Aerosol Indirect Effects in the PNNL-MMF Multi-scale Aerosol-Climate Model

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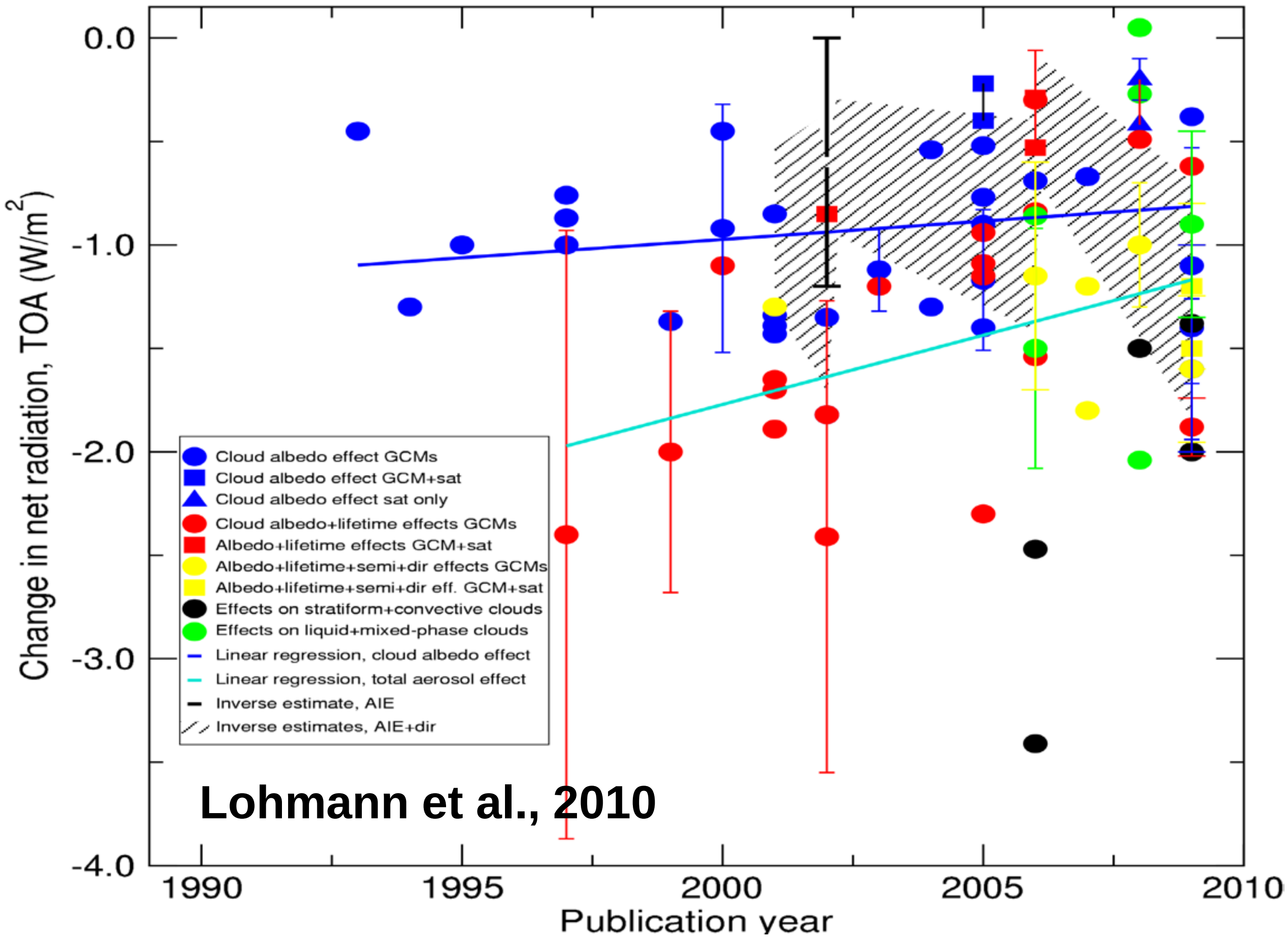
Published estimates of aerosol indirect effects



