + \frac{\partial \ln \tau}{\partial \ln r_e} \frac{\partial \ln r_e}{\partial \ln N_d}$$

$$\simeq \frac{\partial \ln L}{\partial \ln N_d} - \frac{\partial \ln r_e}{\partial \ln N_d}$$

$$\tau \propto \frac{L}{r_e}$$

$L$: liquid water path $r_e$: droplet effective radius

# Factorization of AeroCom Models Reveals Largest Contributors to Uncertainty

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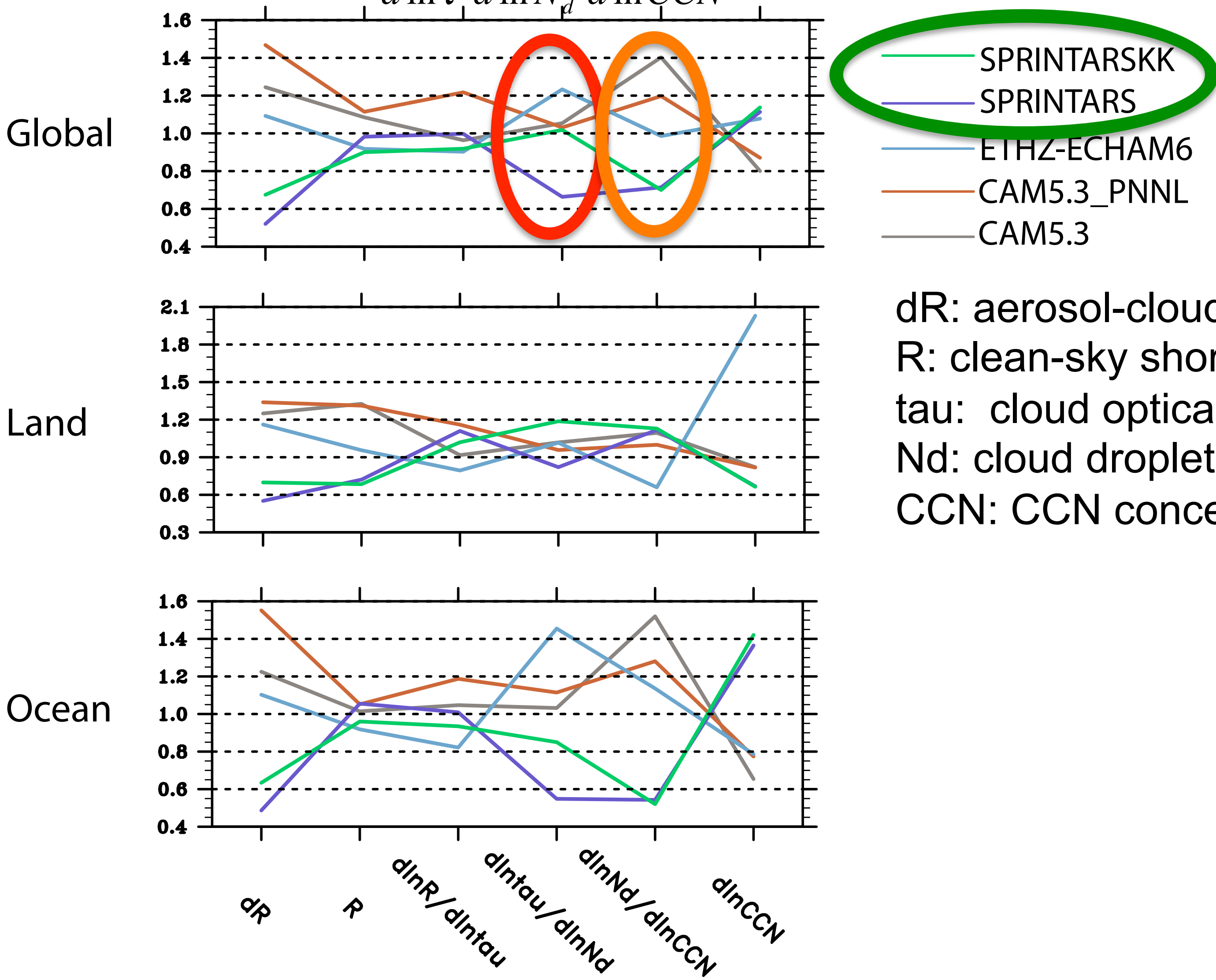
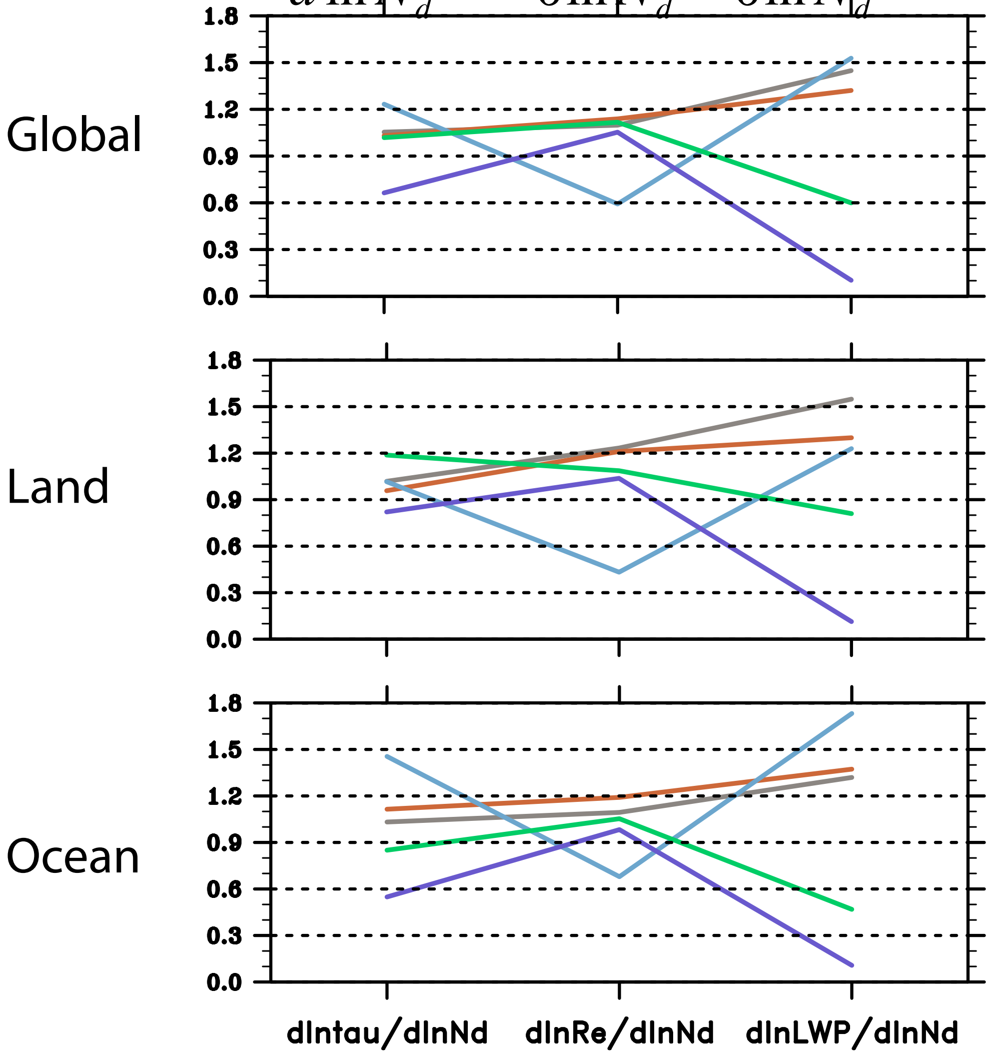
$$\Delta C = C \frac{d\ln C}{d\ln \tau} \frac{d\ln \tau}{d\ln N_d} \frac{d\ln N_d}{d\ln CCN} \Delta \ln CCN$$




dR: aerosol-cloud interactions
R: clean-sky shortwave cloud forcing
tau: cloud optical depth
Nd: cloud droplet number
CCN: CCN concentration

# Separating Contributions to Cloud Optical Depth Sensitivity to Droplet Number

$$\frac{d\ln\tau}{d\ln N_d} \simeq -\frac{\partial\ln r_e}{\partial\ln N_d} + \frac{\partial\ln L}{\partial\ln N_d}$$




tau: cloud optical depth
Nd: cloud droplet number
CCN: CCN concentration
LWP: liquid water path

