Why do Global Climate Models Produce Such Large Estimates of Aerosol Indirect Effects?

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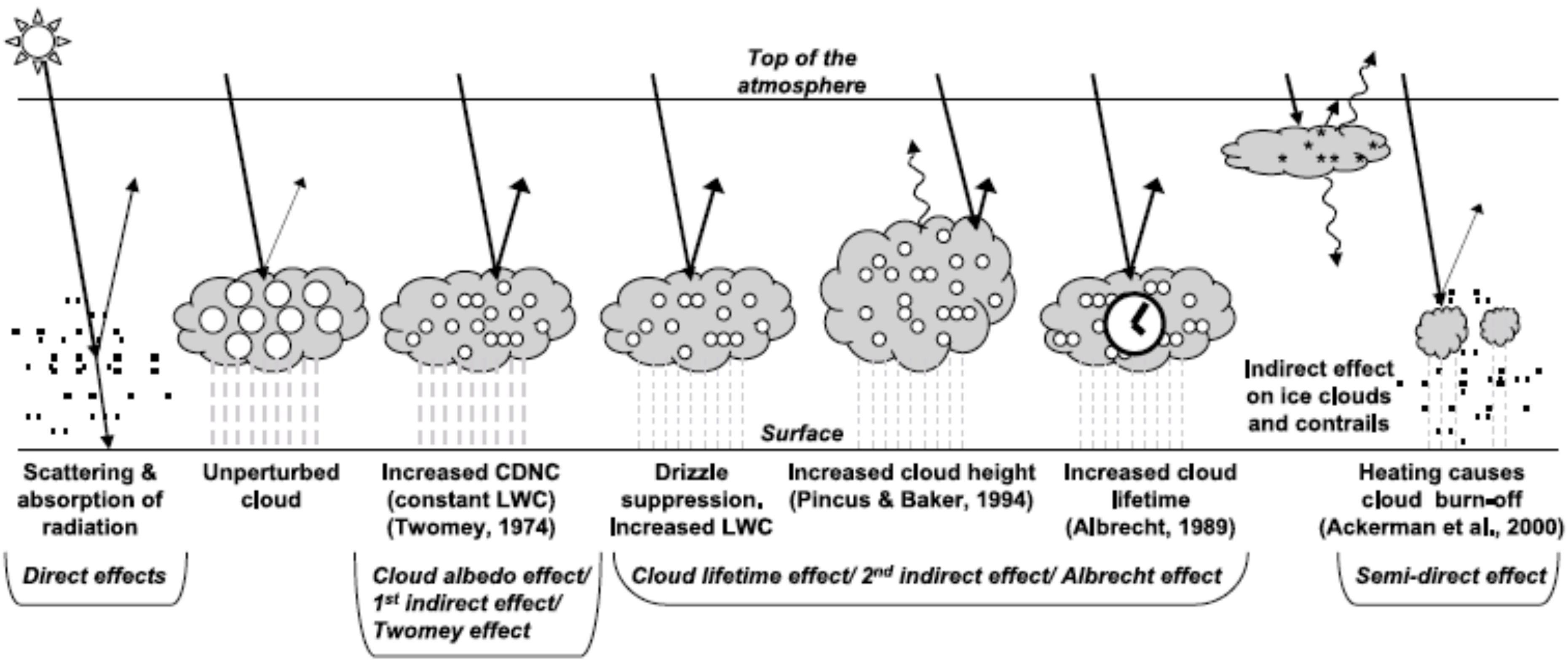
- Why do we think the estimates are too large?
- How can we determine what is causing the large estimates?
- How can ARM data be used to reduce estimates?

Key Challenges

- Use observations at the ARM sites and from IOPs to understand, characterize and quantify the important processes associated with the AIE
- Identify why climate models produce a much stronger increase in liquid water path than CRMs do
- Develop physically-based ways to produce sensitivities to aerosols in climate models that are more in line with high resolution models and observations.

Aerosol Radiative Forcing Mechanisms



IPCC AR4 (2007)

Mathematically Speaking

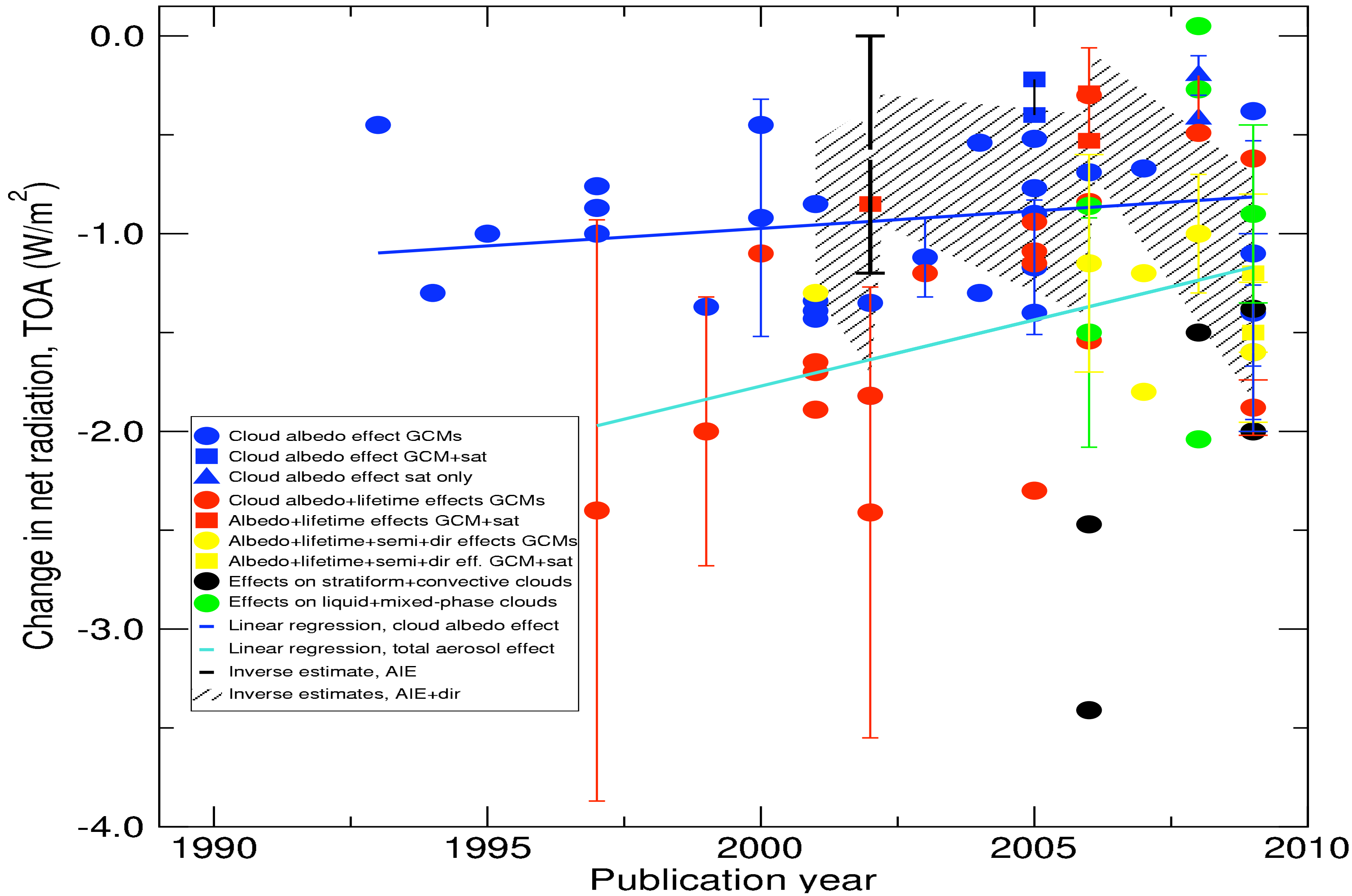
$$\Delta SWCF = \Delta E \frac{dCCN}{dE} \frac{dN_d}{dCCN} \begin{Bmatrix} f_c \dfrac{\partial r_e}{\partial N_d} \dfrac{d\tau_c}{dr_e} \dfrac{d\alpha_c}{d\tau_c} \dfrac{dCF}{d\alpha_c} + \\ f_c \dfrac{\partial L}{\partial N_d} \dfrac{d\alpha_c}{dL} \dfrac{dCF}{d\alpha_c} + \dfrac{\partial f_c}{\partial N_d} \dfrac{dCF}{df_c} \end{Bmatrix}$$

Cloud albedo effect

Cloud lifetime effects

Δ: anthropogenic change
$SWCF$: shortwave cloud forcing
E: emissions
CCN: cloud condensation nuclei concentration
N_d: droplet number concentration
f_c: cloud fraction
r_e: droplet effective radius
τ_c: cloud optical depth
α_c: cloud albedo
CF: cloud radiative forcing
L: cloud liquid water path

Most AIE Estimates Exceed -1 W m^{-2}



Lohmann et al., 2010

Why do we think the estimates are too large?

- Global energy balance
- Observed cloud-aerosol relationships
- Missing natural sources

Global 20th Century Energy Balance

$$\Delta Q = \lambda \Delta T + H$$

(Kiehl, GRL 2007)

$$\lambda \Delta T = \Delta Q_{GG} + \Delta Q_{ADirect} + \Delta Q_{AIndirect} - H$$

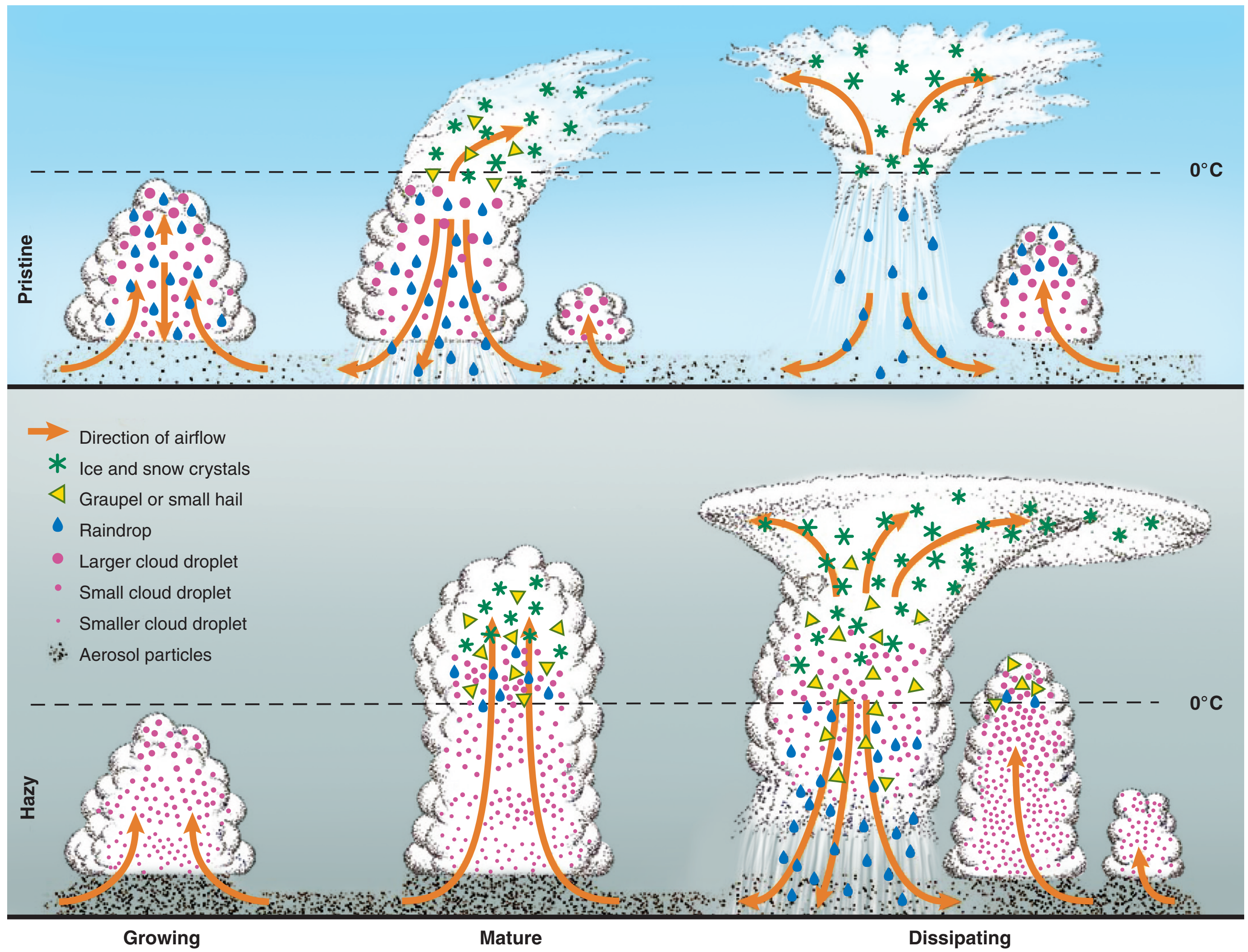
↑

0.6 °C (1850 to 2000)