Challenges in Conventional Climate models

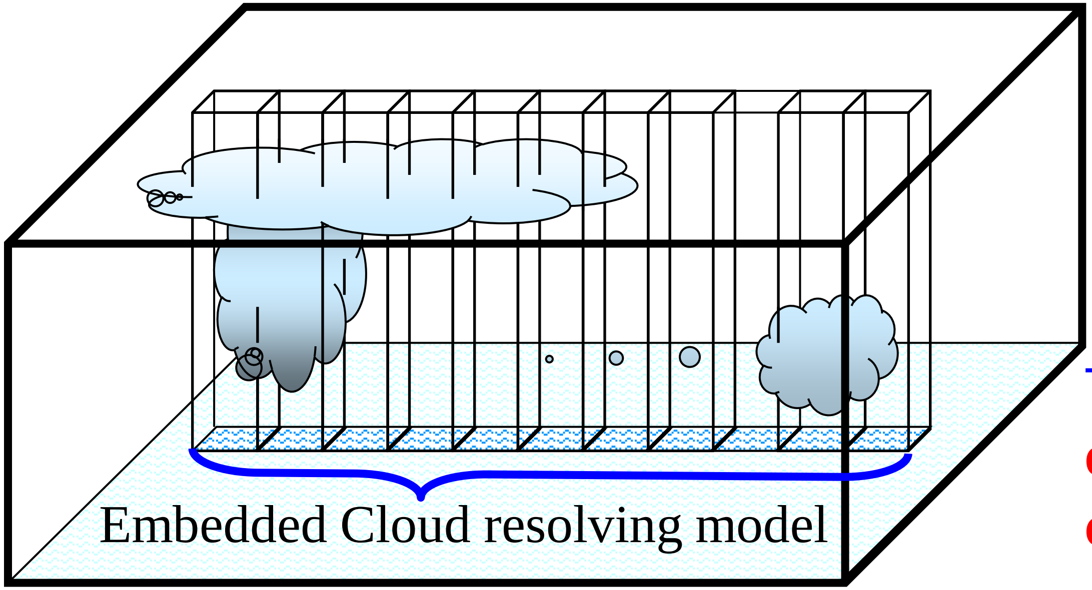
- The treatment of most aerosol and cloud processes in conventional GCMs is highly parameterized and therefore may not be accurate.

- Convective clouds are the most problematic.
  - Aerosol effects on convective clouds are not represented or only crudely represented.
  - Convective processes strongly affect aerosols, and parameterizations of aerosol processing by convective clouds are highly uncertain.

Our solution: A multi-scale aerosol-climate model (PNNL-MMF)

Multi-scale Modeling Framework Approach (MMF) (Super-parameterization)

A Global Climate Model column



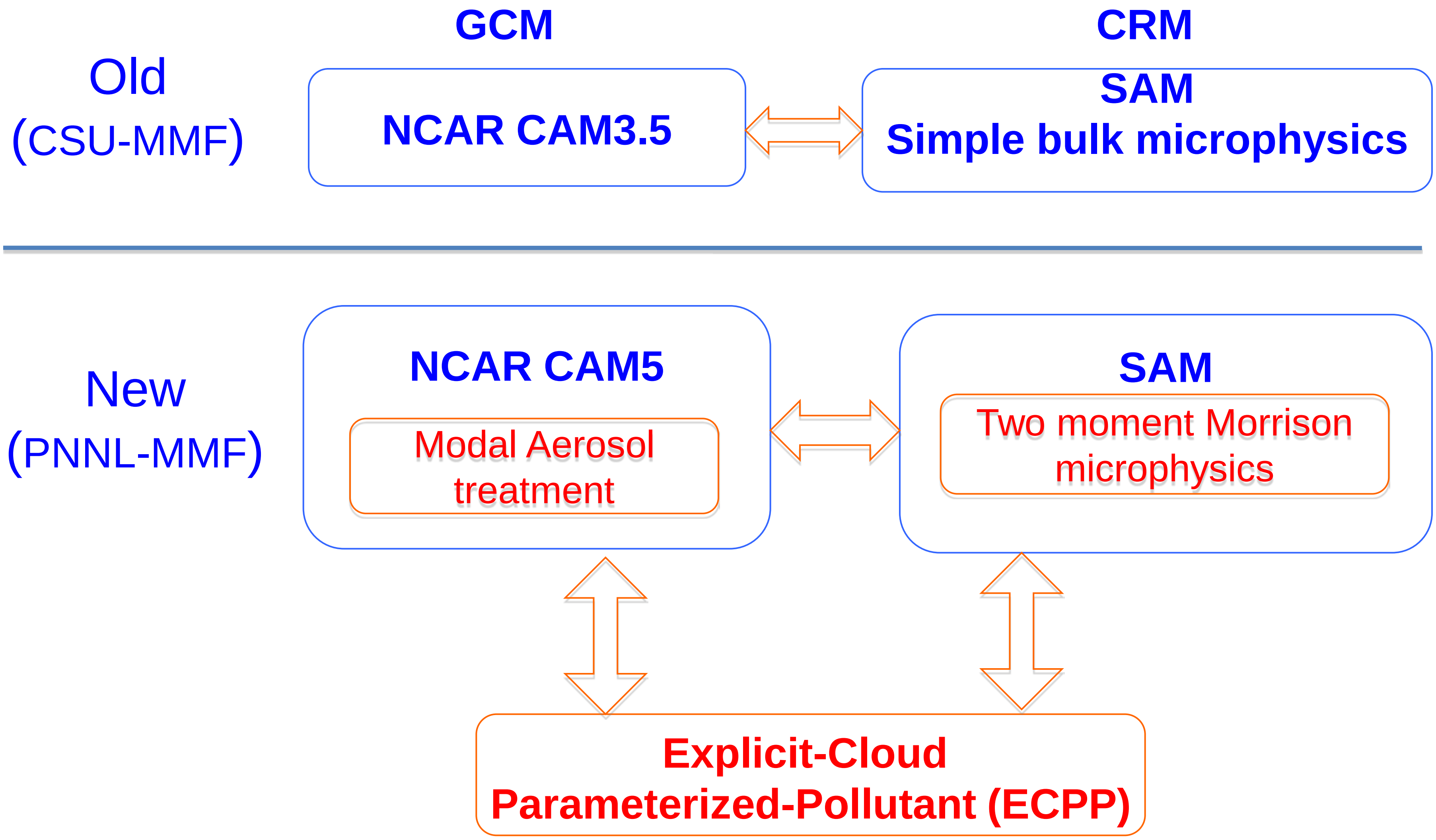
Grabowski, 2001; Khairoutdinov and Randall, 2001.