# Effects on Deep Convection

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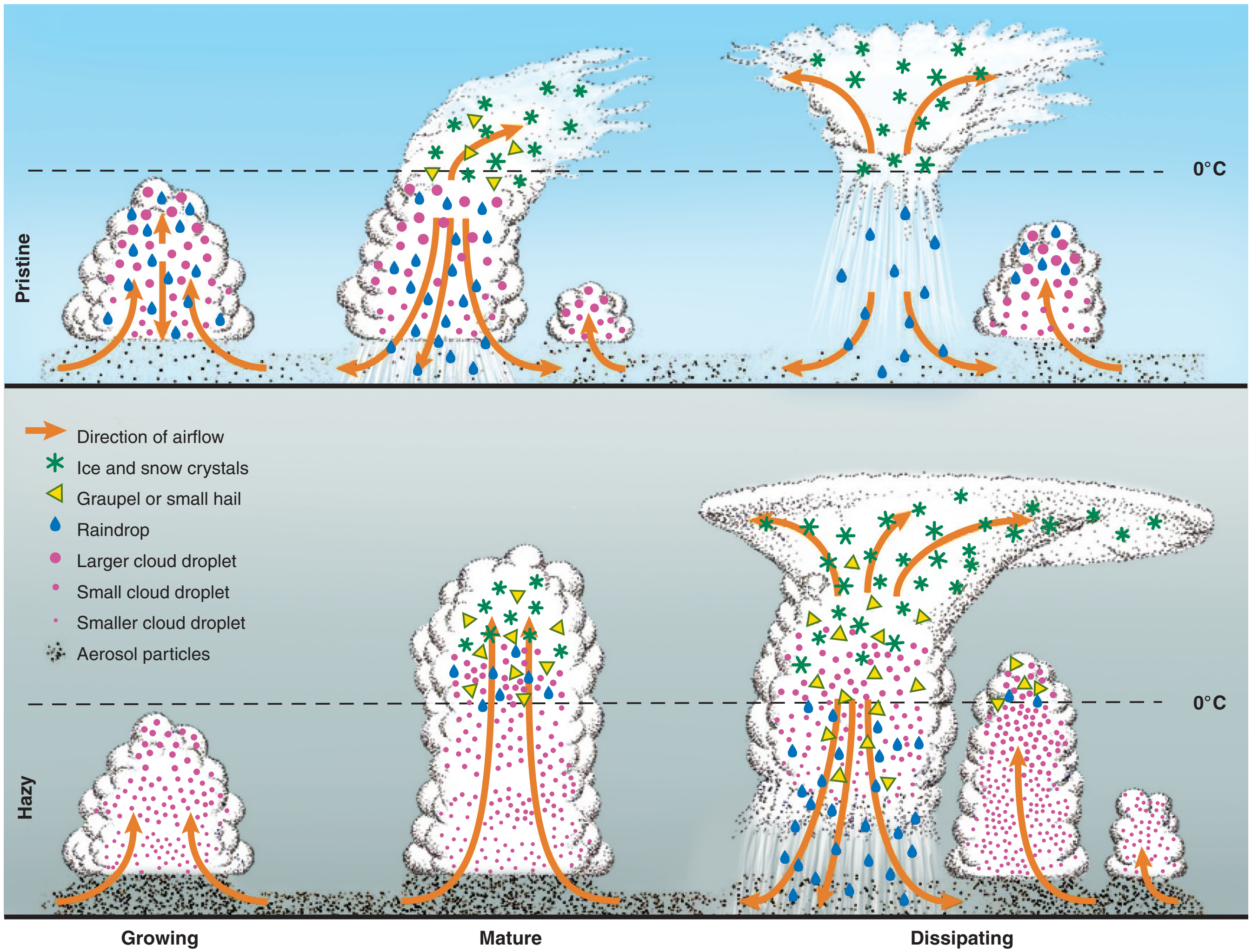
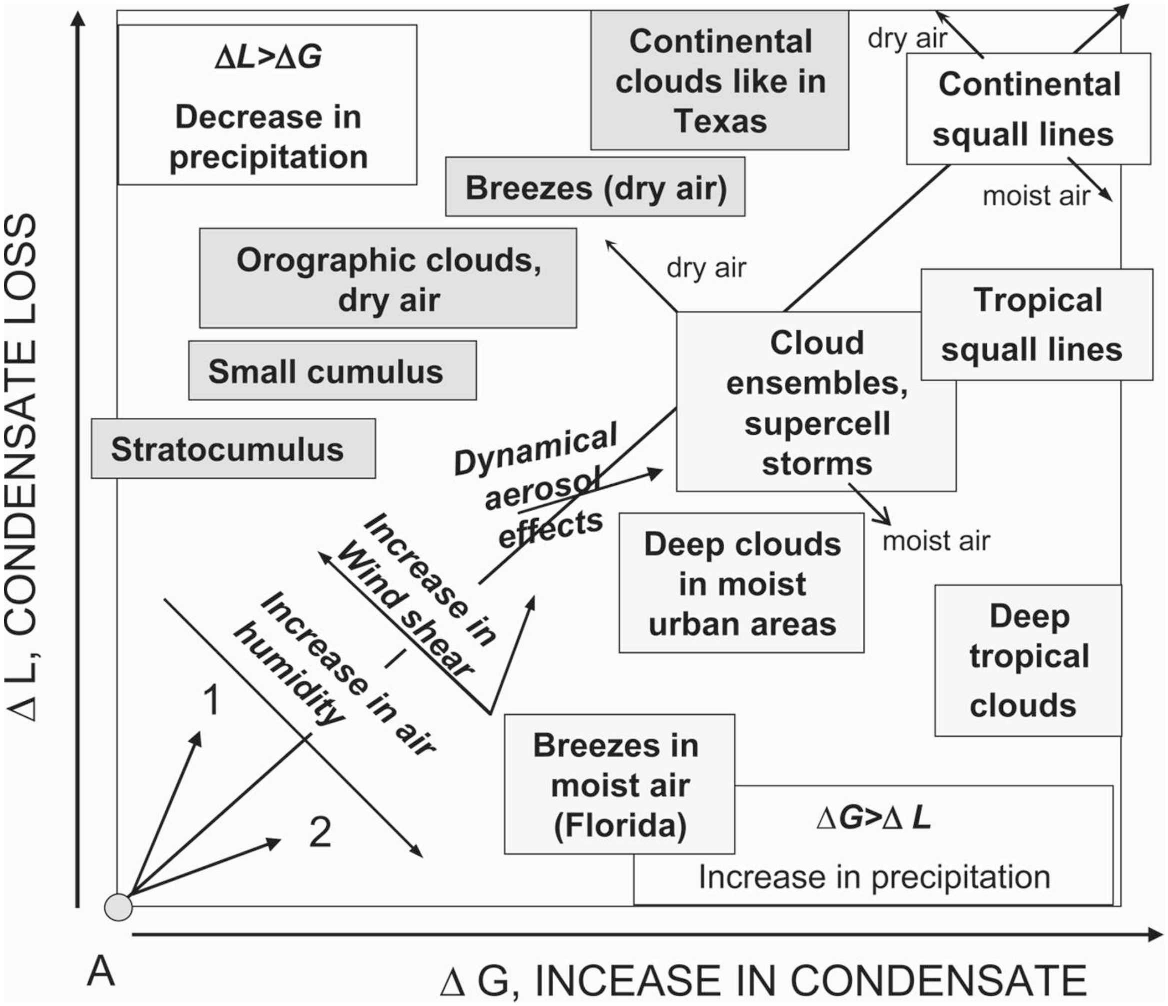



Rosenfeld et al., Science (2008)