λ (W m^{-2} C^{-1})	ΔQ_{GG} (W m^{-2})	$\Delta Q_{ADirect}$ (W m^{-2})	$\Delta Q_{AIndirect}$ (W m^{-2})	-H (W m^{-2})
2.3±0.3	2.6	-0.5	0	-0.7±0.2
0.7±0.3	2.6	-0.5	-1.0	-0.7±0.2
0.0±0.3	2.6	-0.5	-1.4	-0.7±0.2
0.0±0.3	2.6	0	-1.9	-0.7±0.2
0.7±0.3	2.6	0	-1.5	-0.7±0.2

Missing or Underestimated Warming Mechanisms

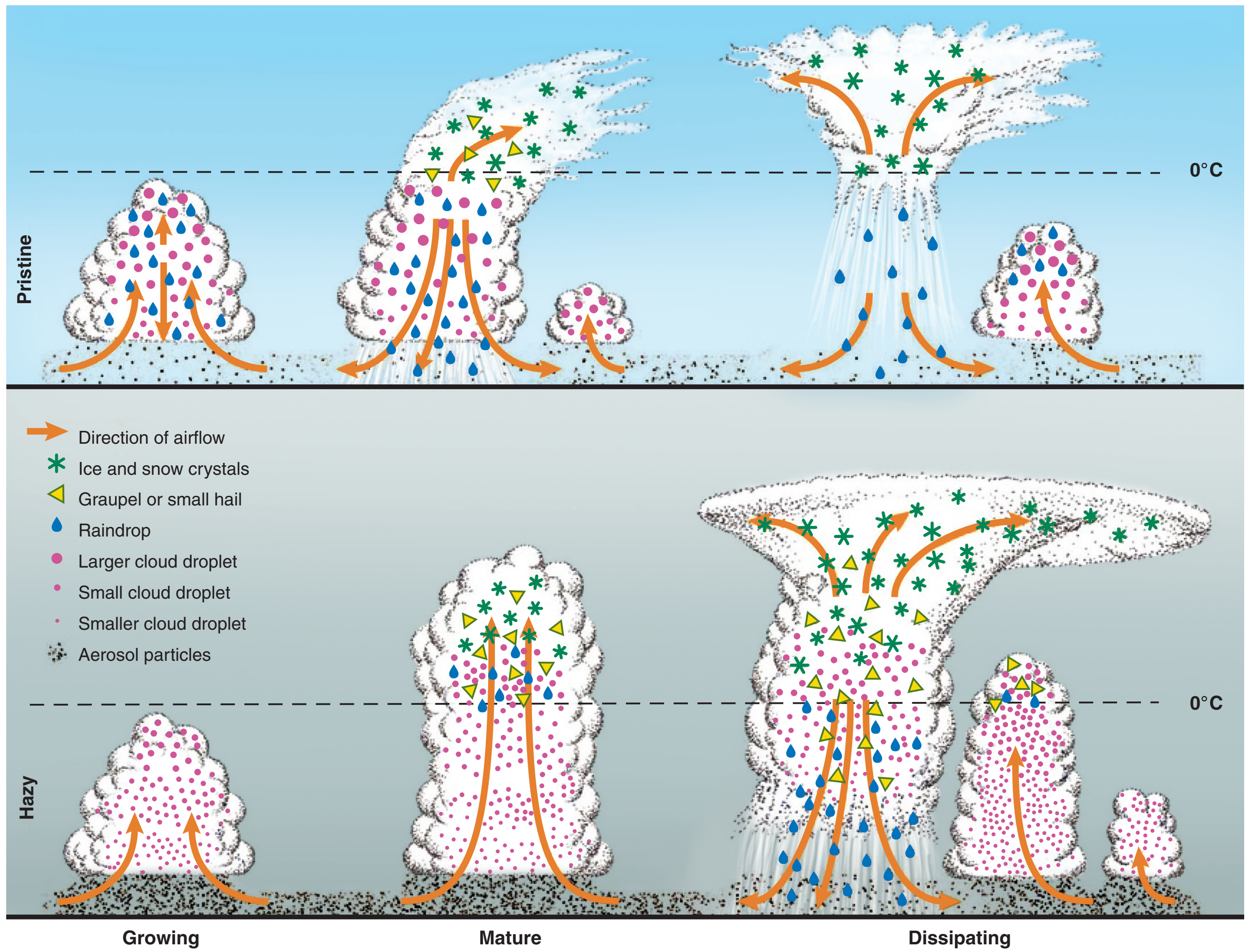
- Effects on homogeneous nucleation of ice crystals: LWCF
- Effects on heterogeneous ice nucleation: SWCF
- Deeper convection and expanded cirrus anvil area: LWCF
- Underestimated black carbon DRF



Rosenfeld et al. Science (2008)

Missing or Underestimated Cooling Mechanisms

- Effects on homogeneous nucleation of ice crystals: SWCF
- Expanded cirrus anvil area: SWCF

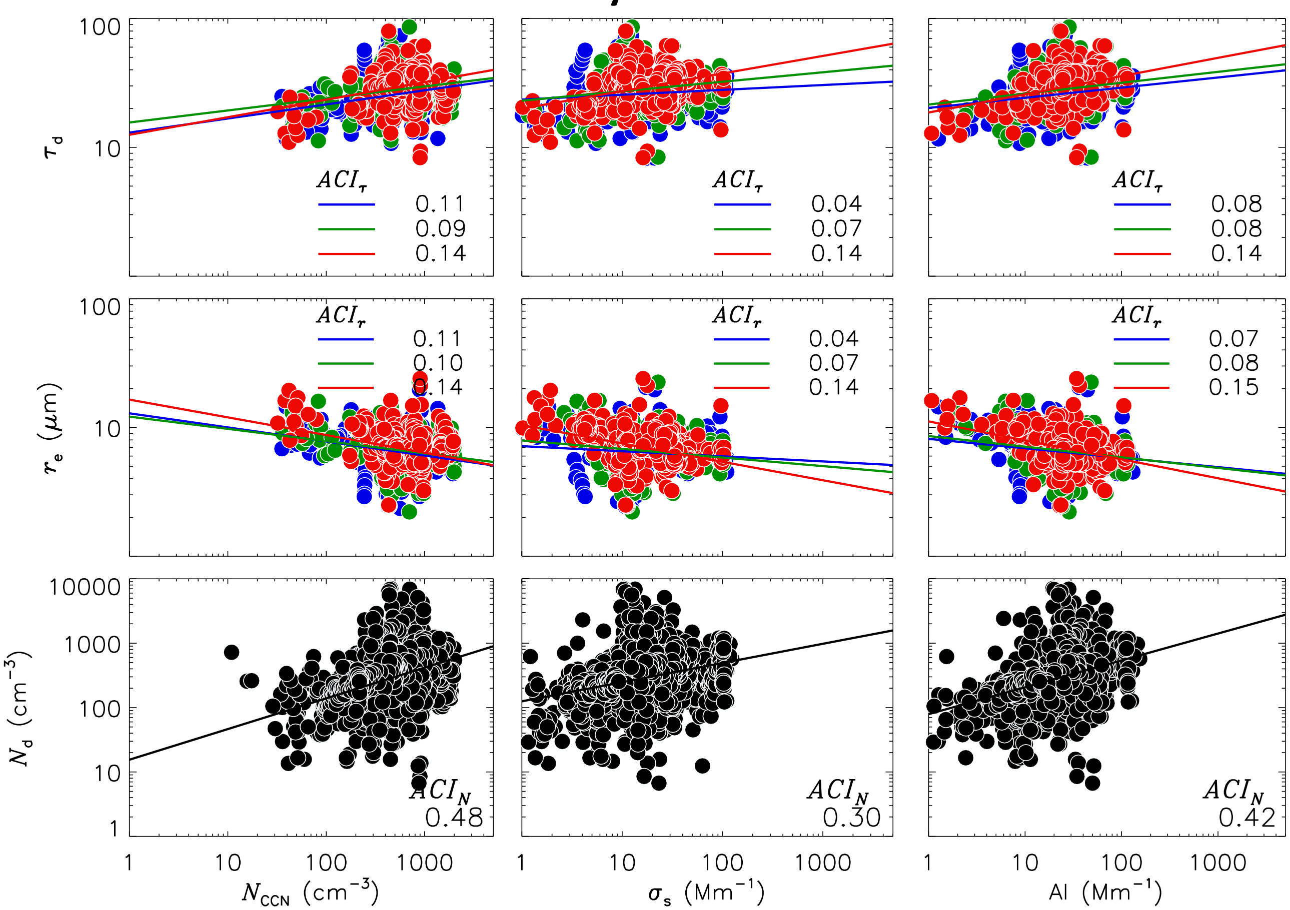


Rosenfeld et al. Science (2008)