The MMF approach permits **explicit simulations of deep convective clouds**.

Limitations in the original MMF:

- No aerosol and chemical processes.
- Oversimplified microphysics in CRM.

We have extended the original MMF to treat aerosol-cloud interactions for the first time

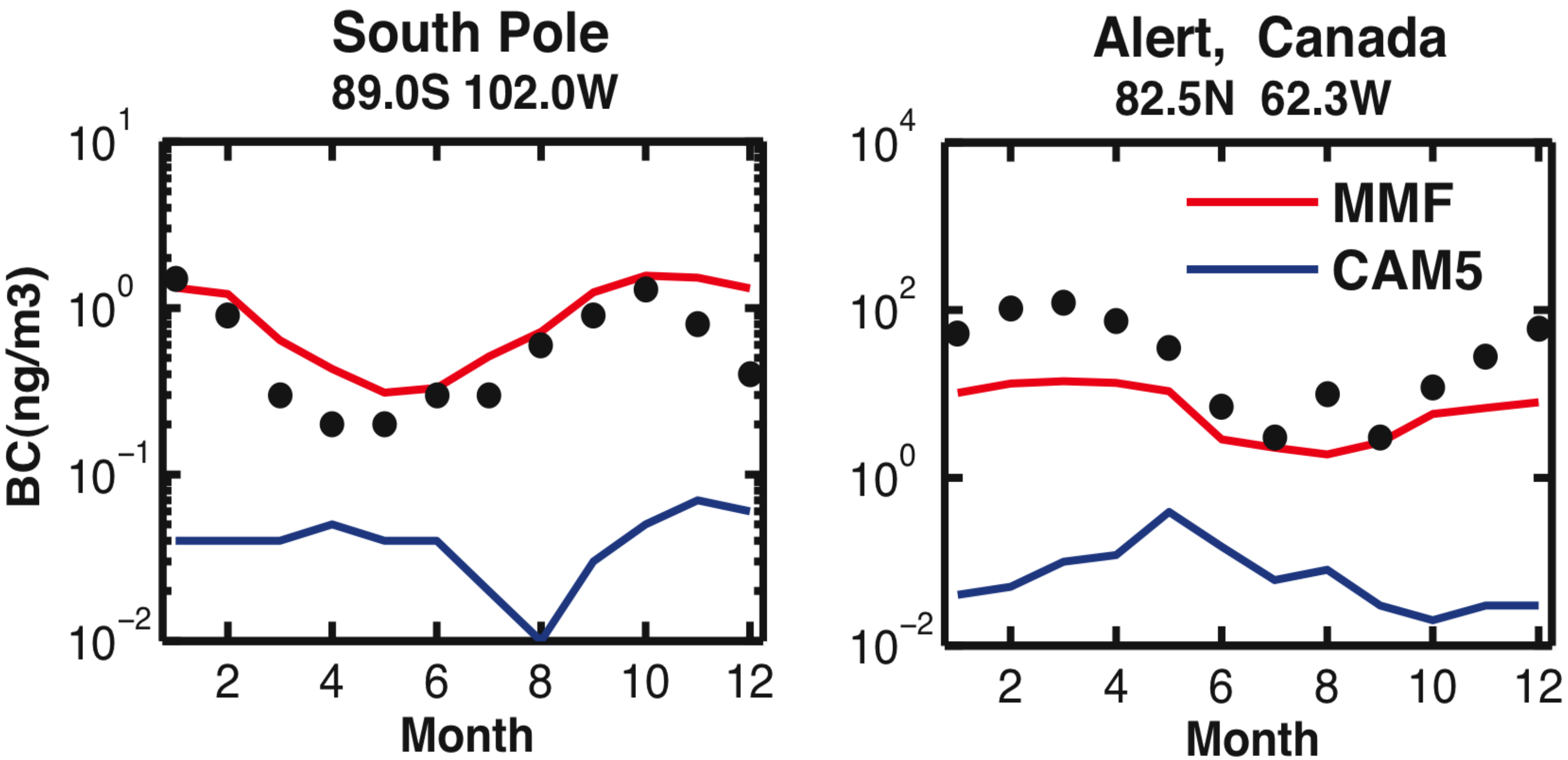


Some unique features of the PNNL-MMF

- Aerosol processing by convective clouds is explicitly treated by using convective cloud fraction, mass flux and vertical velocity in convective updraft from CRM statistics.
- Aerosol water uptake is calculated at each CRM grid point, which accounts for the subgrid variation in relative humidity within each GCM grid cell.
- Droplet activation is calculated at each CRM grid point, using CRM-scale vertical velocity.
- Aerosol effects on both stratiform and convective clouds (and precipitation) are explicitly treated.