# Complications






*Khain et al., JAS, 2008*

# Dependence on Humidity and Wind Shear

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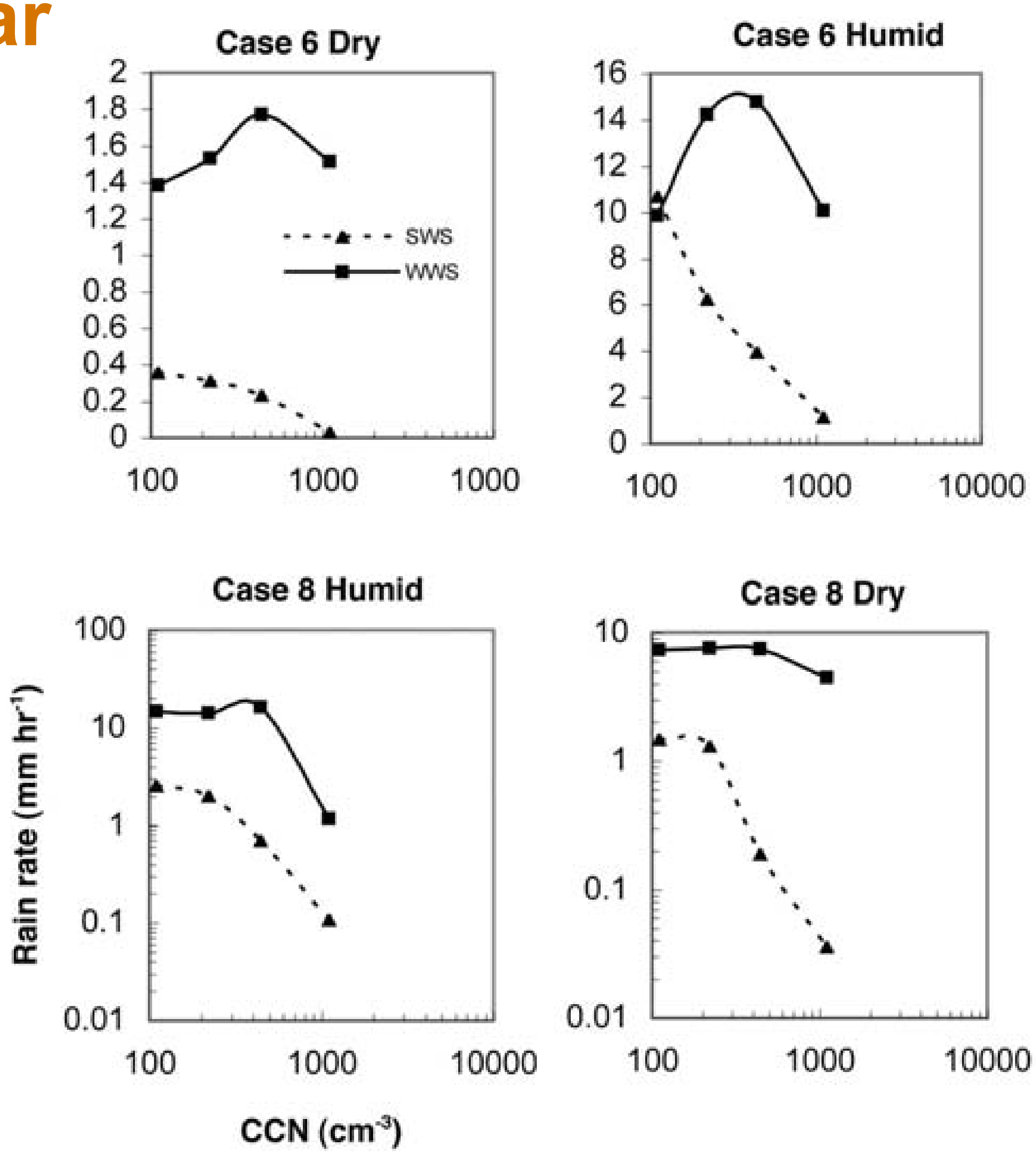
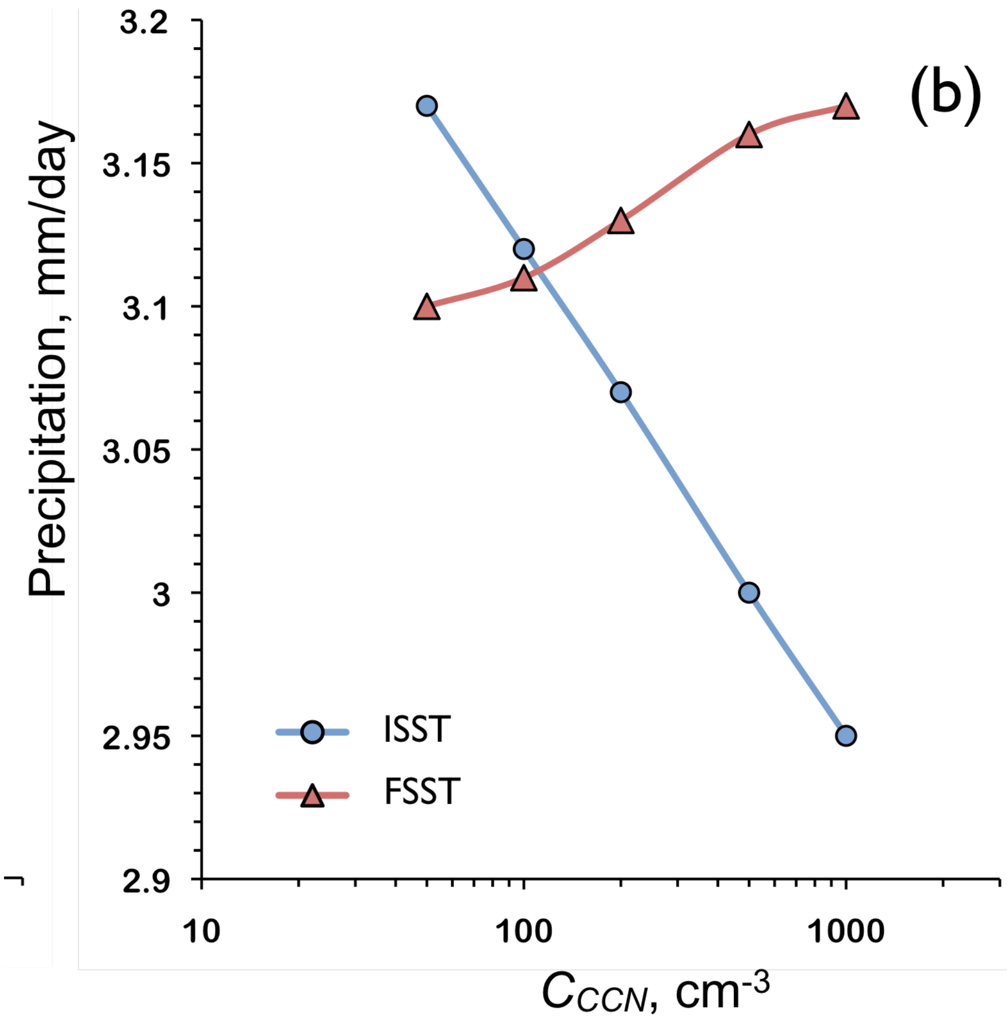



Fan et al.
JGR (2009)

# Longer-Term Response of Precipitation

Precipitation rate is constrained by boundary conditions.




Khairoutdinov and Yang, ACP (2011)

# Cloud Anvil Expands with Increasing Aerosol

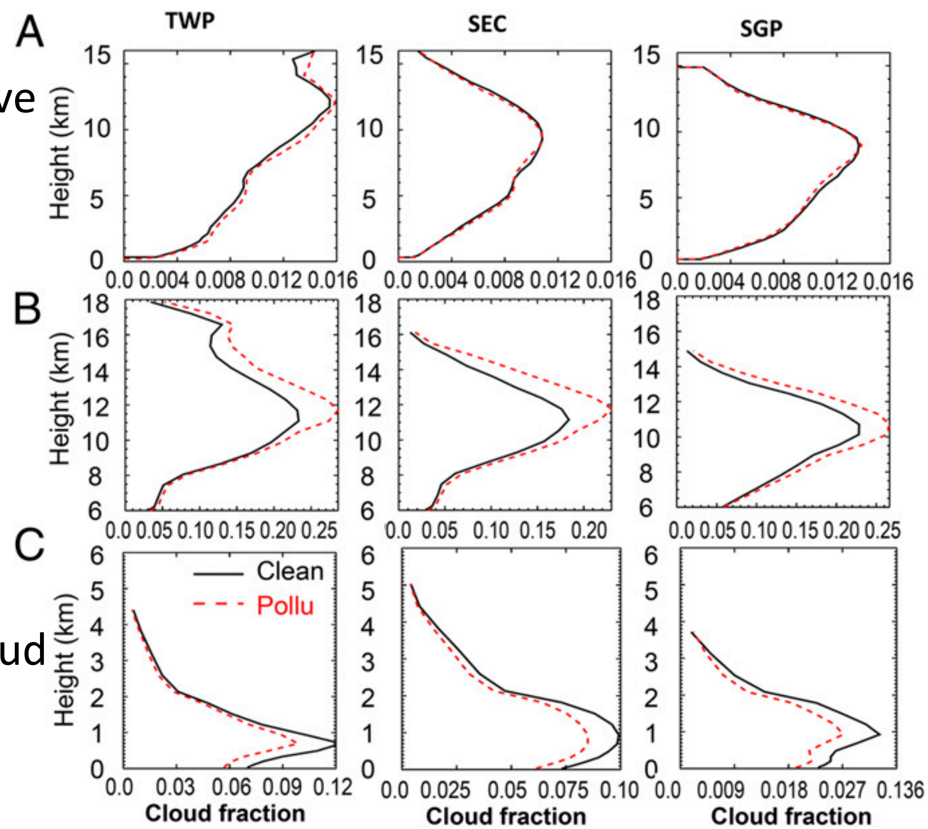
## Driven by microphysics, not intensification

Cloud Fraction

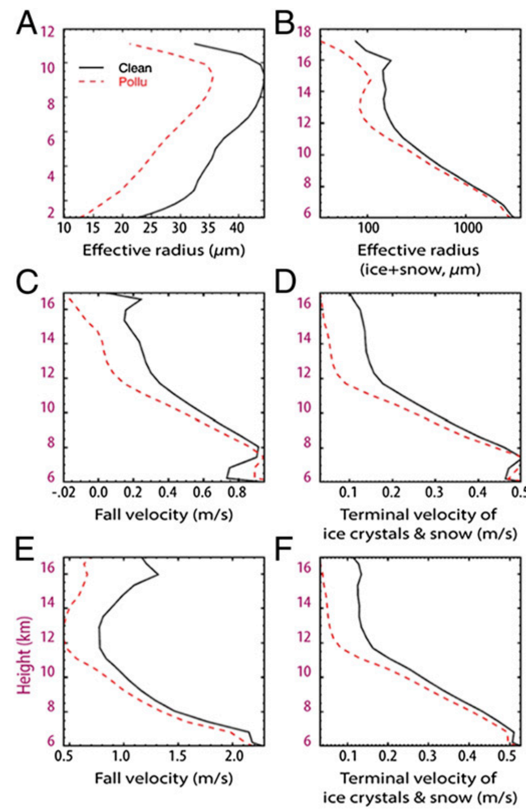
Convective core

Anvil

Low cloud




Smaller cloud particles fall slower




Jiwen Fan et al., PNAS (2013)