Overestimated Cloud Albedo Effect: Surface Observations

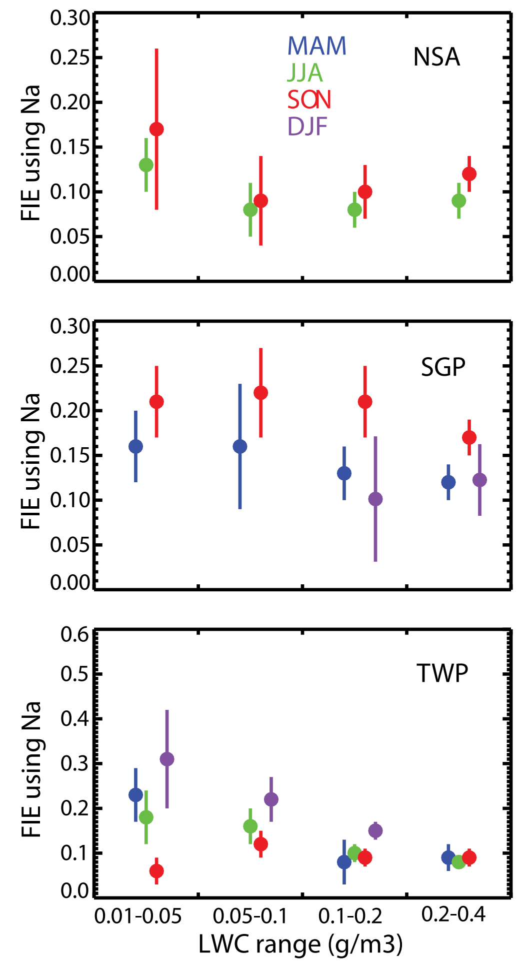
$$ACI = -\frac{d\ln r_e}{d\ln\alpha}$$

Observed Pt. Reyes



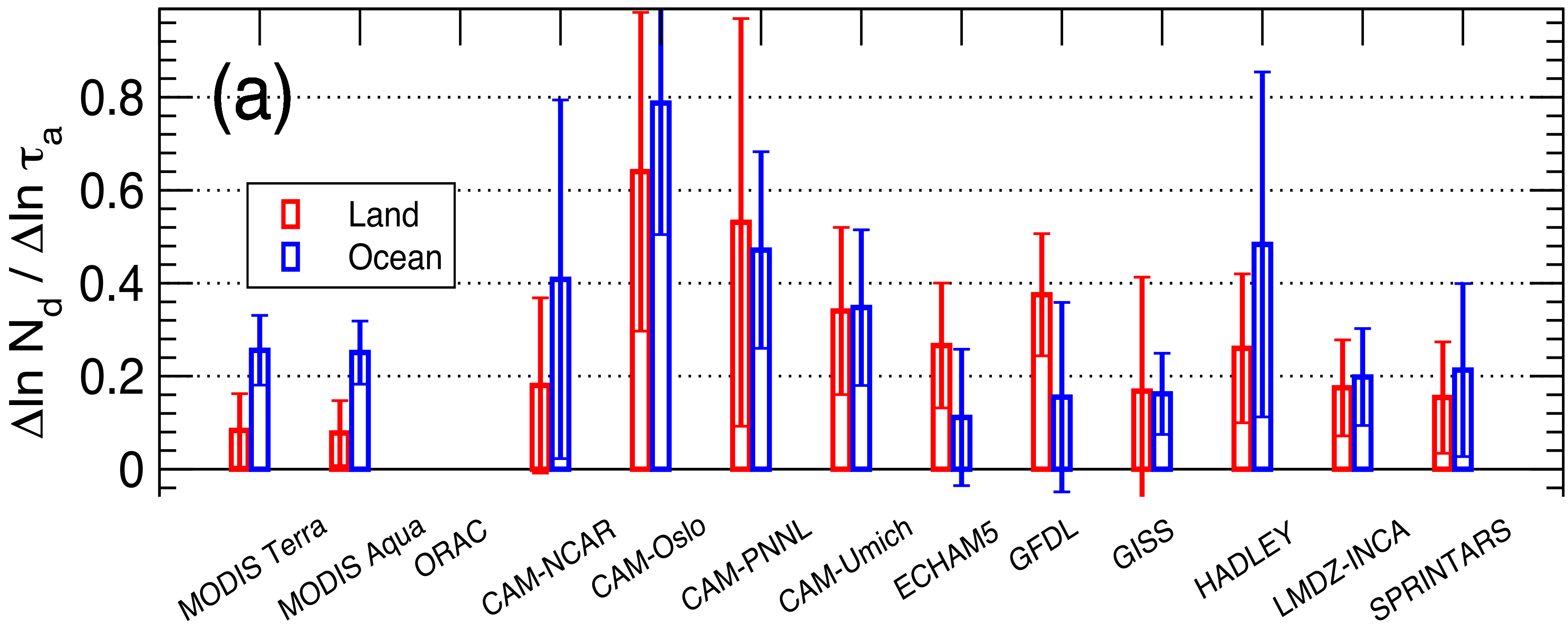
McComiskey et al. (2009)

Simulated



Zhao et al, GRL (2012)

Overestimated Cloud Albedo Effect: Satellite Observations



Quaas et al., ACP (2009)

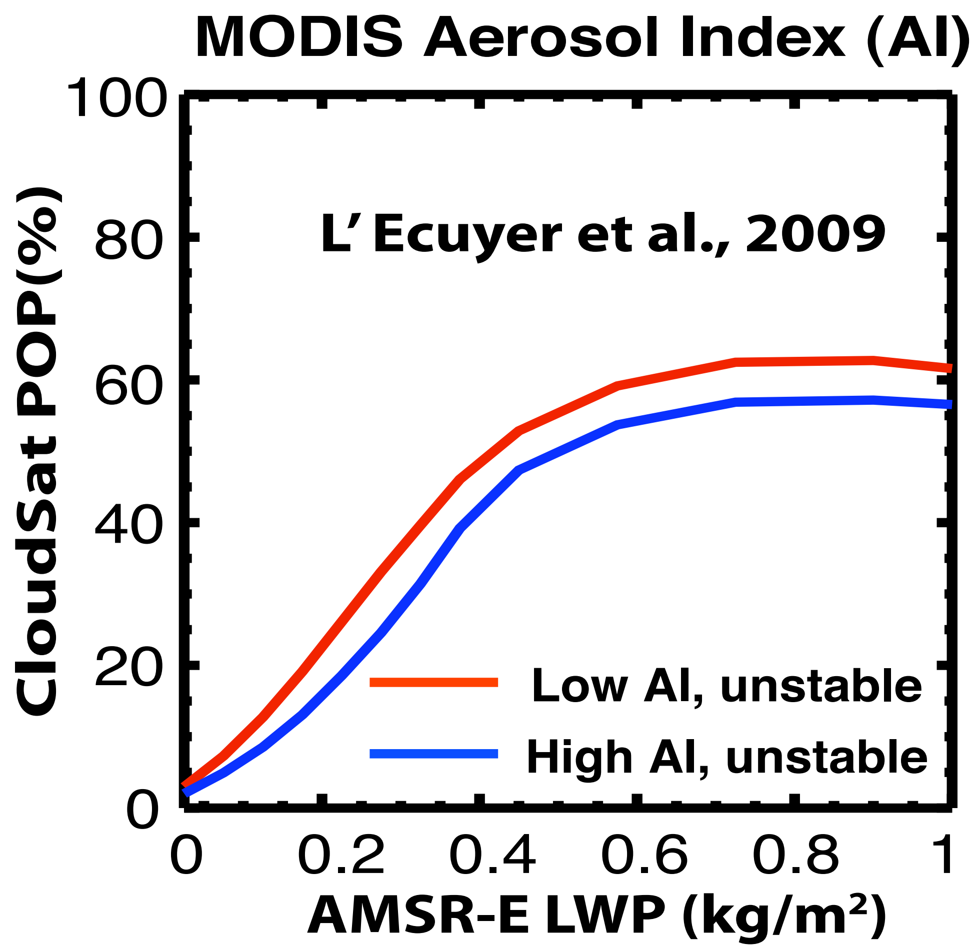
Constraints on Cloud Lifetime Effect from Probability of Precipitation (POP) for warm clouds

At a given LWP:

$POP = N_{rain}/N_c$

N_c: the number of cloud events.

N_{rain}: the number of precipitating events.

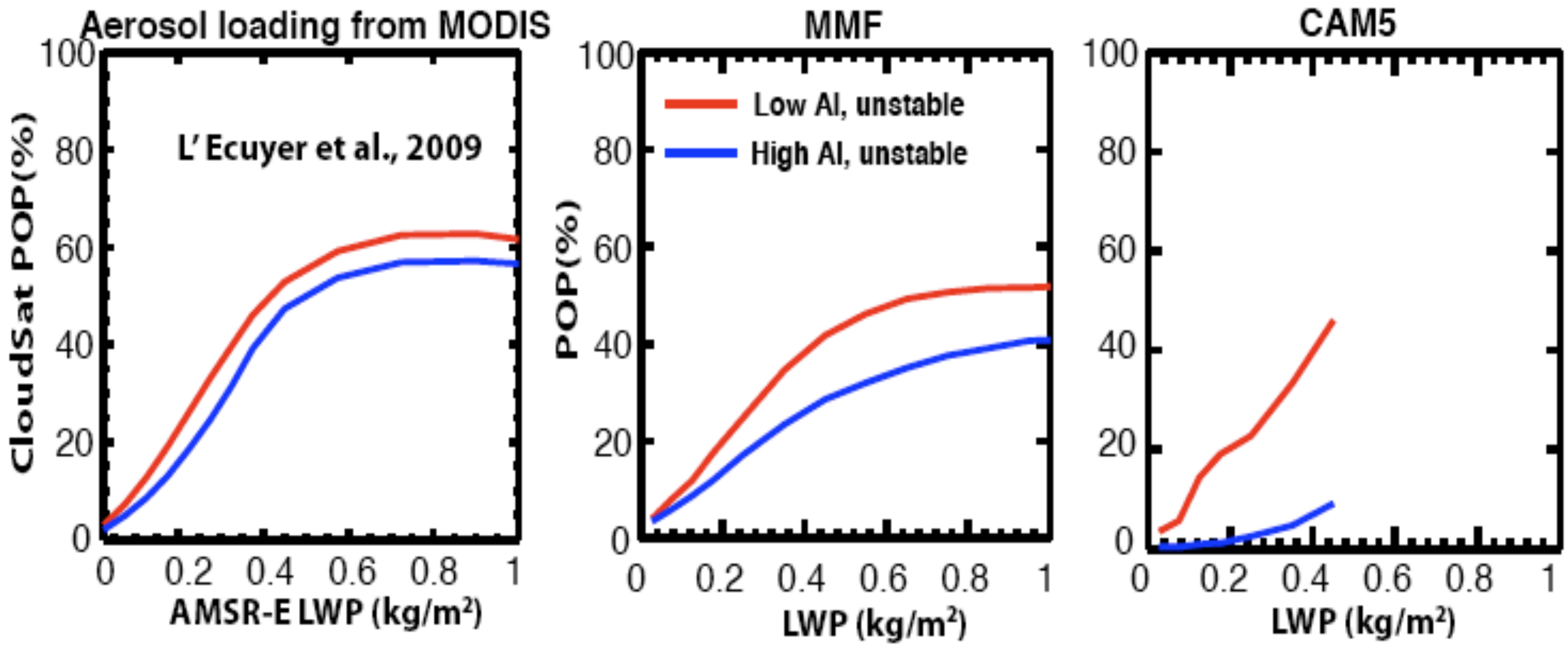


Satellite observations:

more aerosol → smaller POP

Comparing simulated and observed POP dependence on aerosol

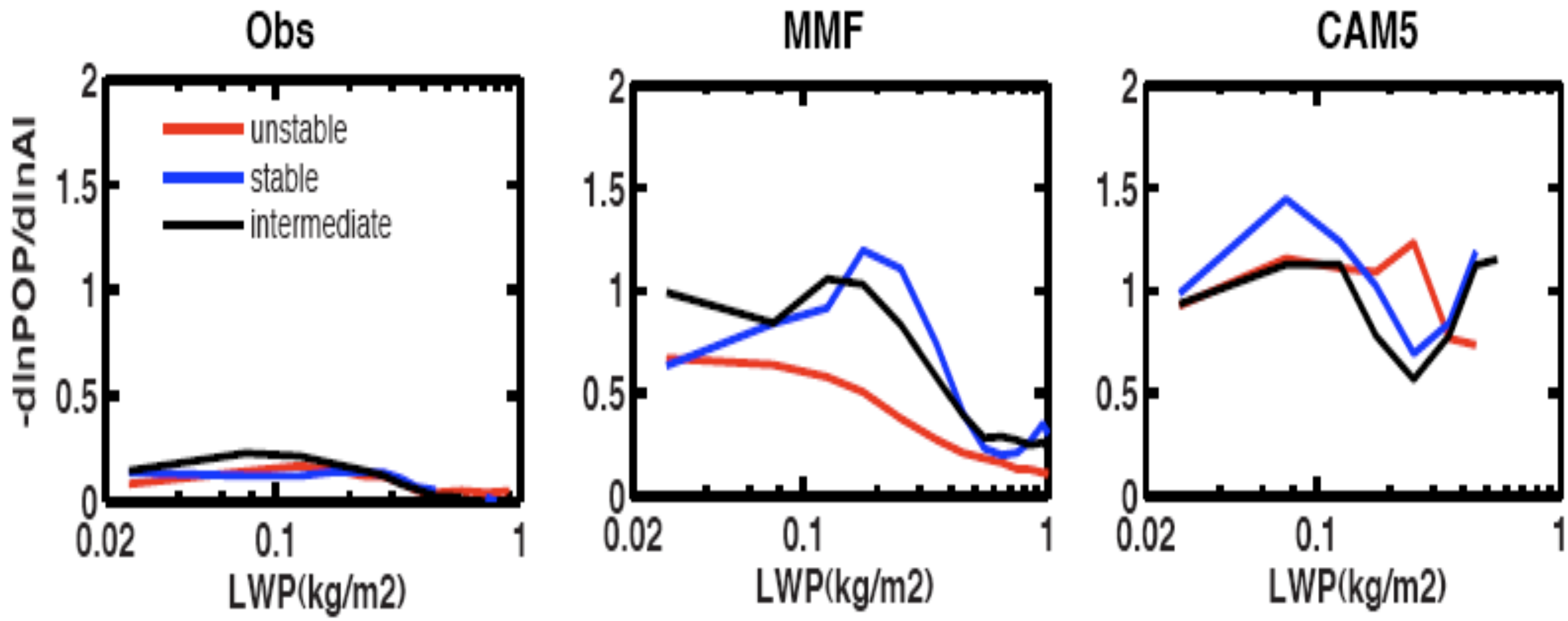
M. Wang et al., GRL (2012)