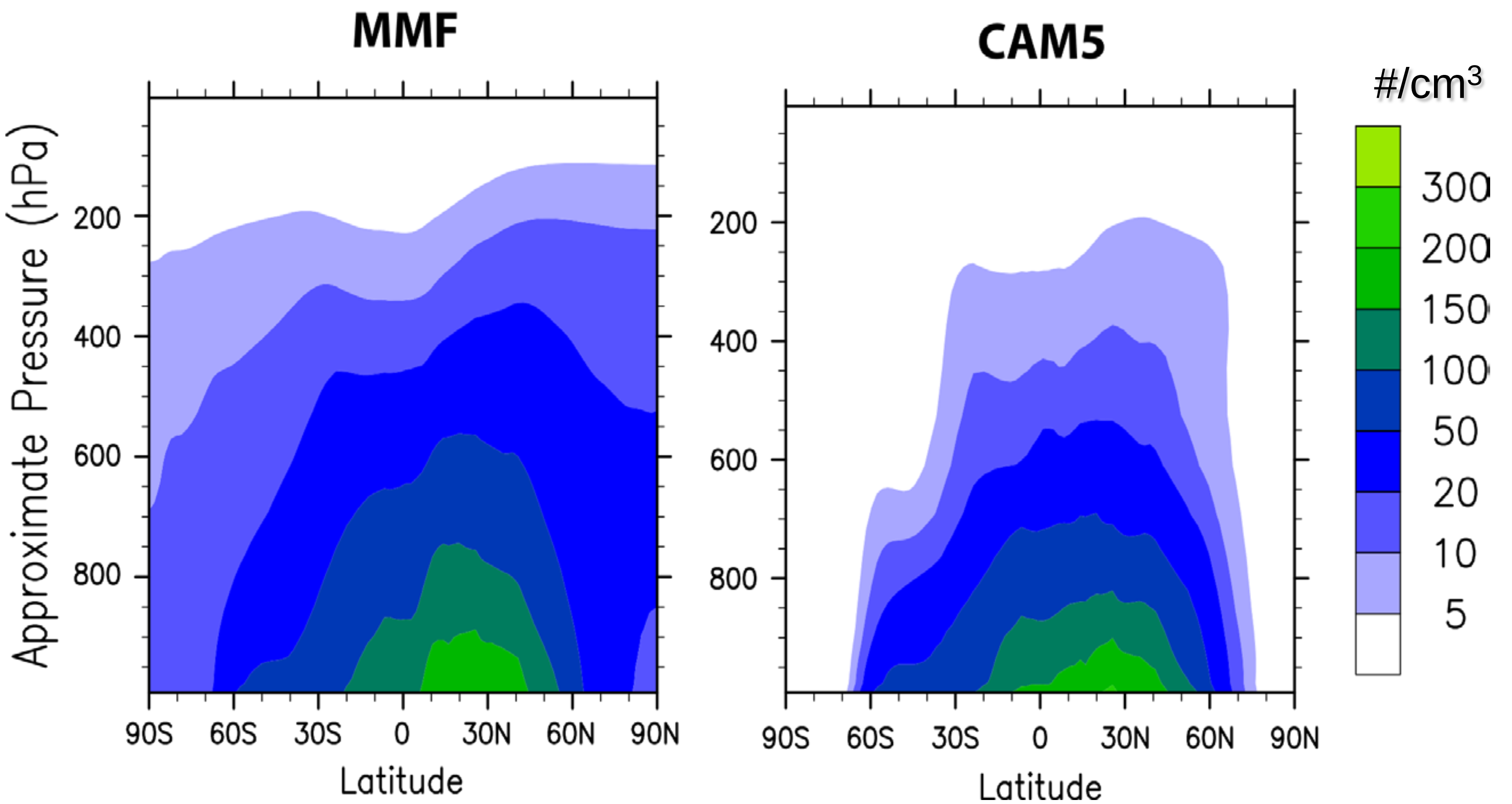
(See Wang et al., 2011, *Geosci. Model Dev.*; Wang et al., 2011, *Atmos. Chem. Phys. Discuss*. for details)

Monthly BC concentrations in the polar regions



- ➢ BC concentrations in MMF agree better with observations.
- ➢ MMF simulates a better seasonal cycle

CCN concentration at 0.1% Supersaturation (Annual)



Anthropogenic aerosol effects

	MMF (PD)	MMF (PD-PI)	CAM5(PD)	CAM5(PD–PI)
Reff (μm)	9.2	**-0.52**	9.0	**-0.46**
LWP (g/m^2)	55.9	**2.11**	48.4 (30.0)	**3.93**
SWCF(W/m^2)	-50.5	**-0.77**	-50.1	**-1.79**