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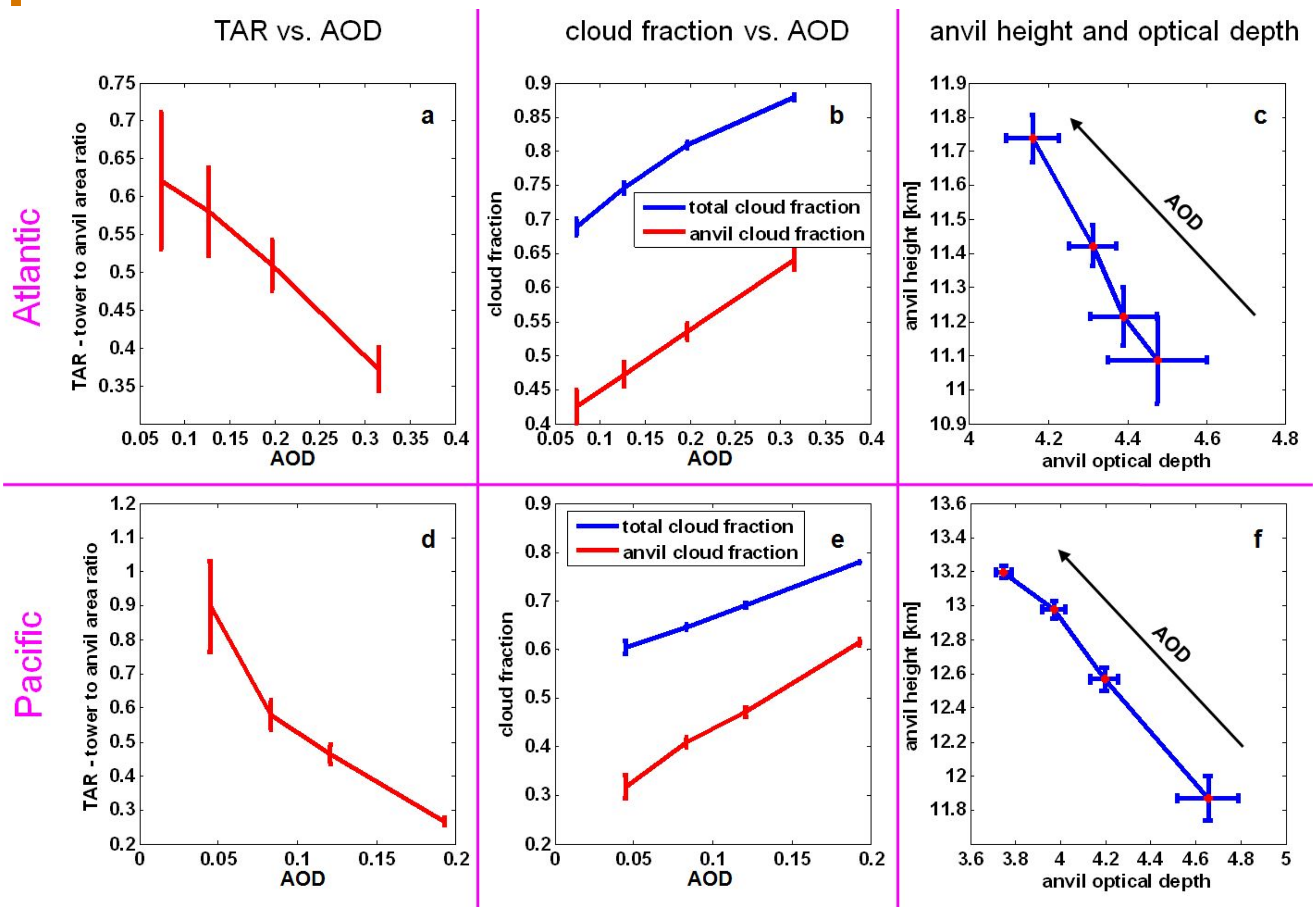
# Observations Confirm Anvil Expansion




Ilan Koren et al., ACP (2010)

# Long Term Radiative Impact Driven by Anvil Expansion

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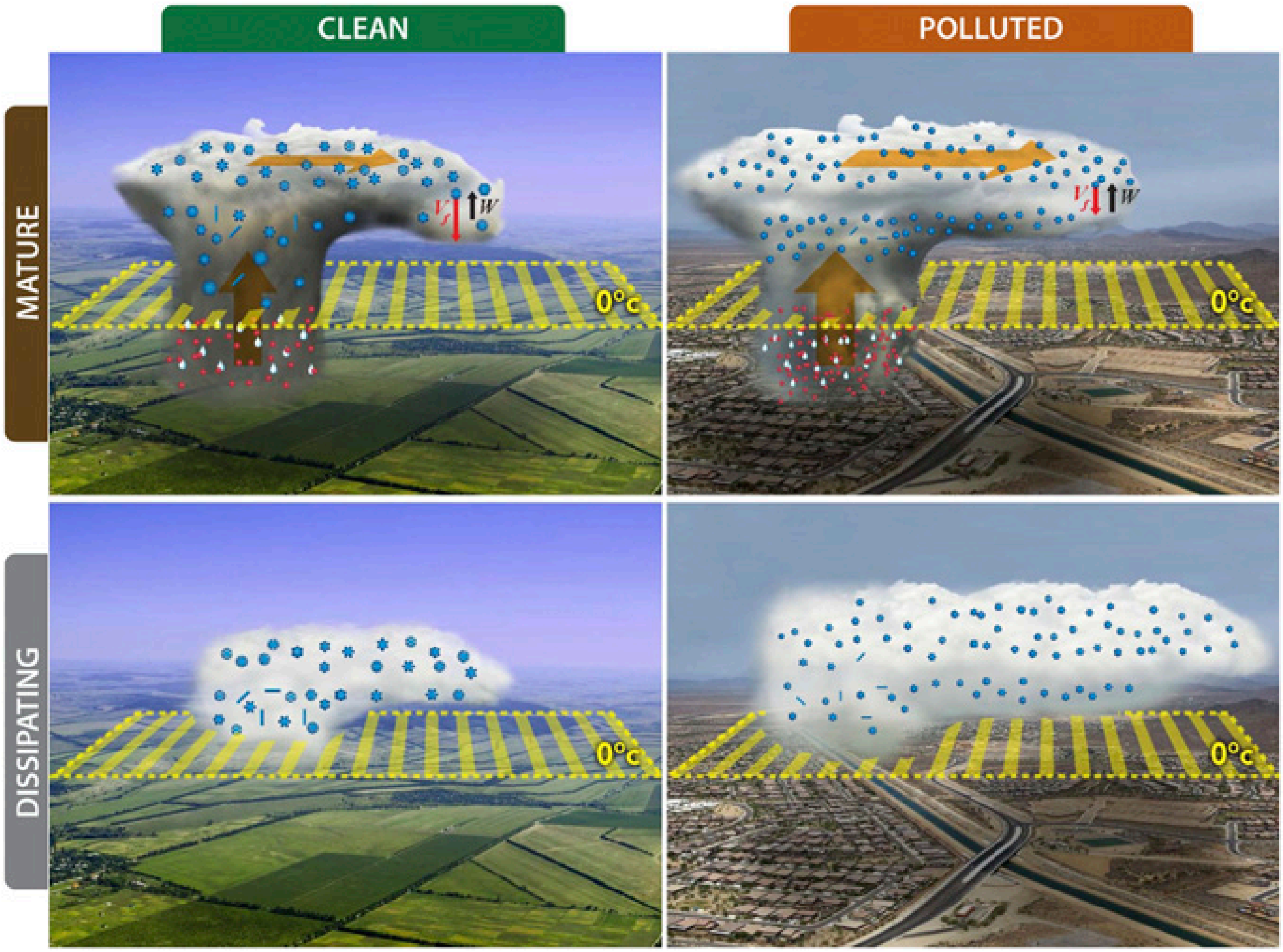
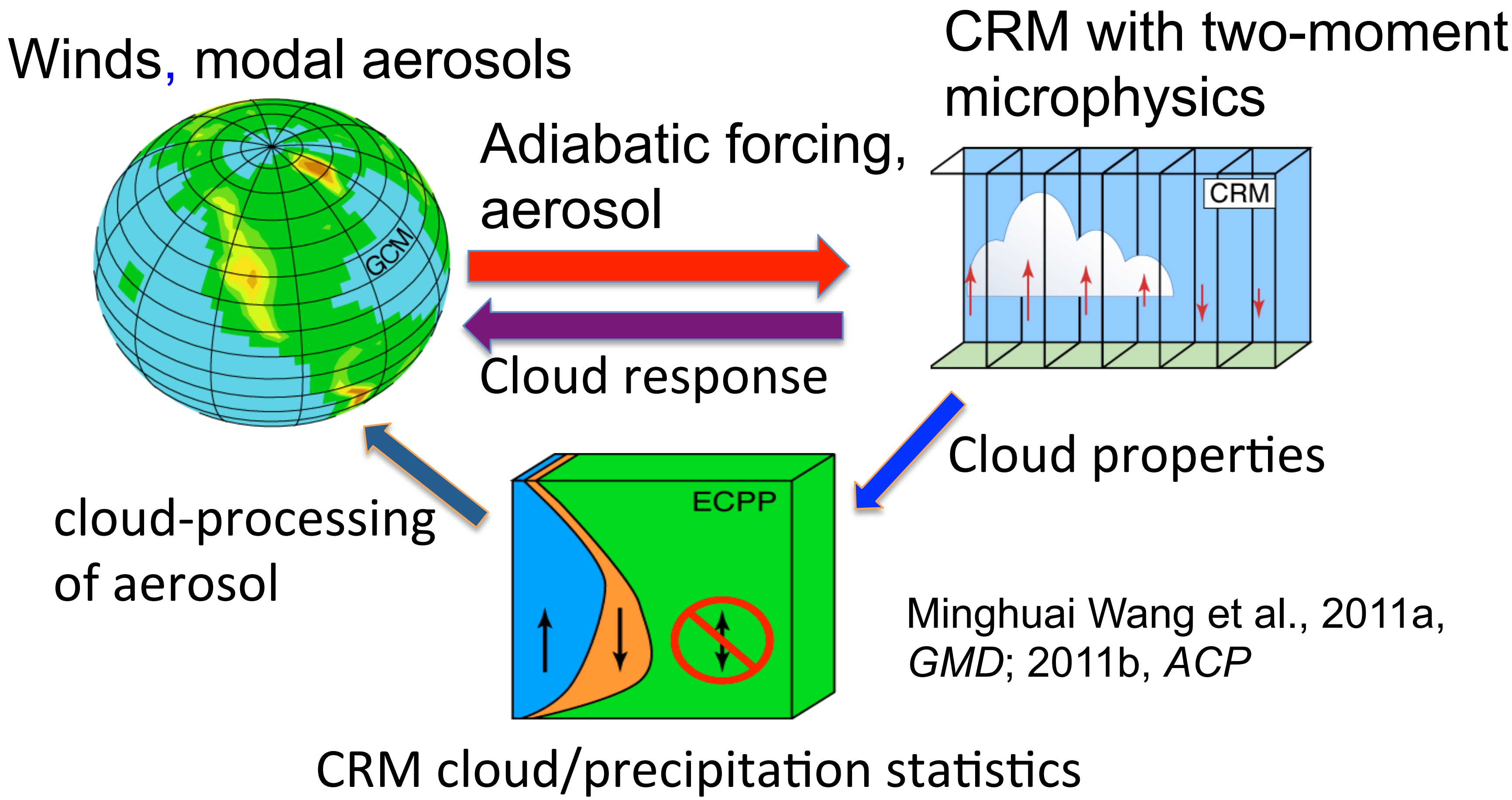