The POP dependence on aerosol loading in MMF

- is weaker than in CAM5
- agrees better with satellite observations

-dlnPOP/dlnAI: A quantitative measure of aerosol effects on precipitation probability

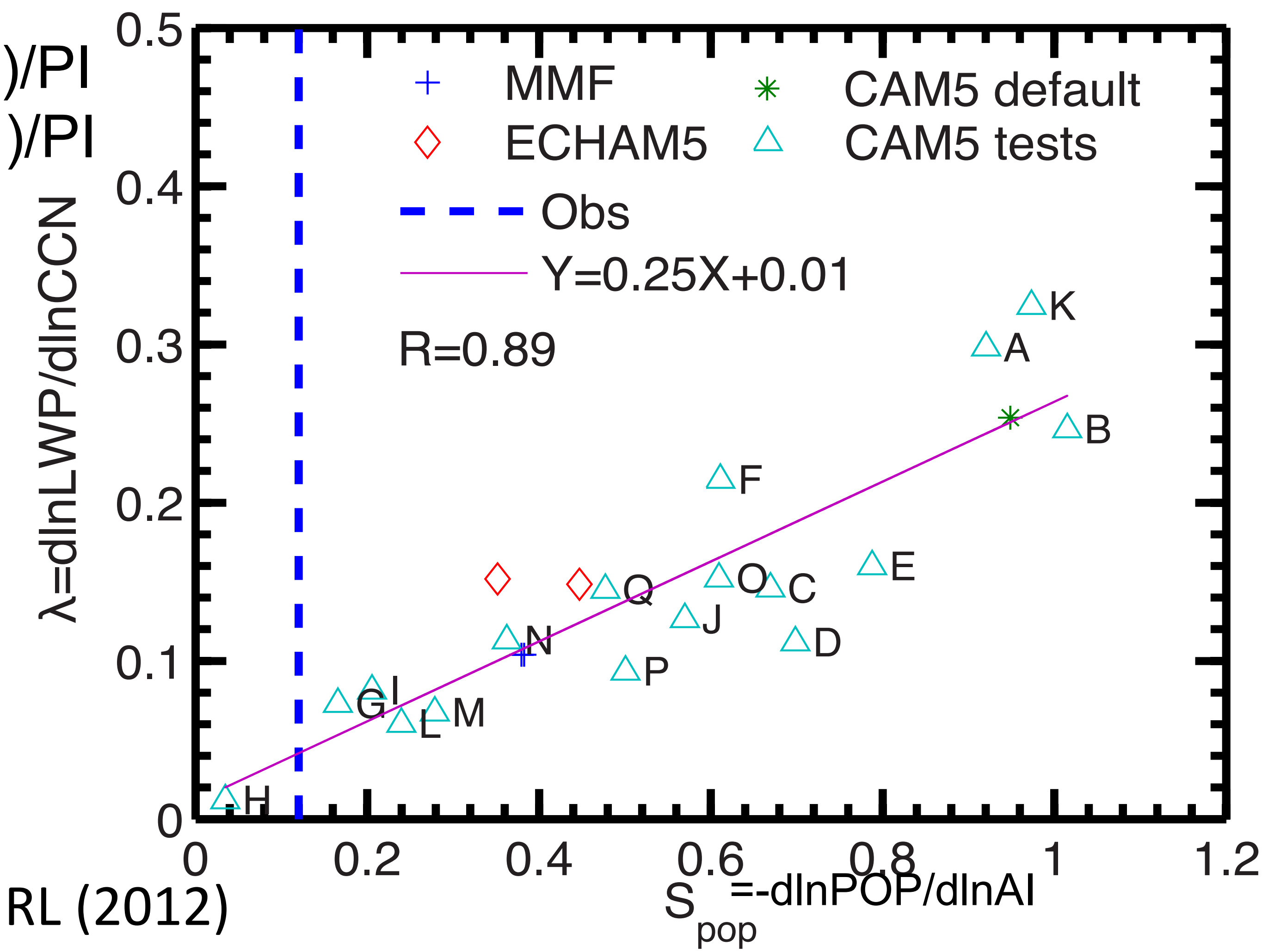


LWP-weighted global average

Obs: 0.12; MMF: 0.42; CAM5: 1.06

Relating S_{pop} to Cloud Lifetime Effect

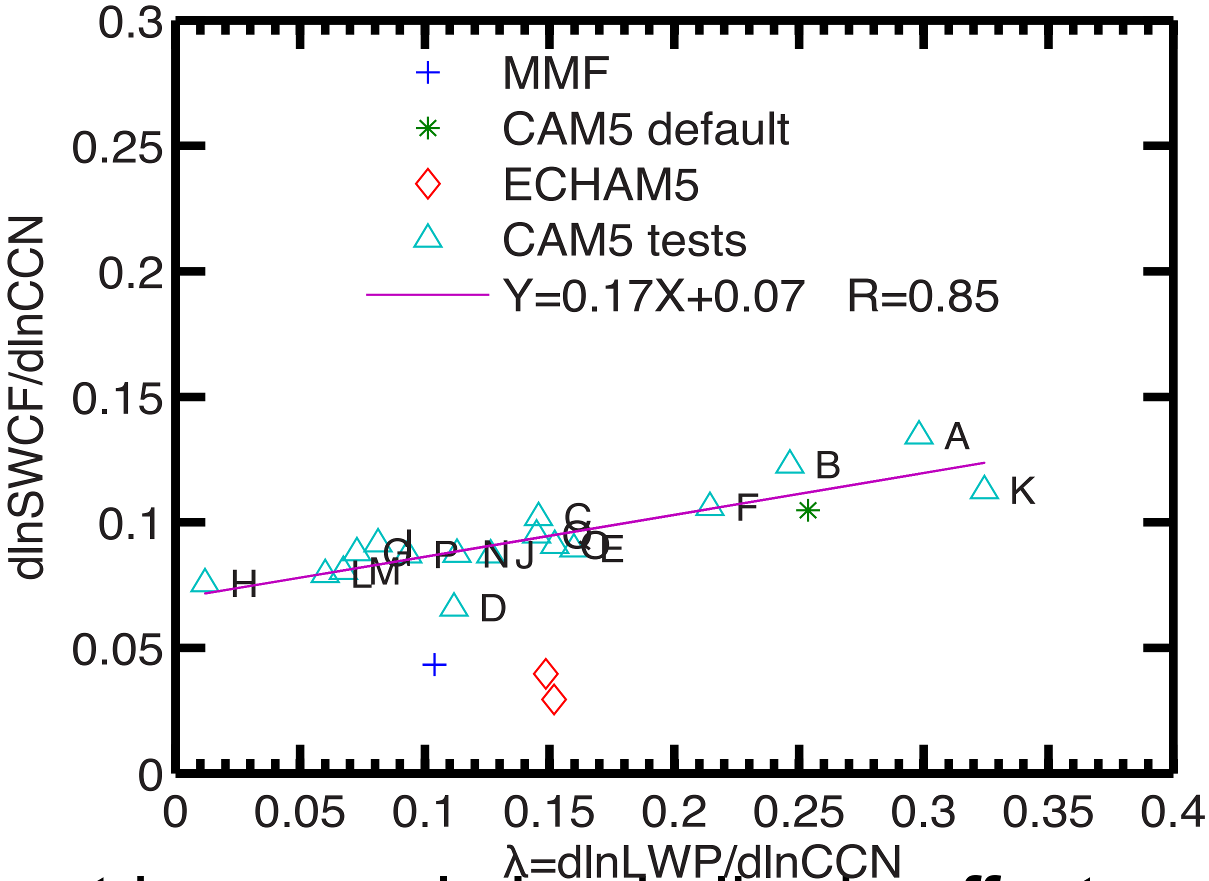
dlnLWP: (PD-PI)/PI
dlnCCN: (PD-PI)/PI



M. Wang et al., GRL (2012)

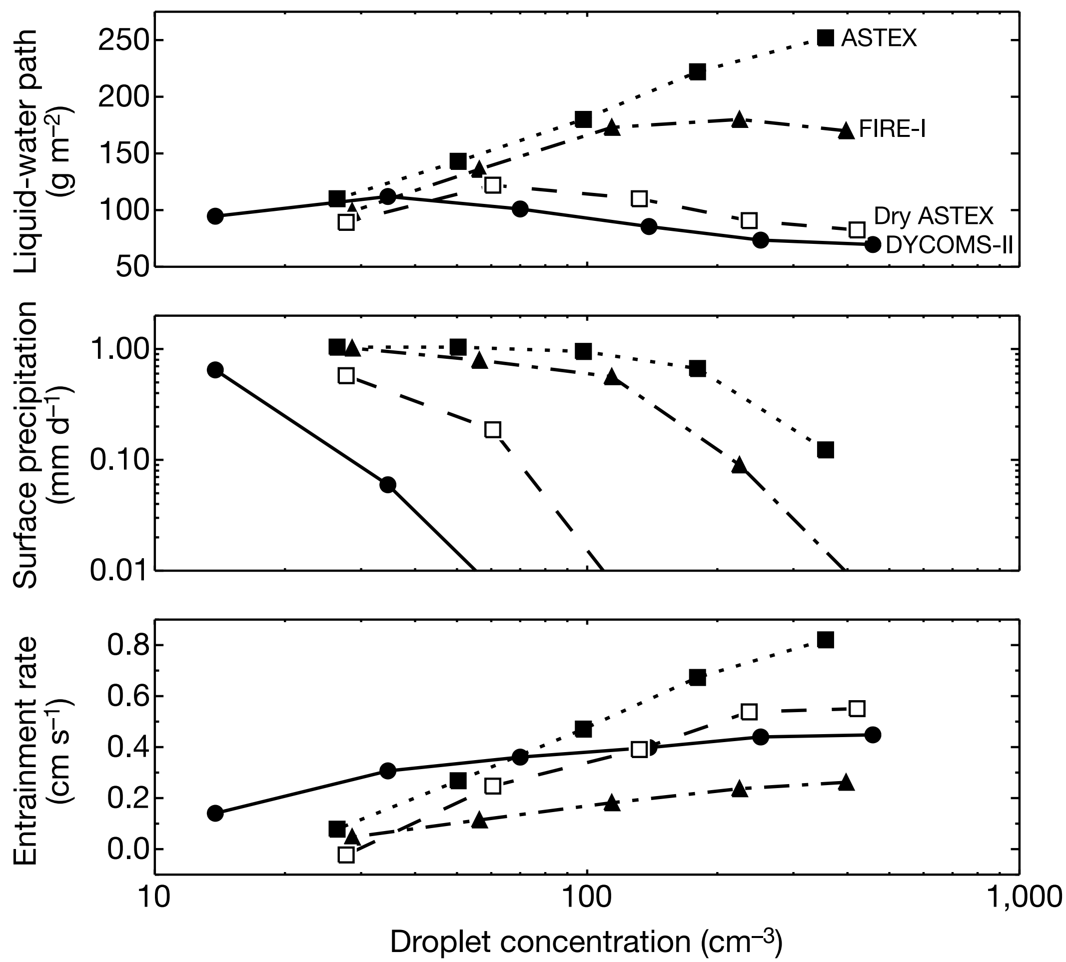
- CAM5 tests change treatment of autoconversion
- Intercept of regression with S_{pop}=0.12 suggests λ=0.04

Expressing indirect forcing in terms of liquid water path sensitivity



- Intercept is aerosol cloud albedo effect
- Value at $\lambda=0.04$ provides estimate of indirect forcing given change in CCN