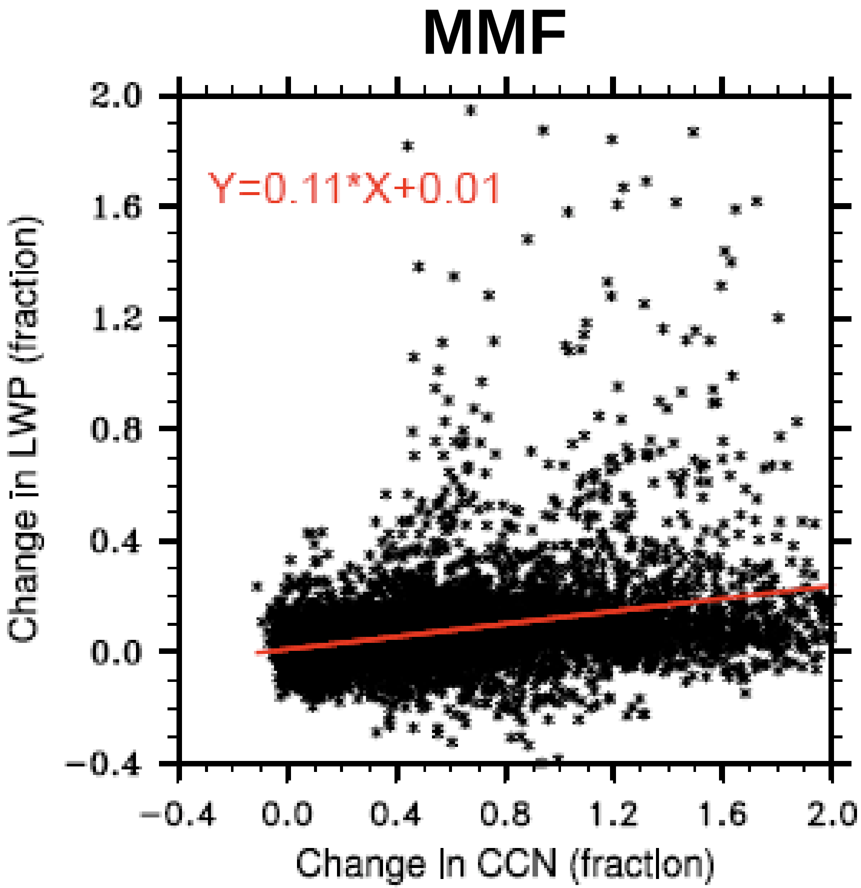
PD: present day; PI: preindustrial

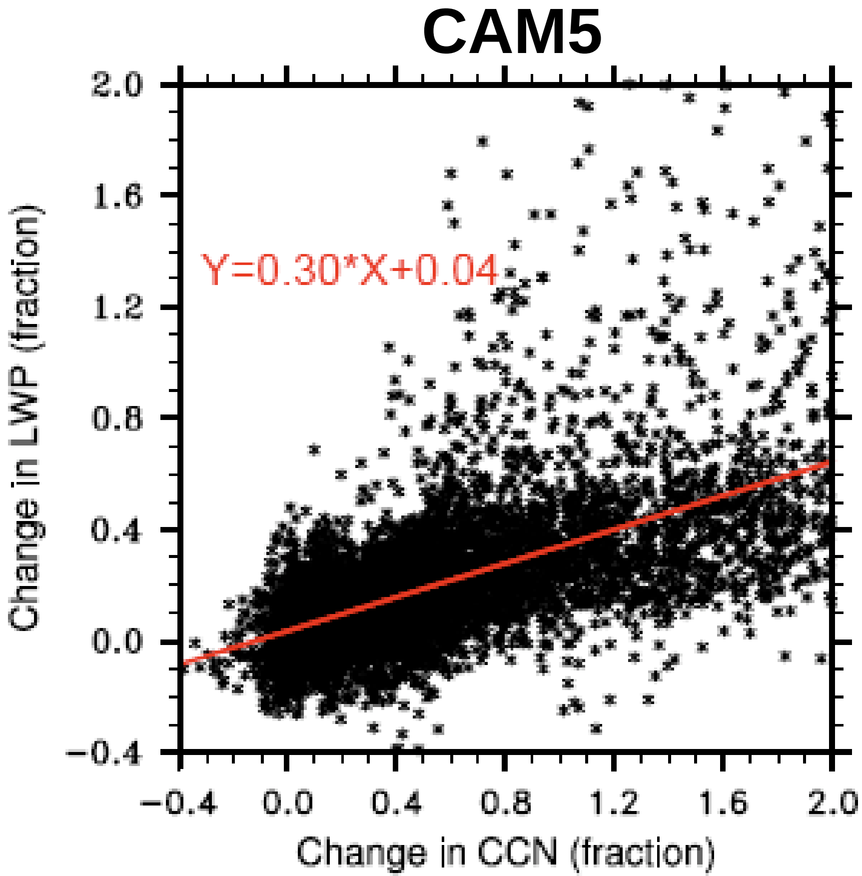
Reff: cloud-top droplet effective radius;

LWP: liquid water path; SWCF: shortwave cloud forcing.

The smaller forcing in the MMF is attributed to its smaller increase in LWP from PI to PD: 3.9% in the MMF vs. 15.6% in the large-scale clouds in CAM5 (four times).