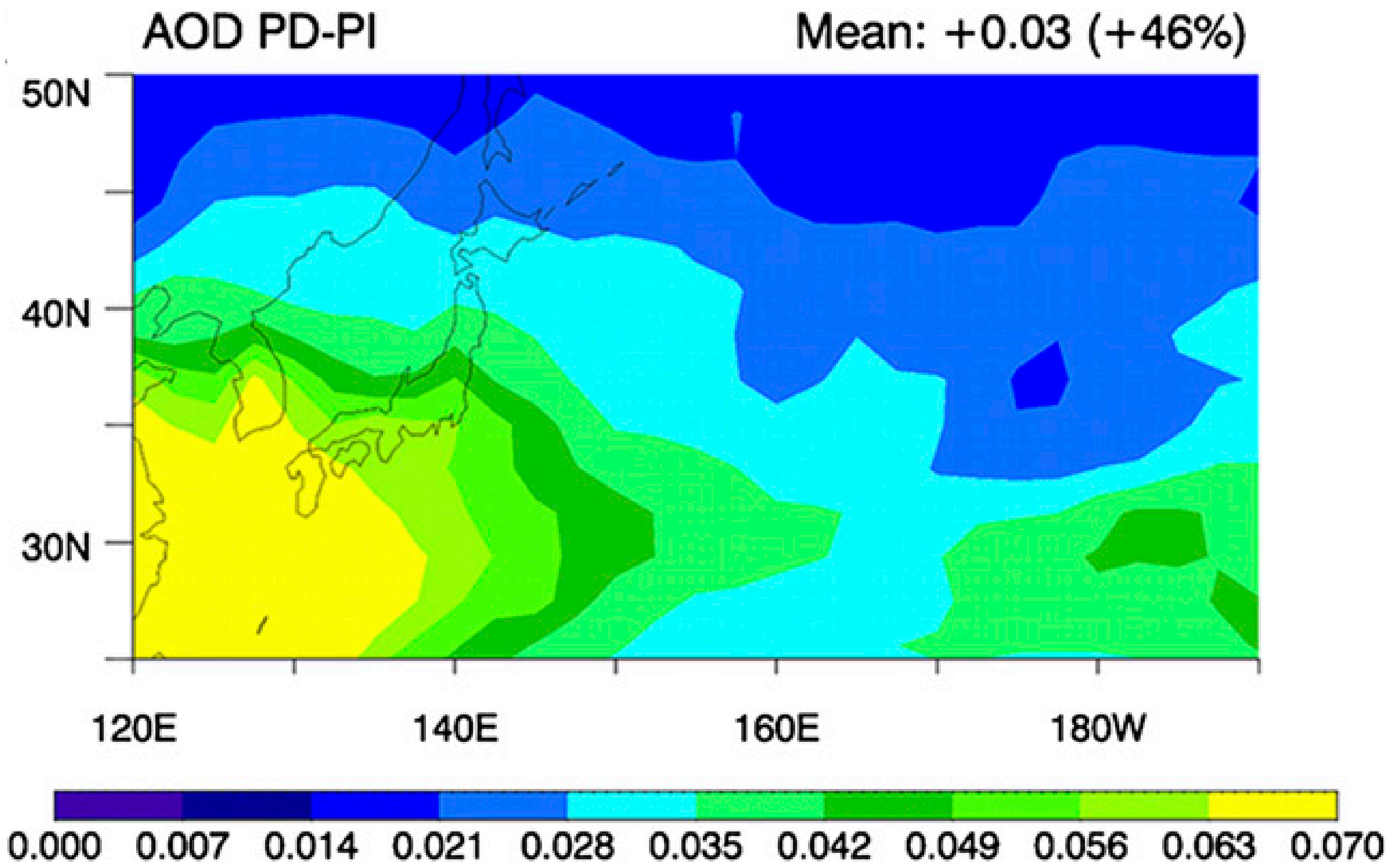

Jiwen Fan et al., PNAS (2013)