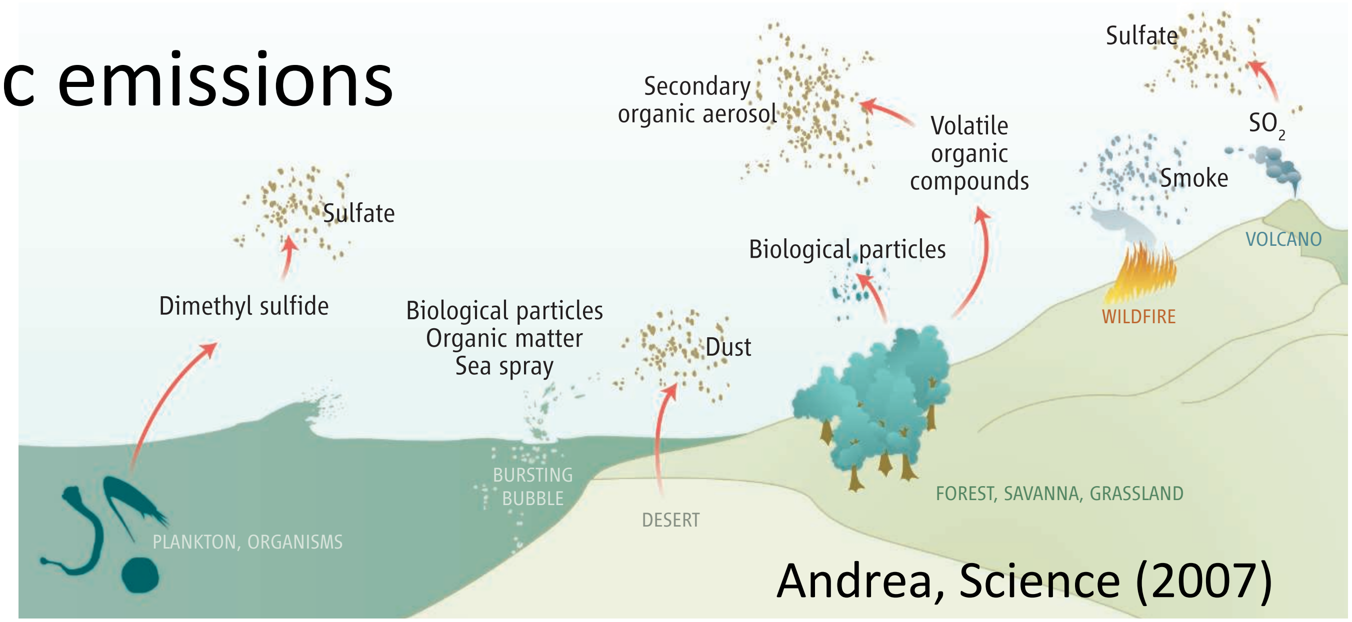
Lessons from LES: L can *decrease* with increasing aerosol



Ackerman et al. Nature (2004)

Missing or Underestimated Pre-industrial Sources

- Secondary marine organic
- Ultrafine primary marine (in some models)
- Land primary and secondary organic particles
- Wildfire emissions
- Domestic emissions

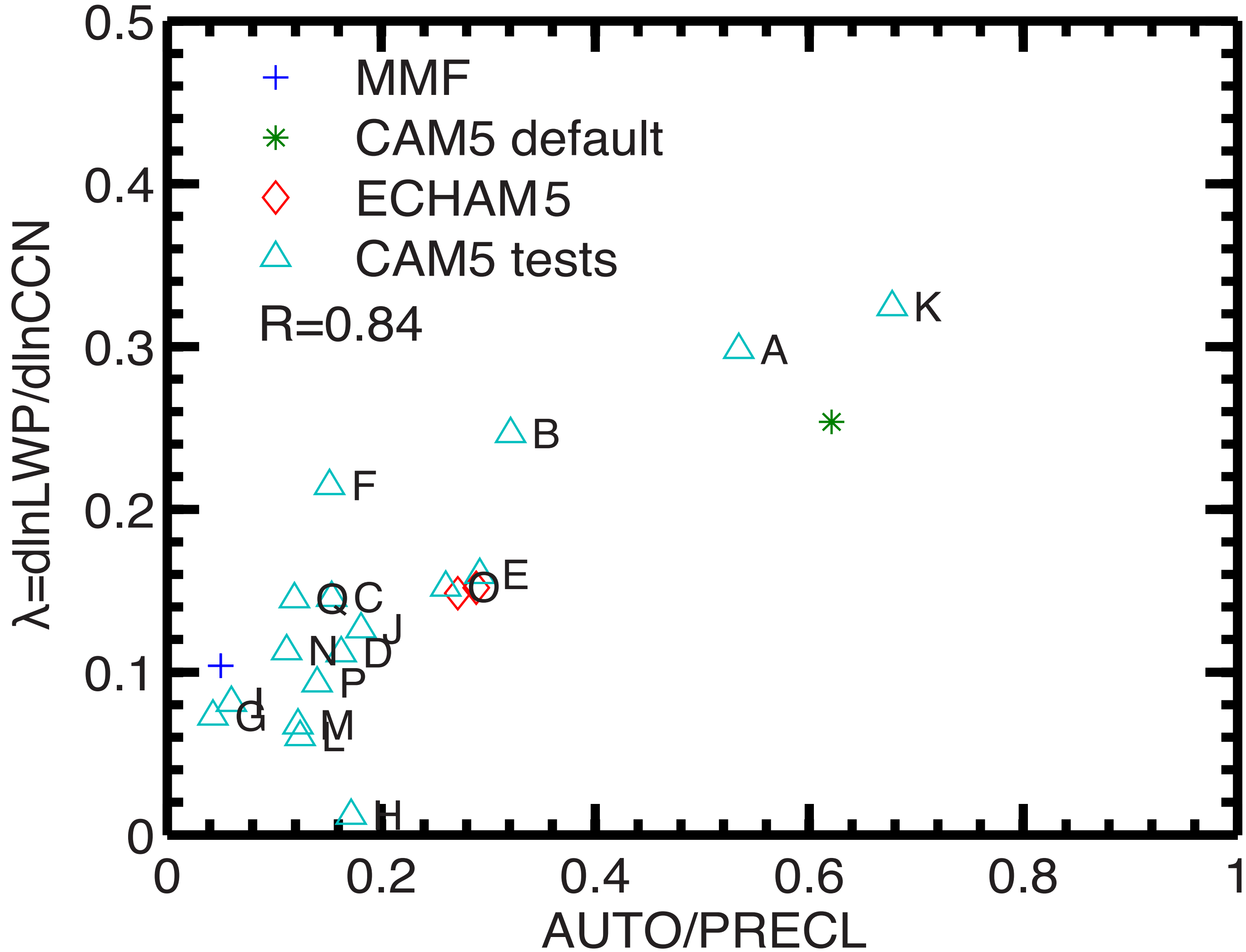


Andrea, Science (2007)

How can we determine what is causing the large estimates?

- Model diagnostics compared with
  - data
  - more realistic models
- Separate dynamical effects from aerosol effects on clouds by mixing combinations of aerosol and large-scale conditions in simulations
- Swapping physics packages and resolution between SCMs and CRMs
- Quantifying parametric uncertainty
- Reducing noise through nudging simulations

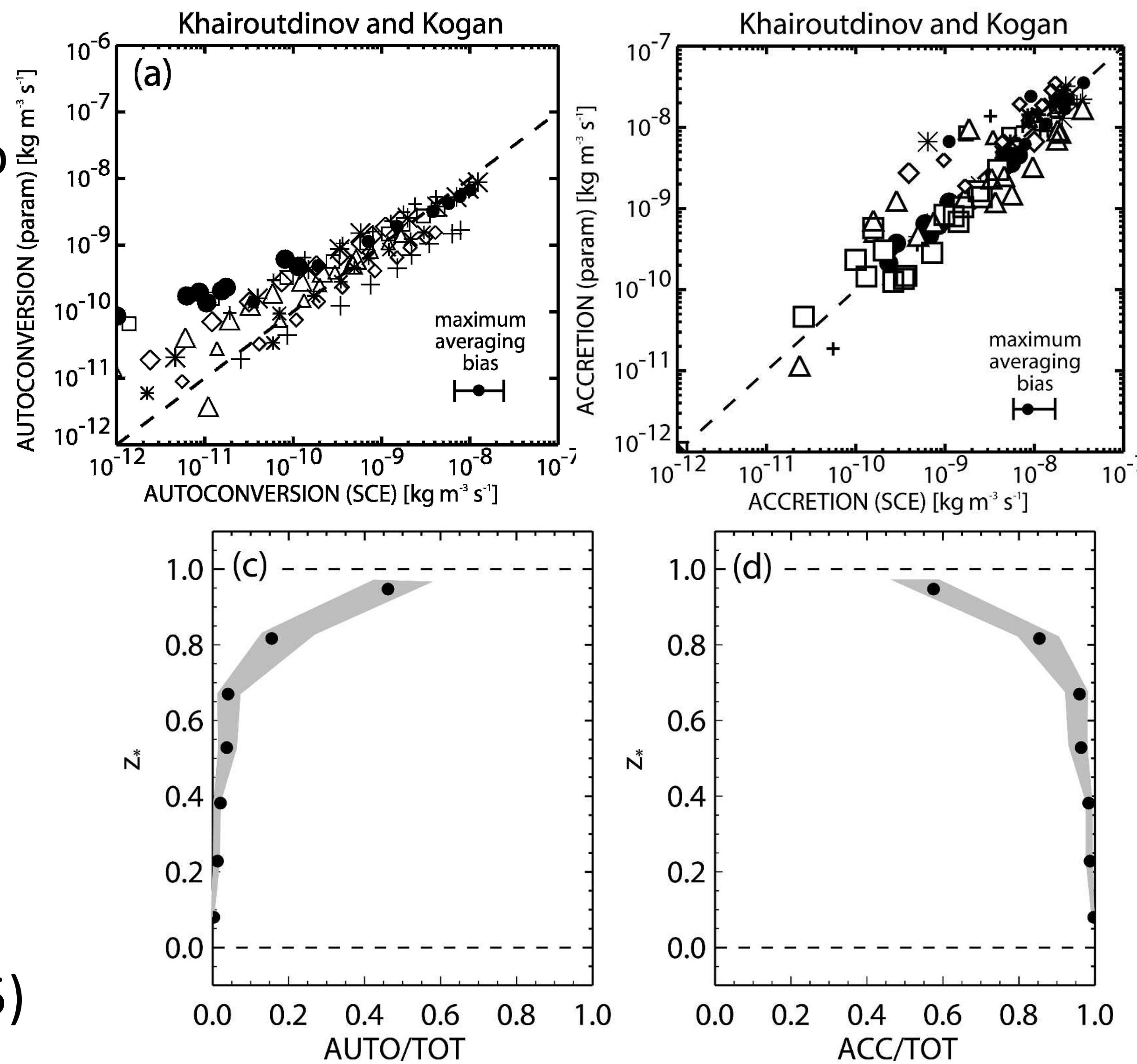
Model diagnostics: simulated contribution of autoconversion to precipitation



- Small role of autoconversion in MMF might be due to prognostic precipitation

Testing microphysics with in situ data

- Applying bulk and bin microphysics to measured droplet size distributions
- Autoconversion important only near cloud top



Wood, JAS (2005)