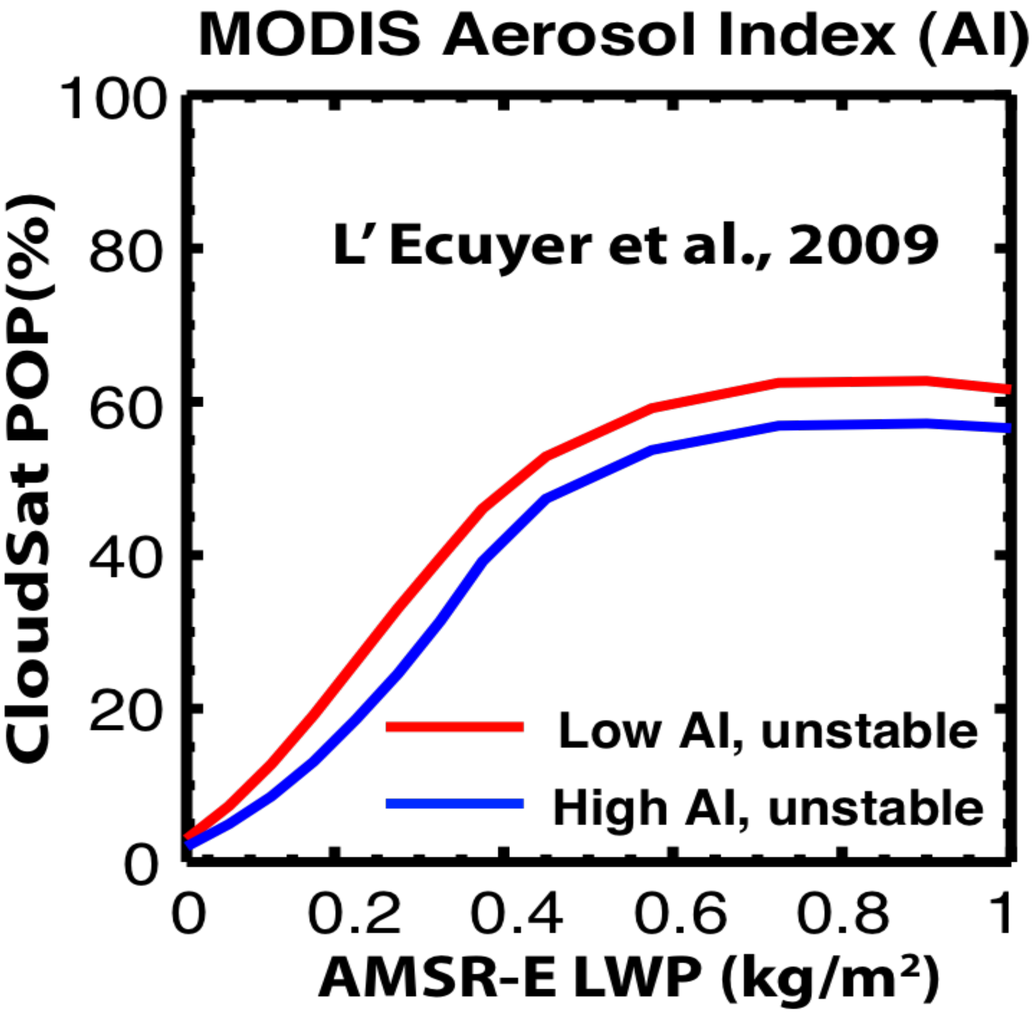
Relative changes in CCN vs. relative changes in LWP: (PD-PI)/PI





The response in LWP to a given CCN perturbation in CAM5 is about 3 times that in the MMF.

Probability of Precipitation (POP) for shallow clouds



At a given LWP:

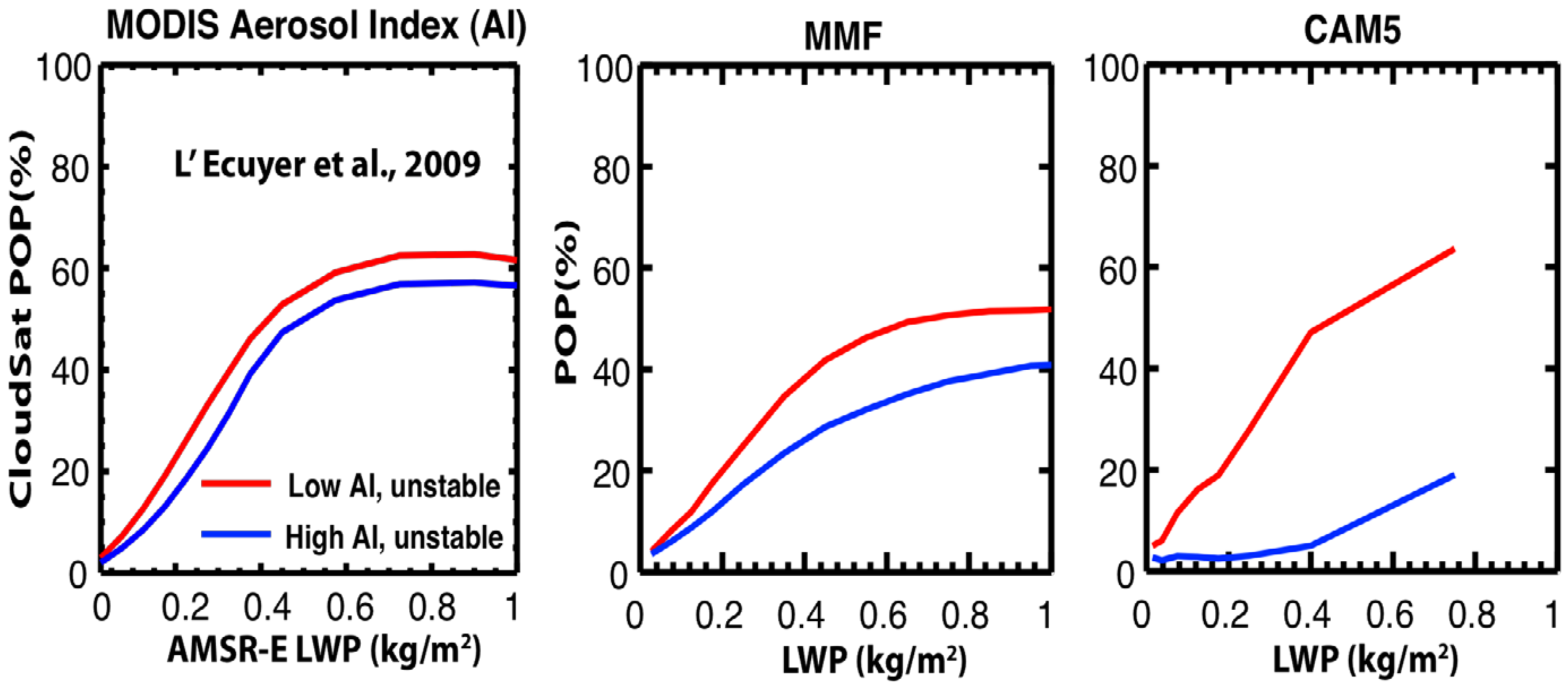
$POP = N_{rain}/N_c$

$N_{c:}$ the number of cloud events.

$N_{rain:}$ the number of precipitating events.