# Does the Multiscale Modeling Framework Produce Aerosol Invigoration of Clouds?



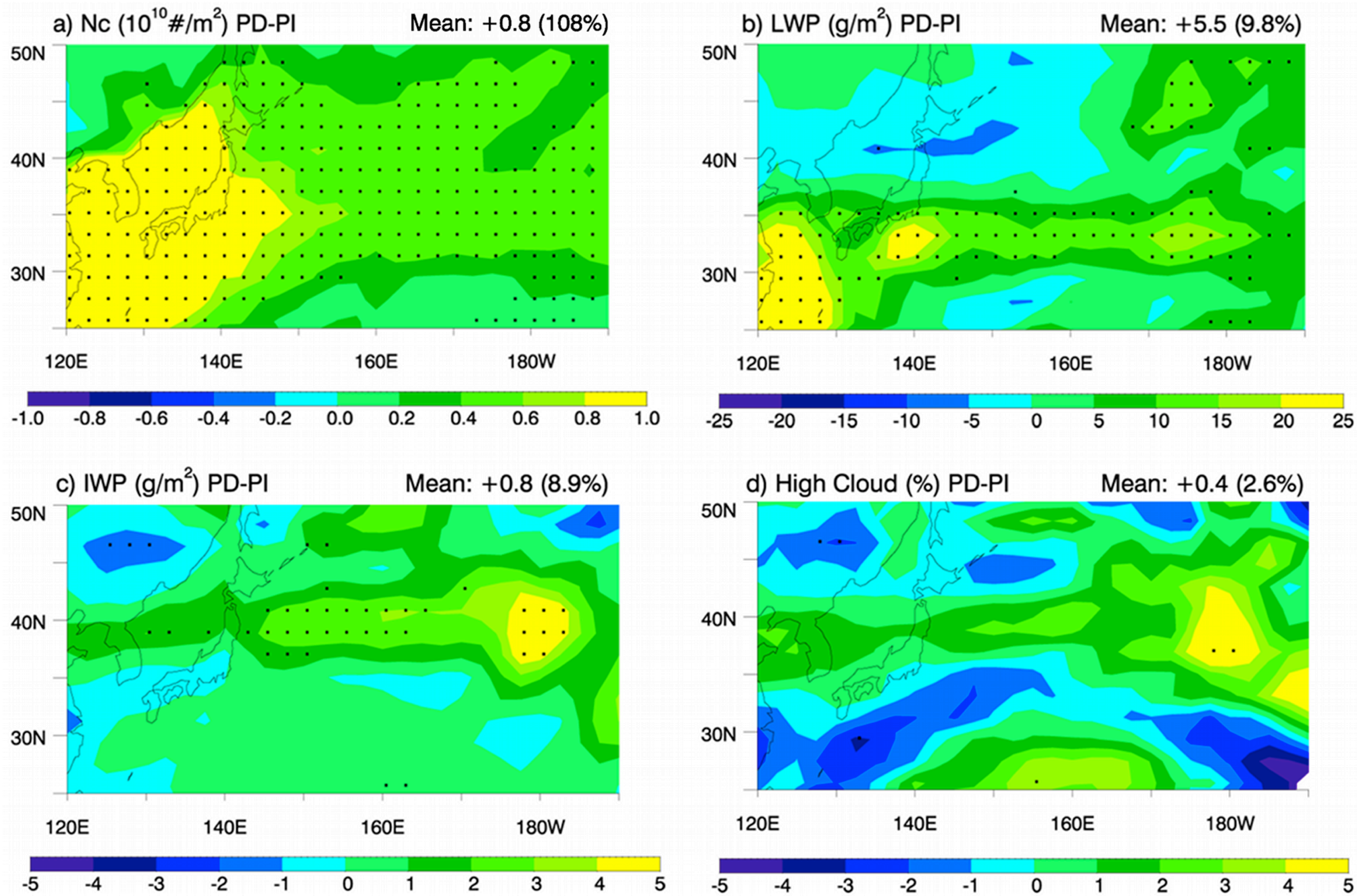

Minghuai Wang et al., 2011a, *GMD*; 2011b, *ACP*

# Anthropogenic aerosol over Northwest Pacific




Yuan Wang et al. PNAS (2014)

# Anthropogenic Aerosol Increases Droplet Number and Cloud water




Yuan Wang et al. PNAS (2014)

# Convection Invigoration in the MMF

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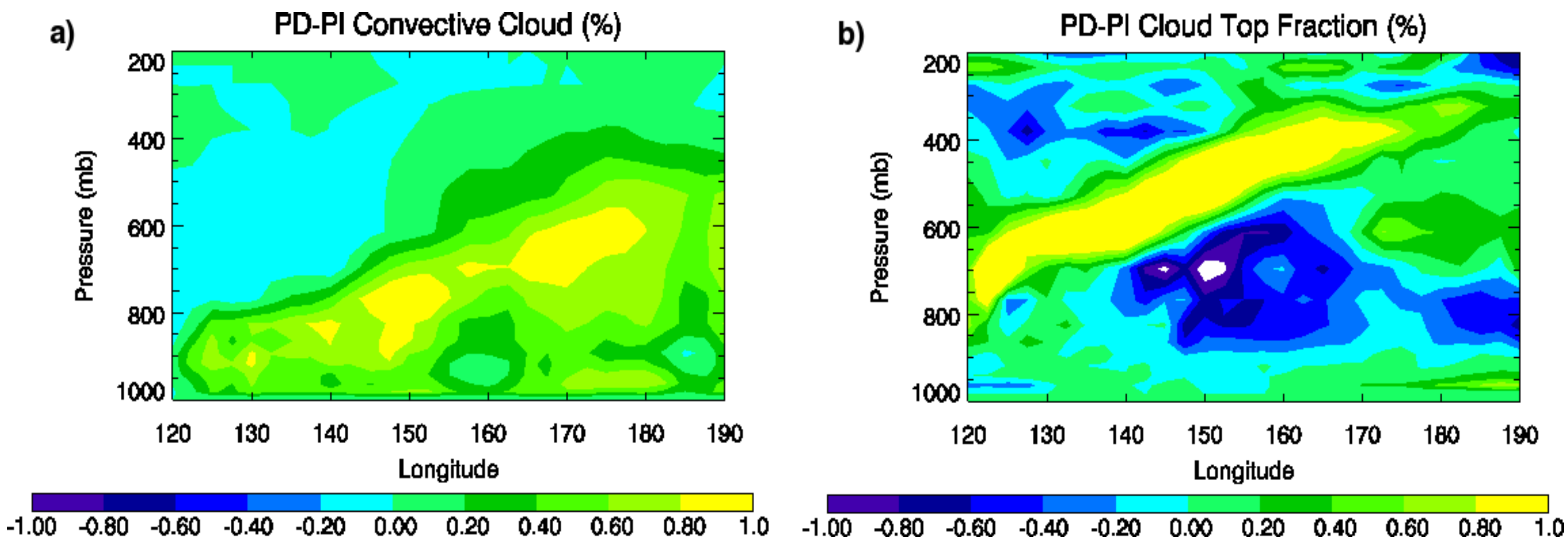
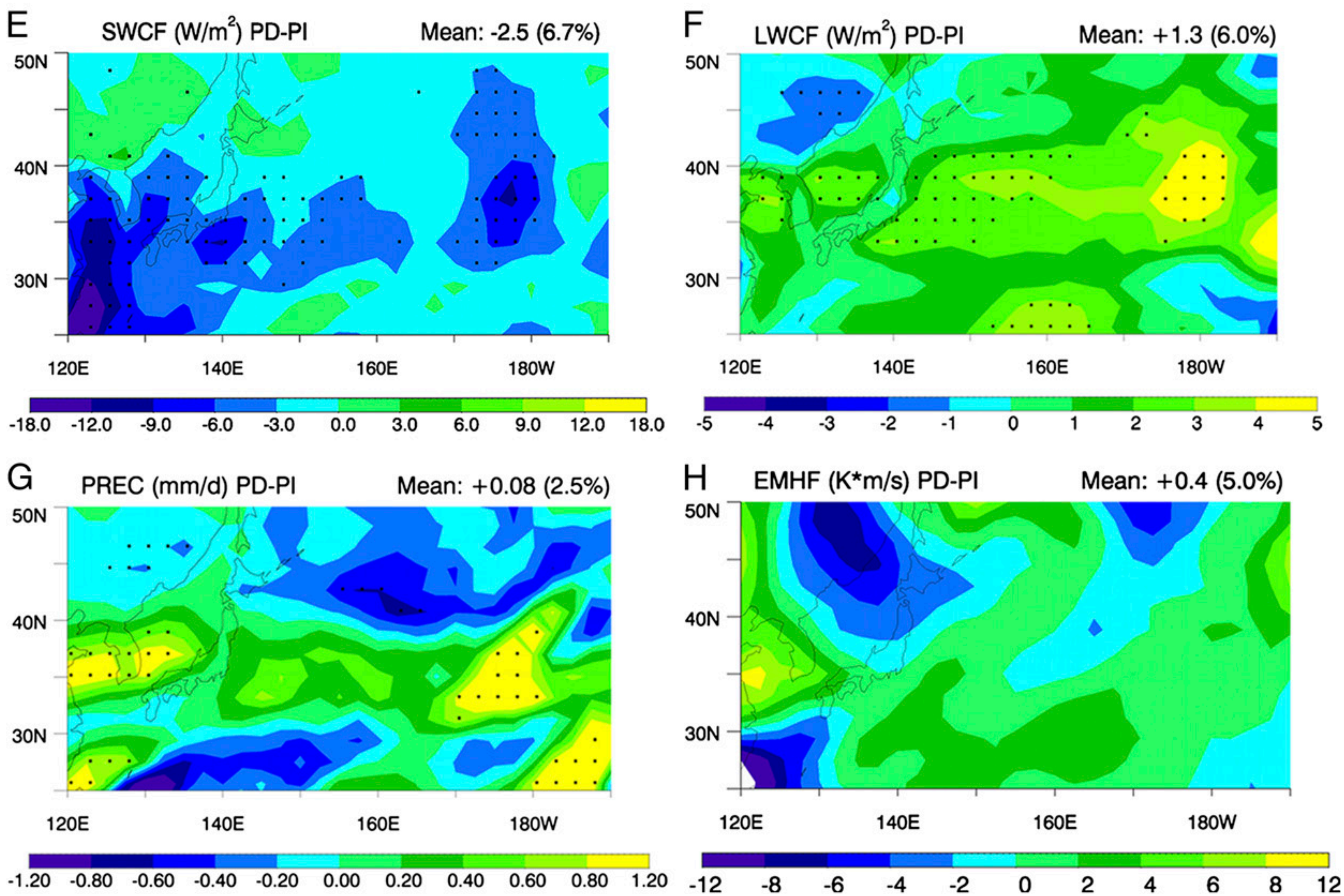



Yuan Wang et al. PNAS (2014)

# Radiative and Hydrologic Response




Yuan Wang et al. PNAS (2014)