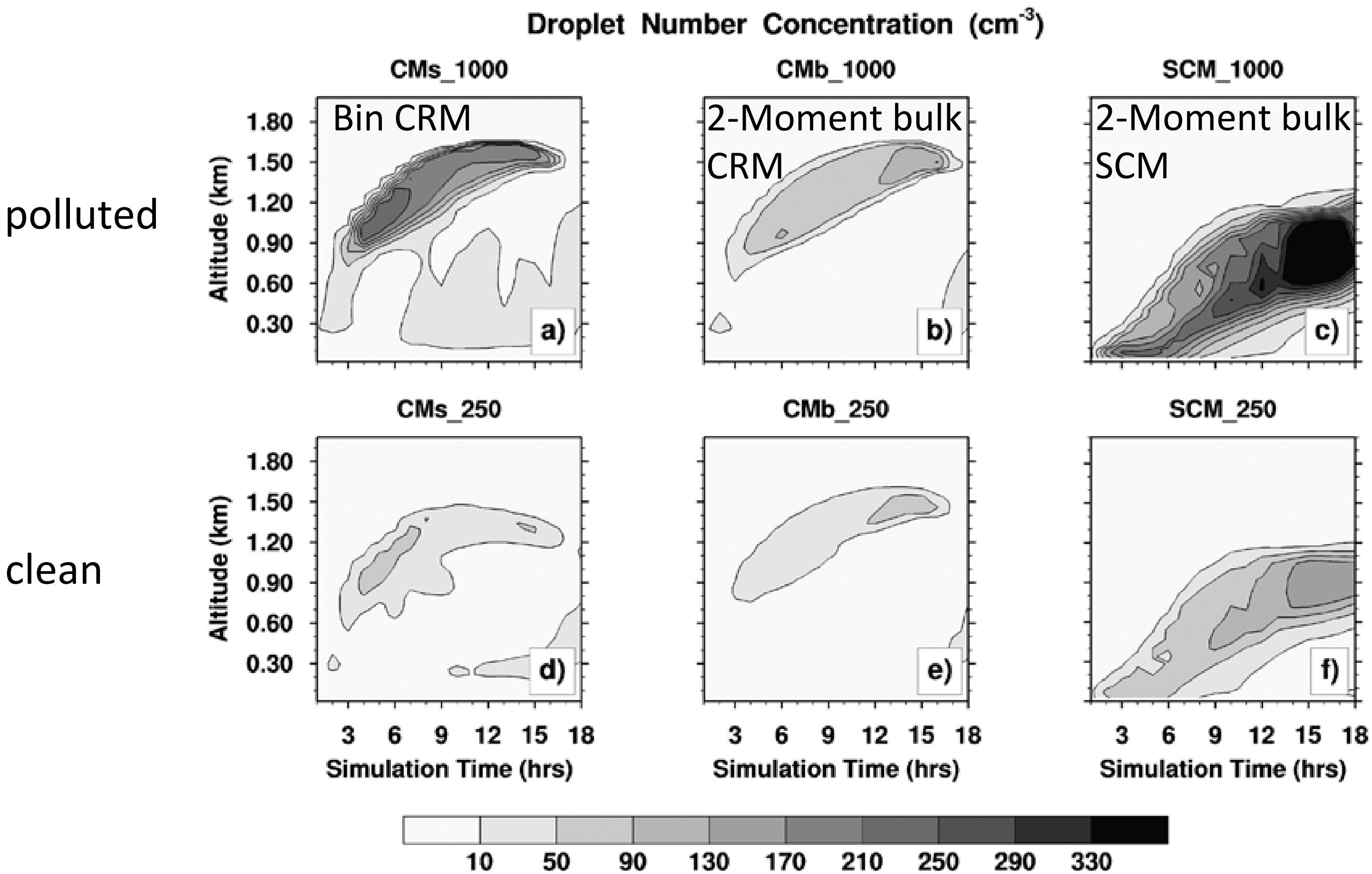
Comparing GCM and CRM Simulations for the Same Boundary Conditions

Model	Aerosol	Boundary Conditions
GCM	PD emissions	simulated
GCM	PI emissions	simulated
SCM	GCM PI simulation	GCM PD simulation
SCM	GCM PD simulation	GCM PI simulation
CRM	GCM PD simulation	GCM PD simulation
CRM	GCM PI simulation	GCM PI simulation
CRM	GCM PI simulation	GCM PD simulation
CRM	GCM PD simulation	GCM PI simulation

Lee and Penner ACP (2010)

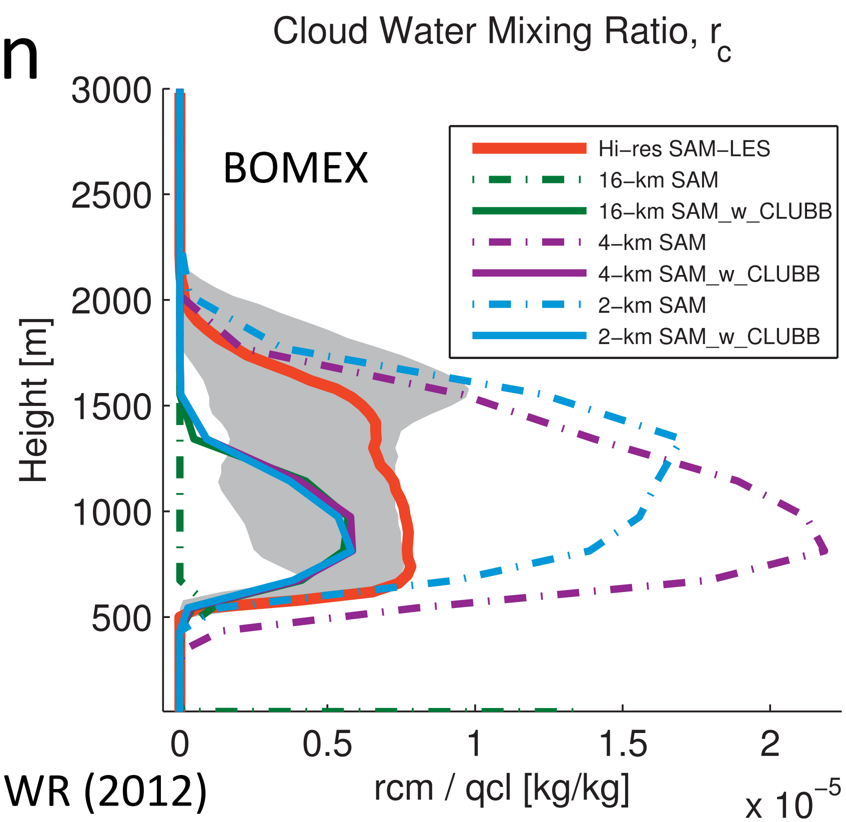
Comparing GCM and CRM Simulations for the Same Boundary Conditions

- Swapping physics
  - Cloud microphysics (Ovchinnikov and Ghan, 2002)



Comparing GCM and CRM Simulations for the Same Boundary Conditions

- Swapping physics
  - Cloud microphysics (Ovchinnikov and Ghan, 2002)
  - Turbulence (Penner, proposed)
- Degrading CRM resolution



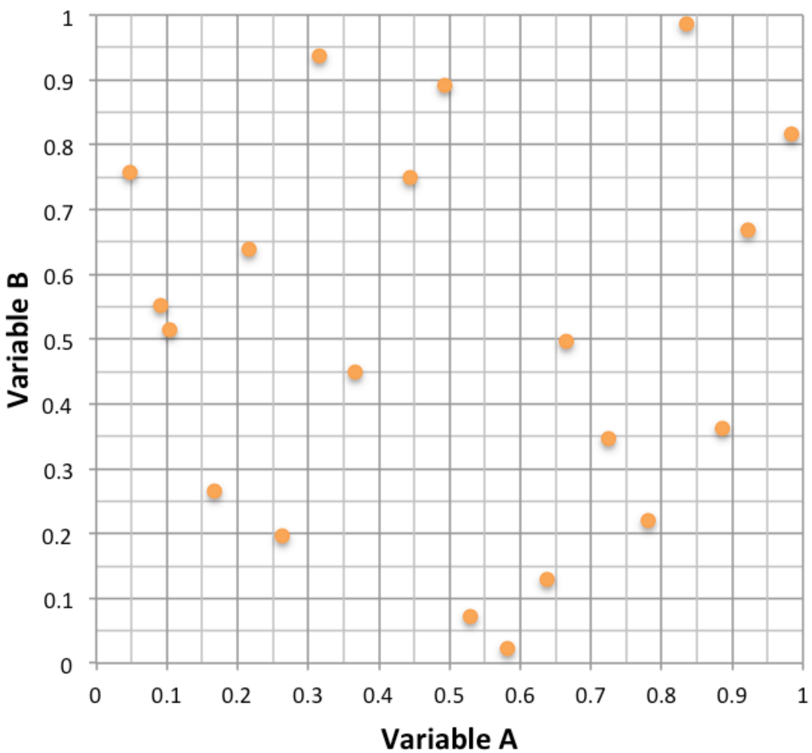
Larson et al., MWR (2012)

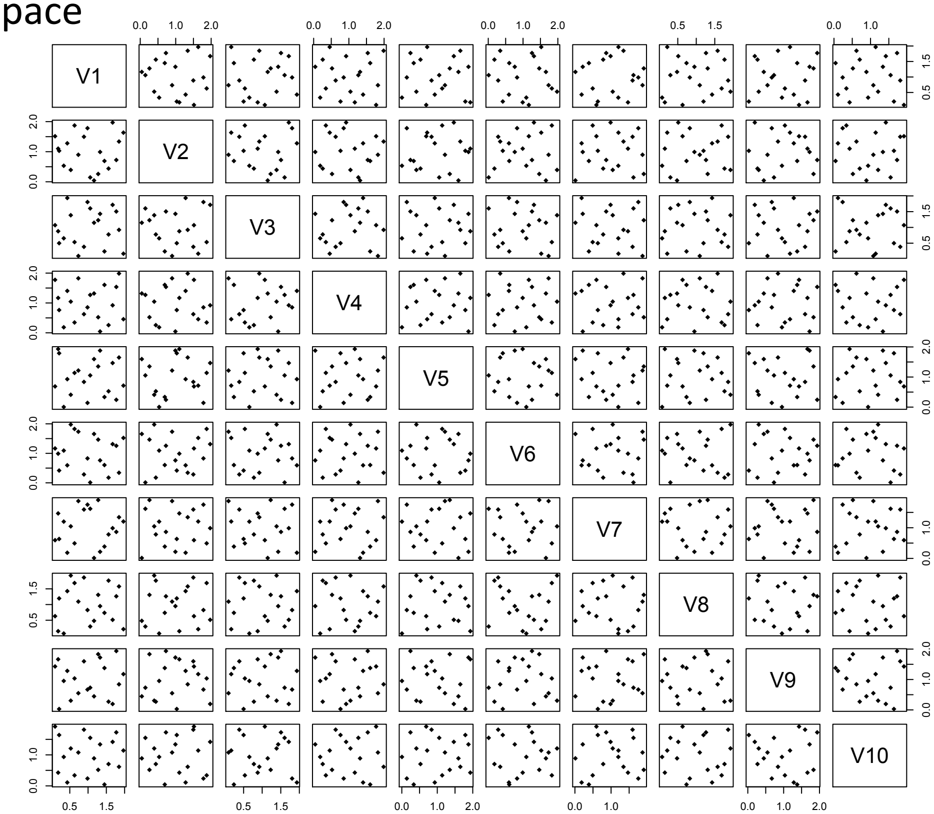
Quantifying Uncertainty in AIE

Liu, Ma, Zhao, Gattiker, Rasch, in preparation

- Design of experiments (DOE) vs. One-at-a-time (OAT)
- Advantage of DOE over OAT (Czitrom, 1999):
  - Greatly **reduce** the number of experiments (**20** vs. 2 x 10, 20 x 10, or 20^{10} experiments)
  - Provide more **precise** estimates of the effect of each parameter
  - Give accurate estimates of the effect of the **interactions** between two factors
  - Cover a **larger portion** of the parameter space

Latin Hypercube DOE (20 samples, 10 variables)



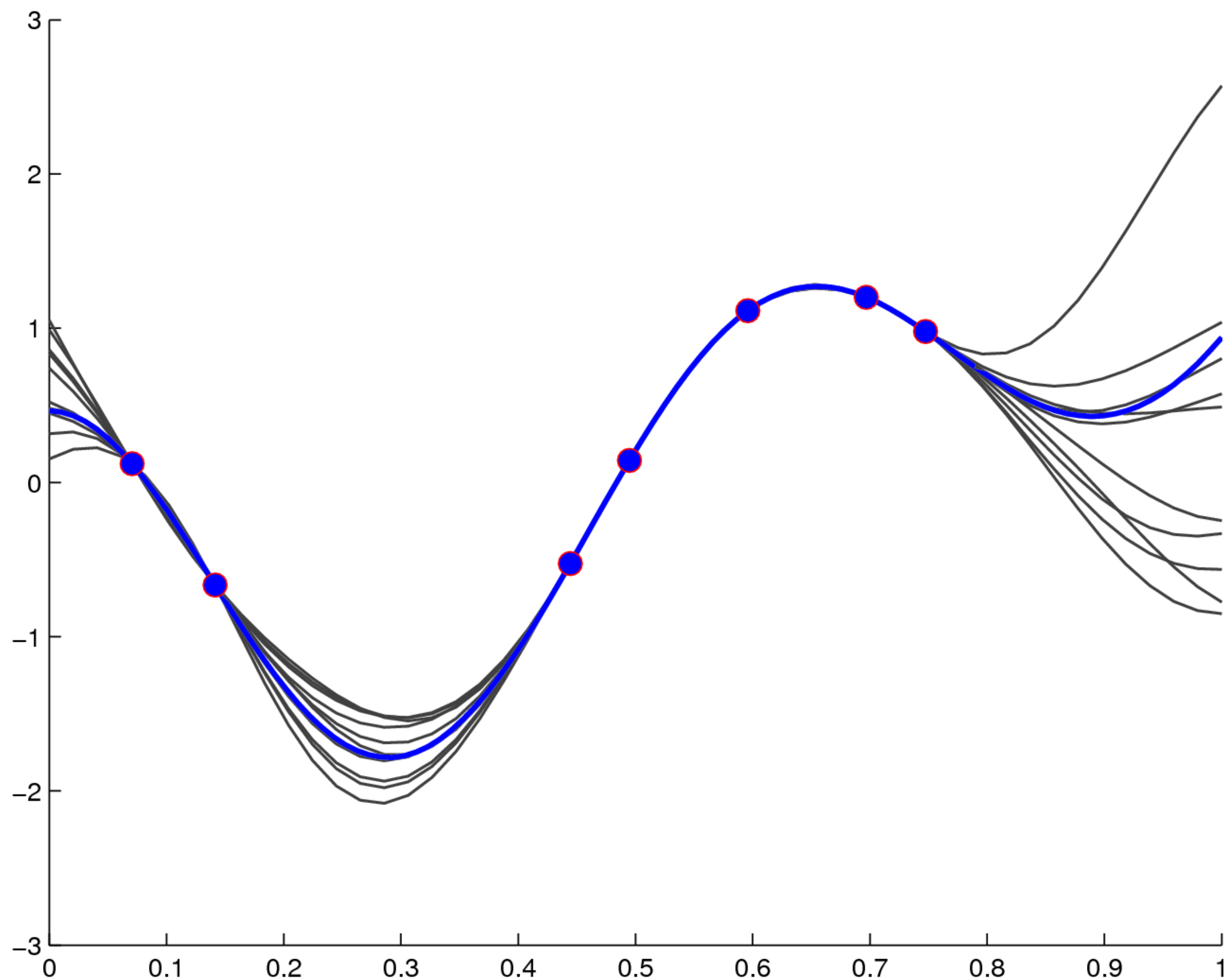


Design of Experiment

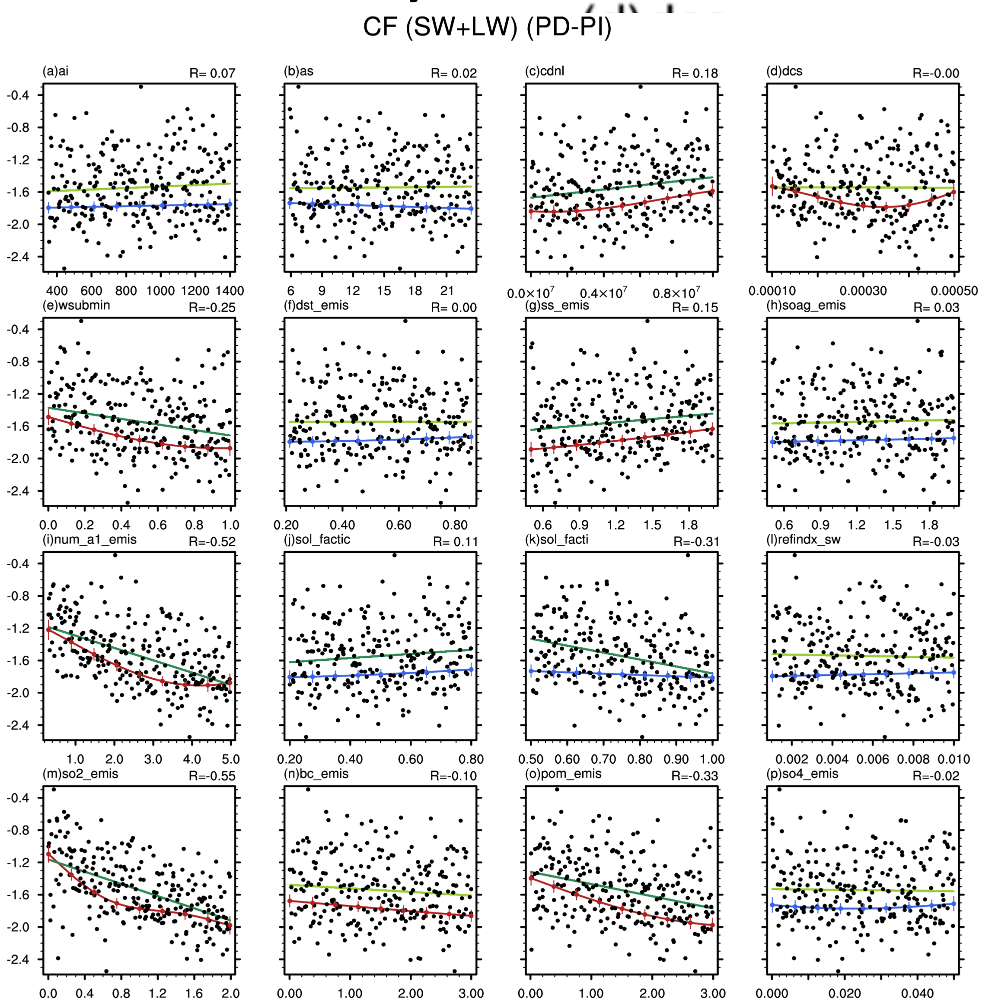
- CAM5 (1.9 x 2.5 degree grid-spacing)
- 256 Pre-industrial (PI) and 256 Present-day (PD) simulations (5-year runs)
- 16 parameters, Quasi Monte Carlo sampling (256 samples)

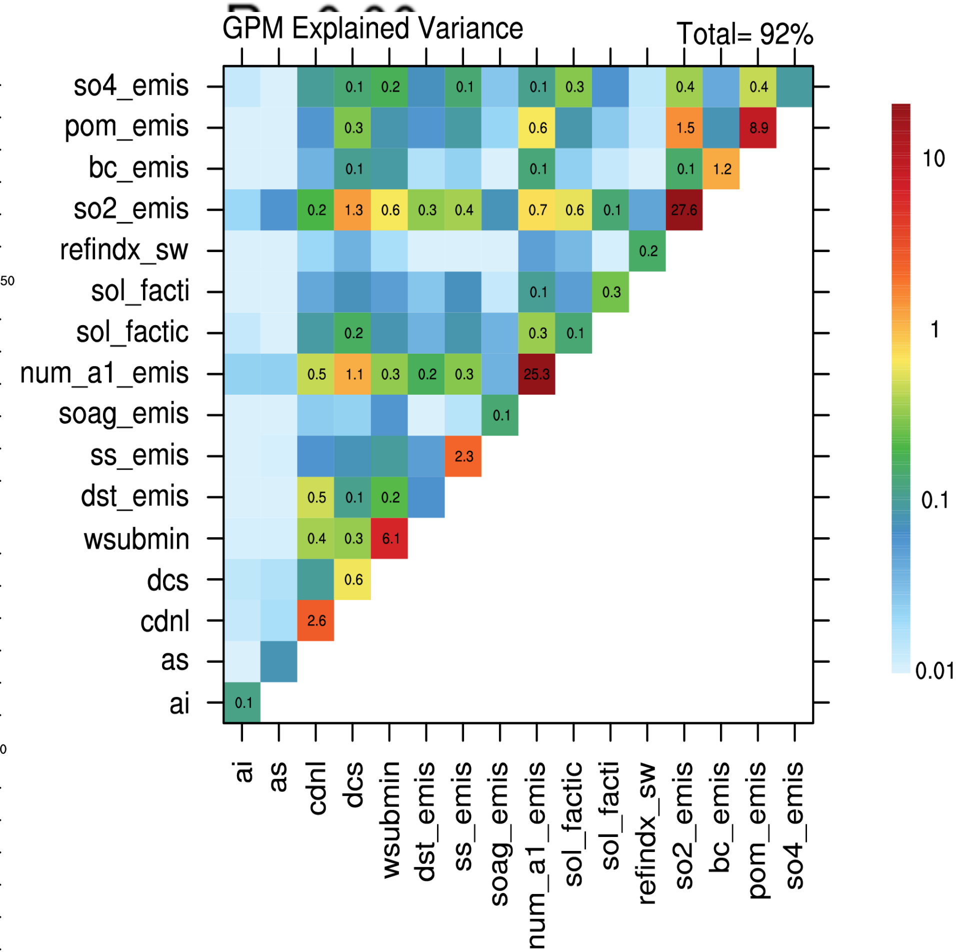
PARAMS	DESCRIPTION	LOW HIGH	DEFAULT
ai	fall speed parameter for cloud ice	350.0 - 1400.0	700
as	fall speed parameter for snow	5.86 - 23.44	11.72
dcs	autoconversion size threshold for ice to snow	100e-6 - 500e-6	400e-6
cdnl	cloud droplet number limiter	0.0 - 1e+6	0
wsubmin	minimum sub-grid vertical velocity	0.0 - 1.0	0.2
sol_factic	interstitial aerosol in convective wet removal tuning factor	0.2 - 0.8	0.4
sol_facti	solubility factor for cloud-borne aerosols in stratiform clouds	0.5 - 1	1.0
refindex_aer_sw	visible imaginary refractive index for dust	0.001 - 0.01	0.005
emis_so2_fact	emission scale factor for SO2	0 - 2	1
emis_so4f_fact	molar fraction of sulfur emission as sulfate	0 - 0.05	0.025
emis_bc_fact	emission scale factor for BC	0 - 3	1
emis_pom_fact	emission scale factor for POM	0 - 3	1
dust_emis_fact	dust emission scale factor	0.21 - 0.86	0.35
sst_emis_fact	sea salt emission scale factor	0.5 - 2.0	1.35
soag_emis_fact	SOA (g) emission scale factor	0.5 - 2.0	1.5
num_a1_surf_emis_fact	number emission scale factor for fossil fuel aerosol	0.3 - 5.0	1

Statistical surrogate model, or "emulator": Gaussian process model



The emulator explains most of the parametric uncertainty in the indirect effect



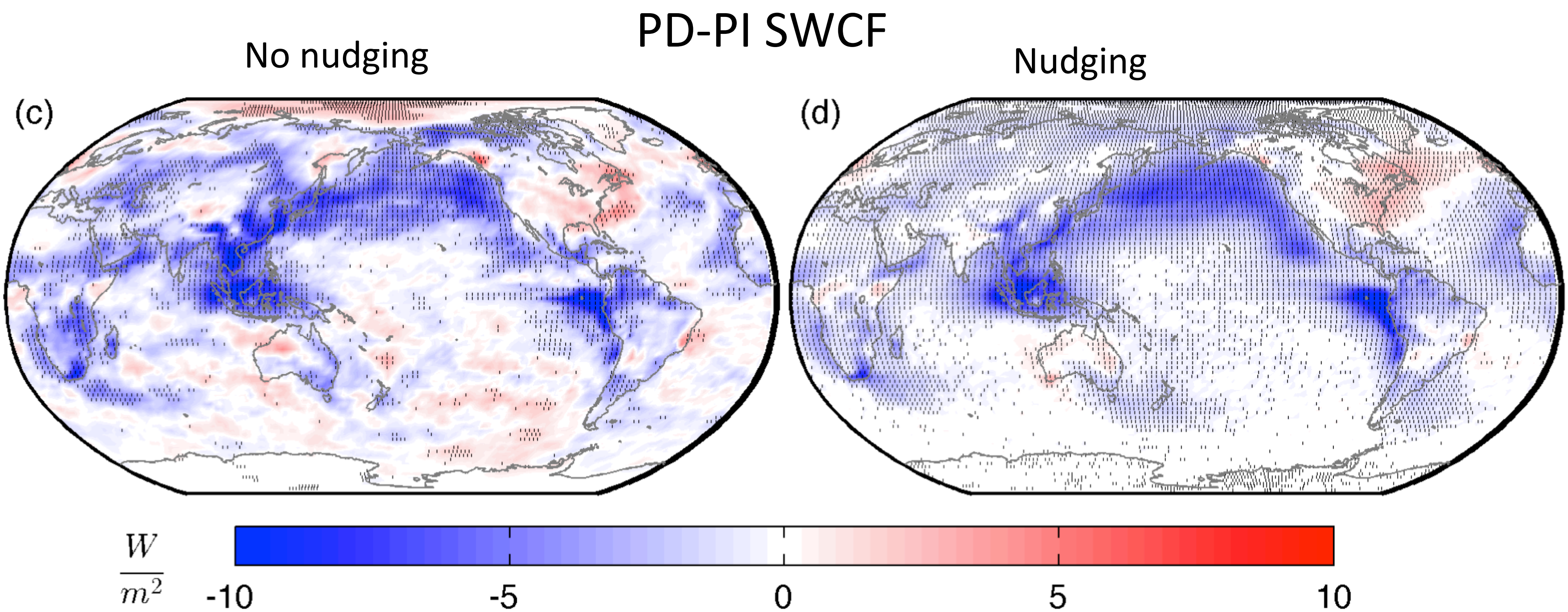


- Perturbing all 16 parameters simultaneously gives **noisy** results
- Cloud forcing ranges from **-0.4 to -2.4** W/m^2
- The emulator (GP) is able to extract the **main (single) effects** and the **joint (interaction) effects**