# How Much of this Signature is Due to the Multi-scale Treatment of Clouds?

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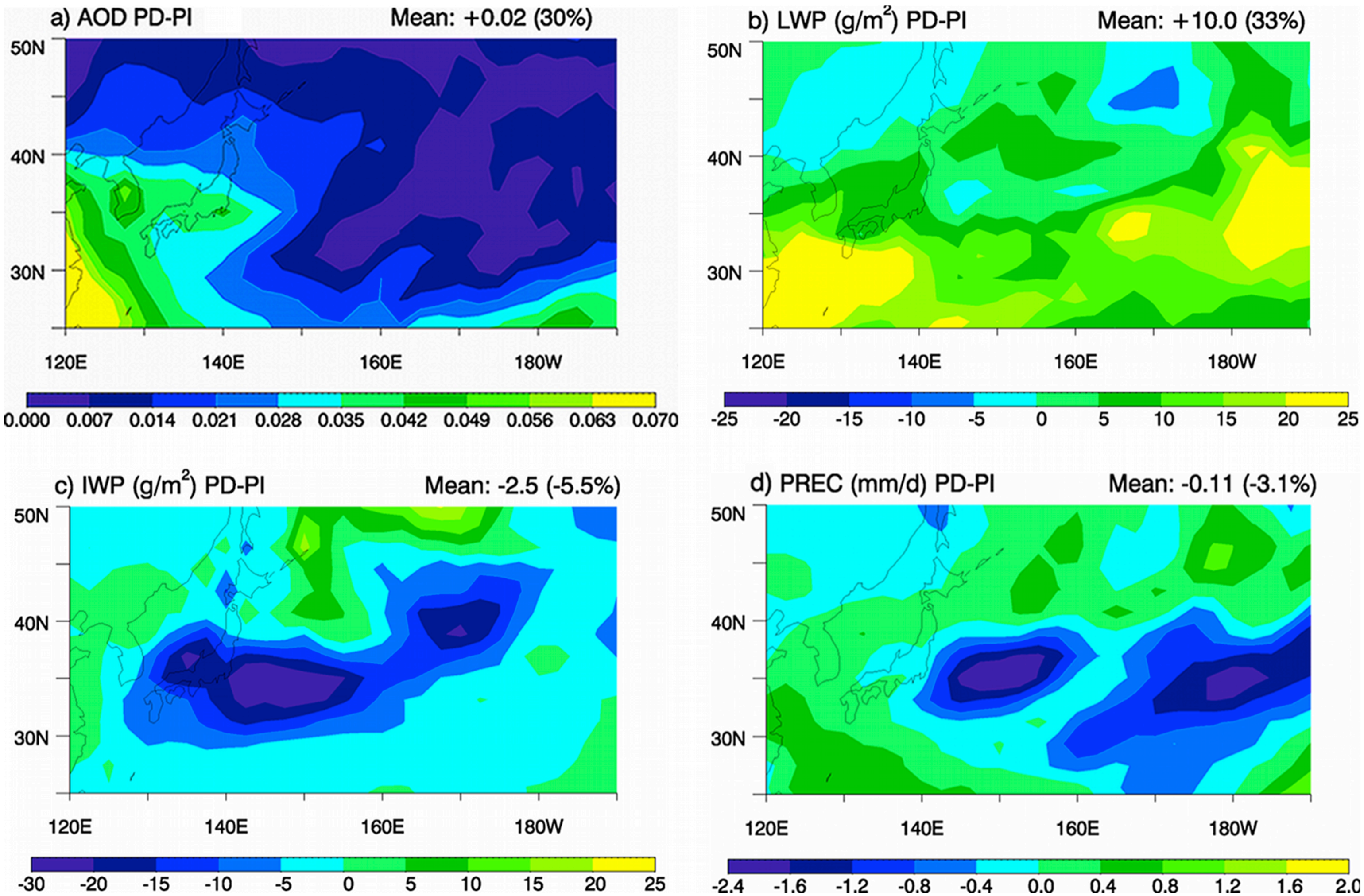
- CAM5 does not produce enhancement of high cloud by aerosol




Yuan Wang et al. PNAS (2014)

# 3. Understanding the Coupled Cloud-Aerosol System

- Baker and Charlson (1990) multiple equilibria
- Role of autoconversion
- Prognostic vs diagnostic precipitation
- Diversity in global estimates of forcing
- Effects on deep convection
- Explicit saturation vs saturation adjustment

# Lessons from CRMs with Bulk and Bin Microphysics

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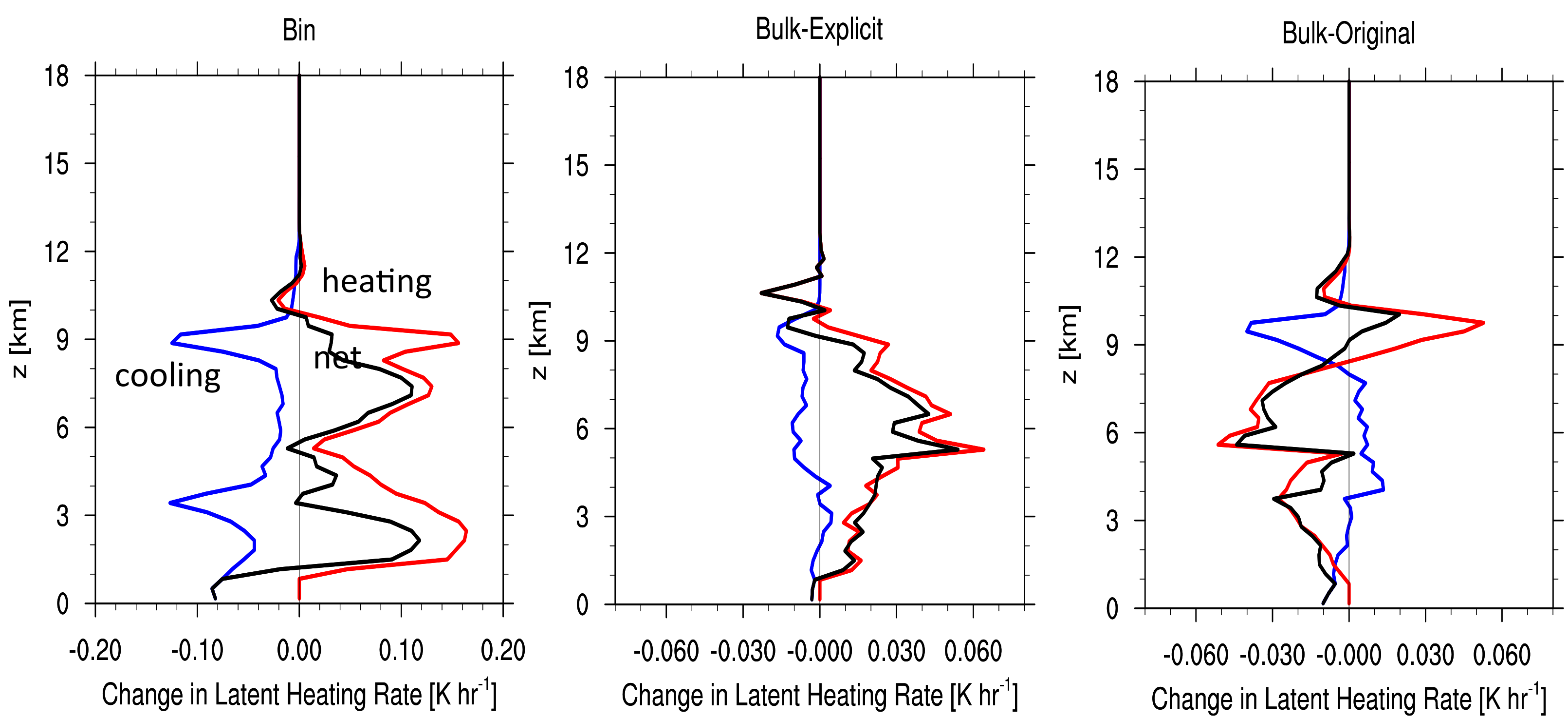
- The saturation adjustment method in most bulk microphysics schemes overestimates condensation in clean conditions
- This biases the cloud sensitivity to increasing aerosol




Zach Lebo et al. ACP (2012)