Using Nudging to Suppress Natural Variability

Kooperman et al. JGR, accepted

- Suppresses natural variability in L
- Permits evaluation on much shorter time and space scales



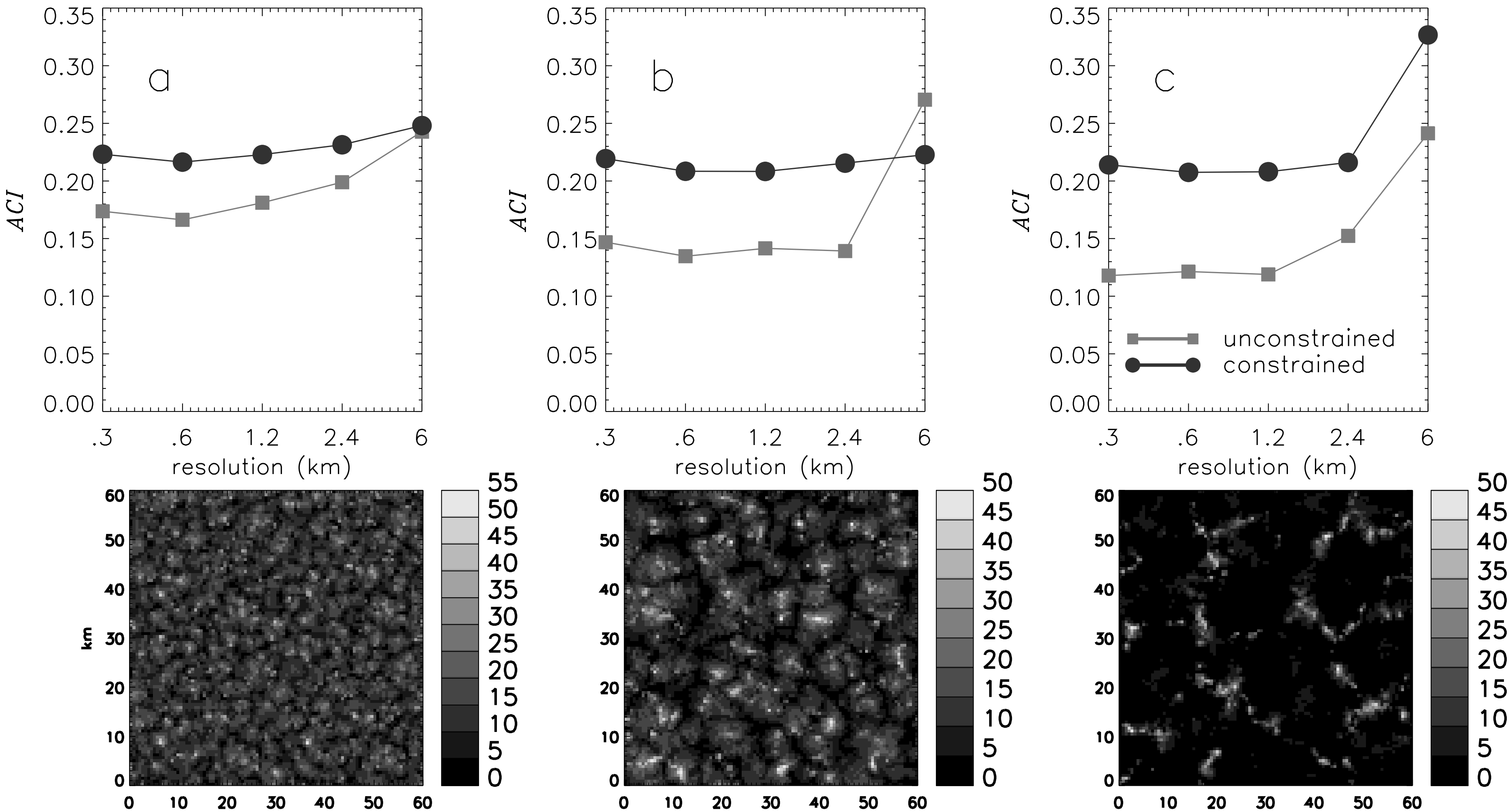
A Roadmap

- For local conditions, use measurements to evaluate
  - CCN
  - N_d sensitivity to CCN
  - r_e sensitivity to N_d (binned by L)
  - L sensitivity to N_d (binned by L)
  - POP (binned by L)

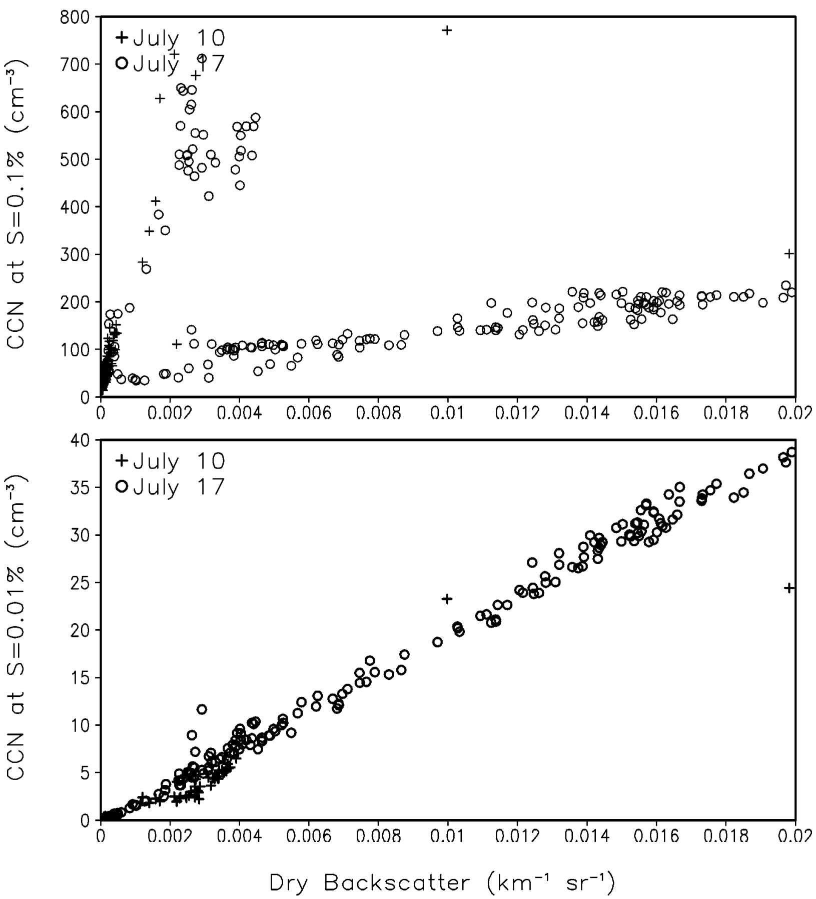
  simulated by SCM and CRM driven by boundary conditions from a global model nudged by analyzed winds

Issues of Scale

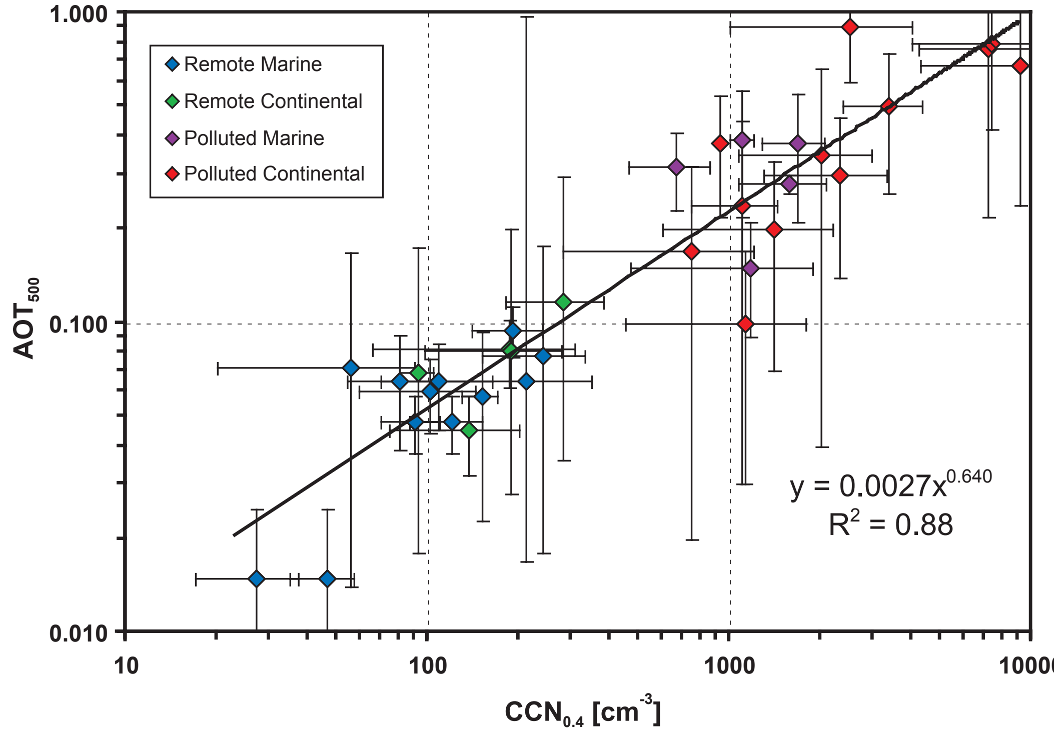
- McComiskey and Feingold (2012) : Averaging biases estimated AIE



Extinction and AOD as proxy for CCN



Ghan and Collins, JAOTech (2004)



Andrea, ACP (2009)

A Roadmap

- Separate dynamical and aerosol effects on simulated clouds by mixing aerosol and boundary conditions
  - High aerosol and meteorology for high aerosol
  - Low aerosol and meteorology for low aerosol
  - High aerosol and meteorology for low aerosol
  - Low aerosol and meteorology for high aerosol

A Roadmap

- Use CRMs to guide SCM improvements by selectively swapping physics
  - Microphysics
    - Bin vs double-moment bulk
    - Prognostic vs diagnostic rain
  - Turbulence
  - Grid size

A Roadmap

- After structural explanations for differences have been identified and remedied, quantify the uncertainty in the AIE using sensitivity experiments and an emulator

How can ARM data be used to constrain estimates?

- Use VAPS to quantify relationships amoung
  - CCN
  - N_d
  - L
- Analysis of long-term data to quantify factors in the AIE budget and separate aerosol effects from dynamical effects
- Intensive field experiments
  - Past and current
    - MASE, VOCALS, ISDAC, Azores, MAGIC
  - Future
    - MAGIC2, Azores, …