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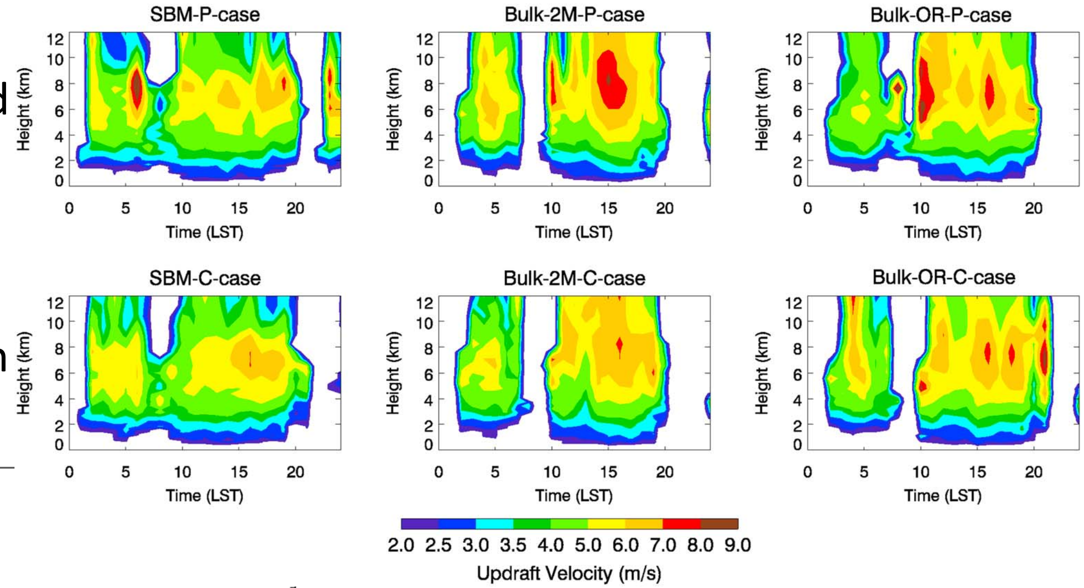
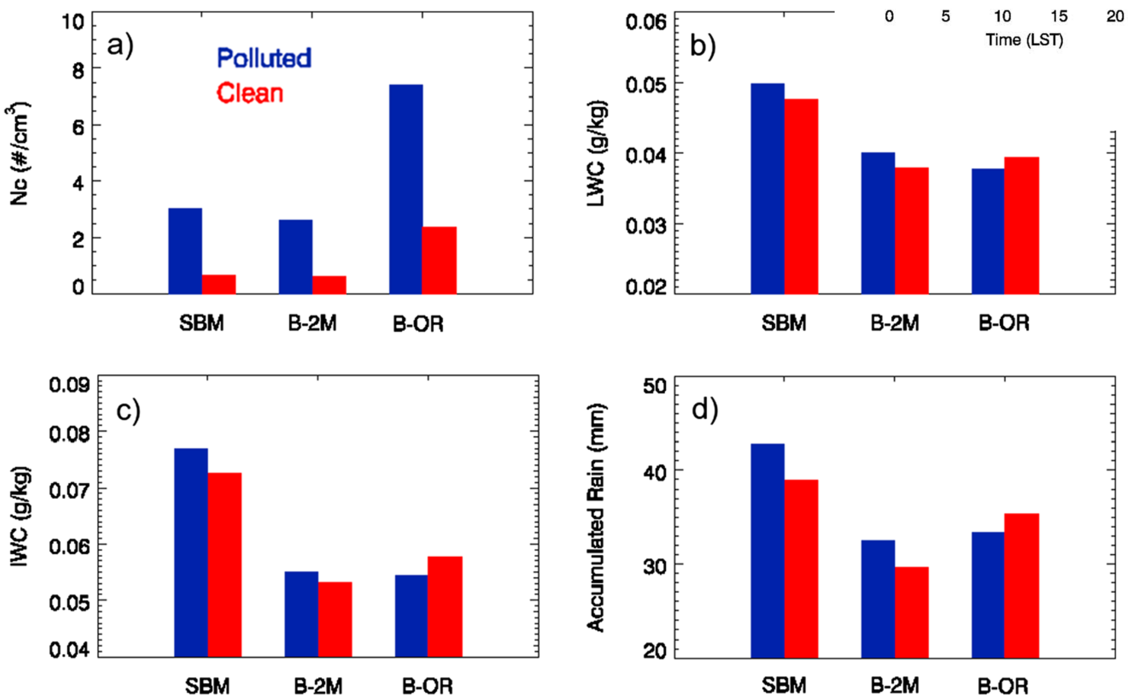
# Latent heating bias drives bias in cloud updraft and hydrometeor response

Polluted

Clean

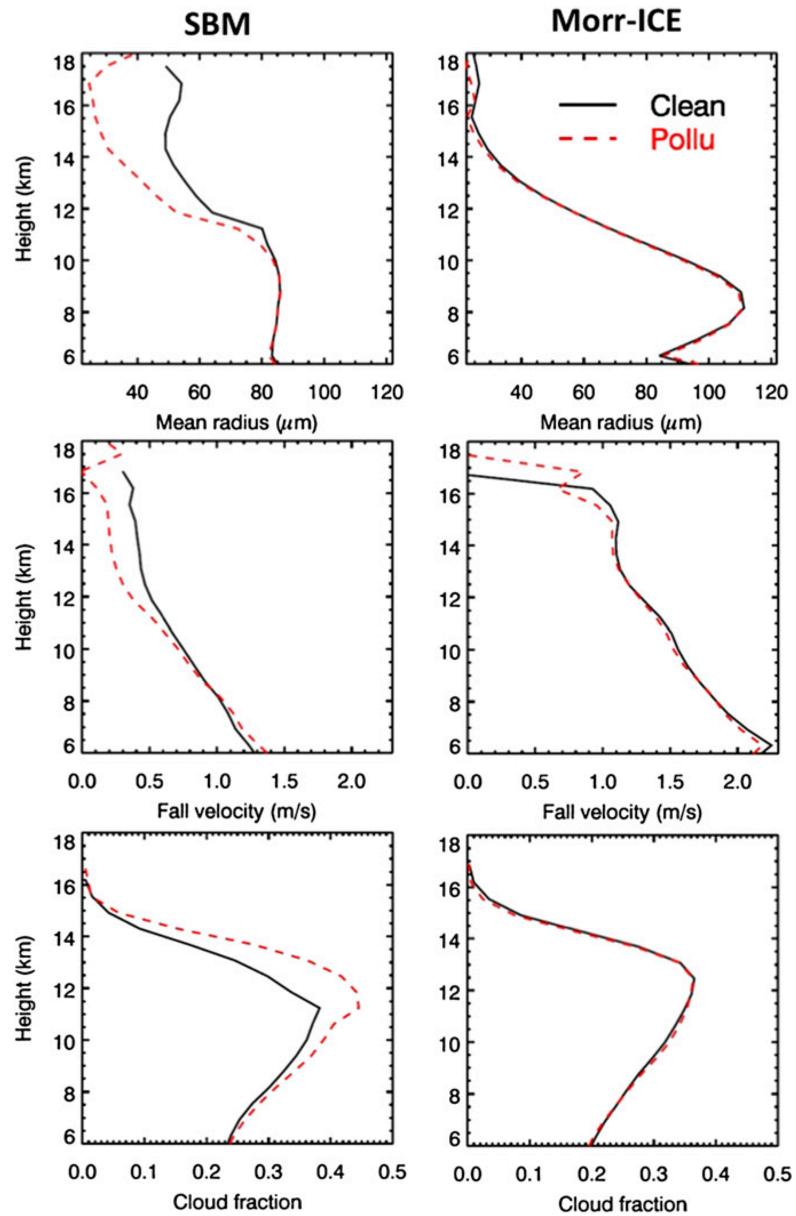



Yuan Wang et al., JGR (2013)

# Bulk microphysics underestimates impact on anvil

- Underestimate is likely due to condensation bias for clean conditions
- Fixed shape of condensate particle size distributions could also contribute




Fan et al., PNAS (2013)

# Challenges

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- Is double-moment microphysics sufficient?
- Explicit supersaturation requires
  - 1 km grid for deep convection
  - 100 m grid for shallow convection and stratocumulus
- Interaction between clouds and large-scale spans scales 1 km – 10,000 km
  - Brute force GCRM computationally prohibitive
  - MMF represents a wide variety of scales more efficiently, but currently neglects direct interactions between cloud systems in adjacent grid cells

# 4. A Path Forward

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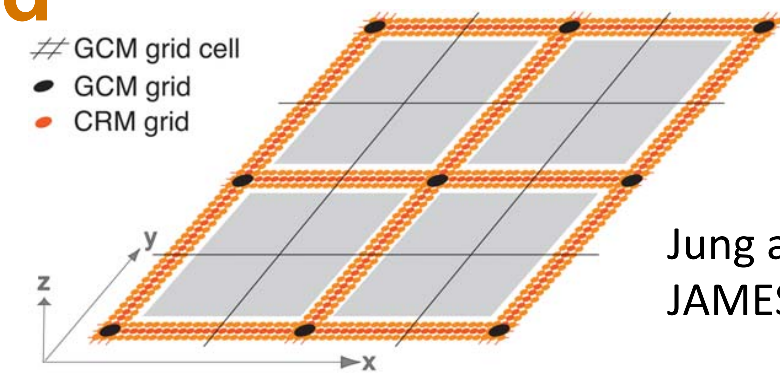


Jung and Arakawa
JAMES (2014)

- Q3D MMF to allow cloud systems to propagate between grid cells
- Improve turbulence using higher order scheme
- Triple-moment cloud microphysics?
- Full aerosol lifecycle on the outer grid. ECPP
- Nudge large-scale winds toward analyses
- Multi-year simulations
- Focus on radiative impact, which drives global climate response

# Supersaturation

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- Option A
  - Diagnose supersaturation in cloud interior from $\frac{dS}{dt} = \alpha w - bS$
  - Diagnose condensation rate from supersaturation: $C = aS$
- Option B
  - Explicit supersaturation for interior of deep convection
  - Subgrid parameterized supersaturation at cloud base or new cloud