Satellite data:
high Aerosol → low POP

POP for shallow clouds in PD simulations

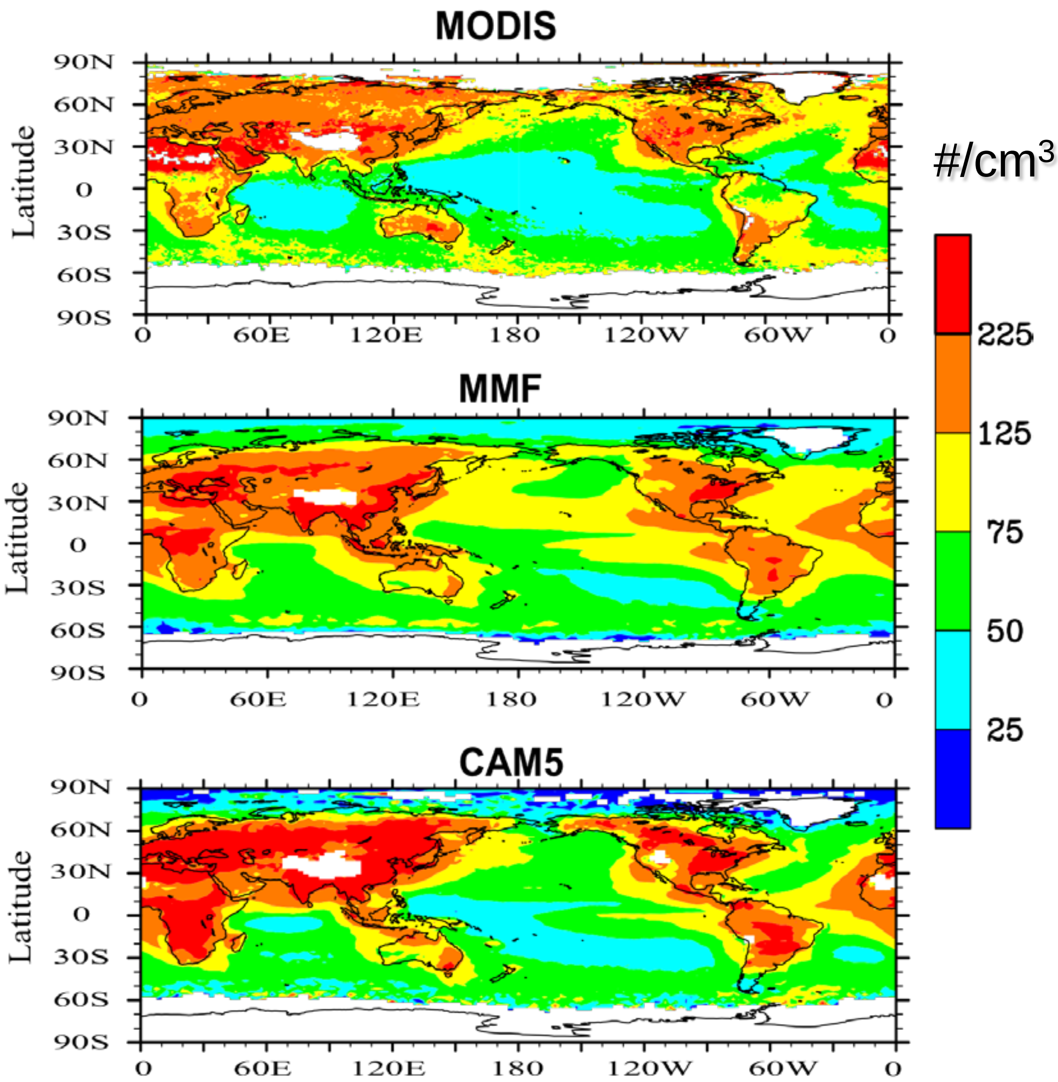


- ➢The MMF agrees better with satellite observations.
- ➢The smaller difference in POP between the low AI and high AI in the MMF is consistent with its smaller increase in LWP from PI to PD.

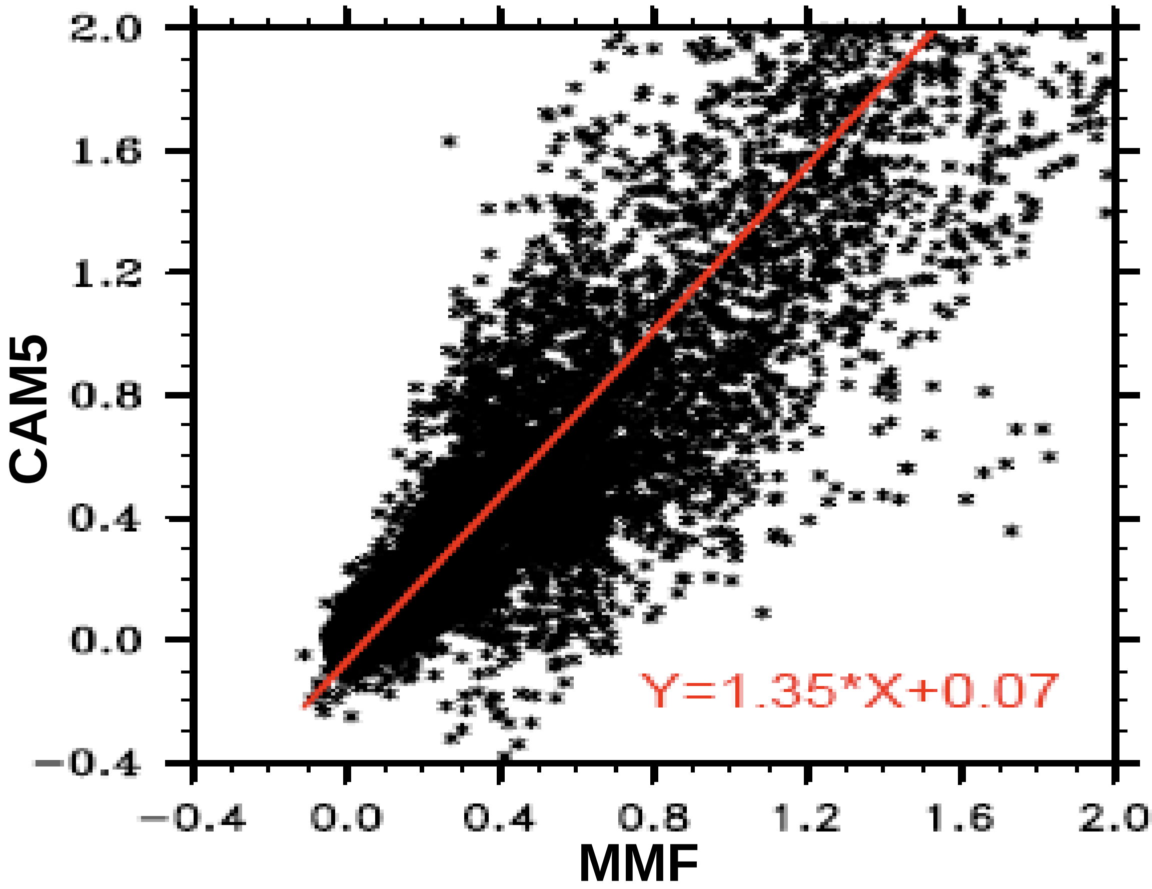
Summary

- The PNNL-MMF explicitly simulates aerosol-cloud interactions on clouds and precipitation for the first time.
- The simulated change in shortwave cloud forcing from anthropogenic aerosols in the MMF is much smaller than that in CAM5 (-0.77 W/m^2 vs. -1.79 W m^{-2}), which is attributed to its much smaller increase in LWP (3.9% vs. 15.6%).
- The MMF predicts much smaller differences in POP between the low AI and high AI than CAM5, which agrees better with satellite observations and is consistent with its much smaller increase in LWP.
- Further improvements on low clouds and ice nucleation are needed.

Cloud top droplet number concentrations (warm, low level, and liquid clouds only) (PD)



Relative changes in CCN (ΔCCN): (PD-PI)/PI



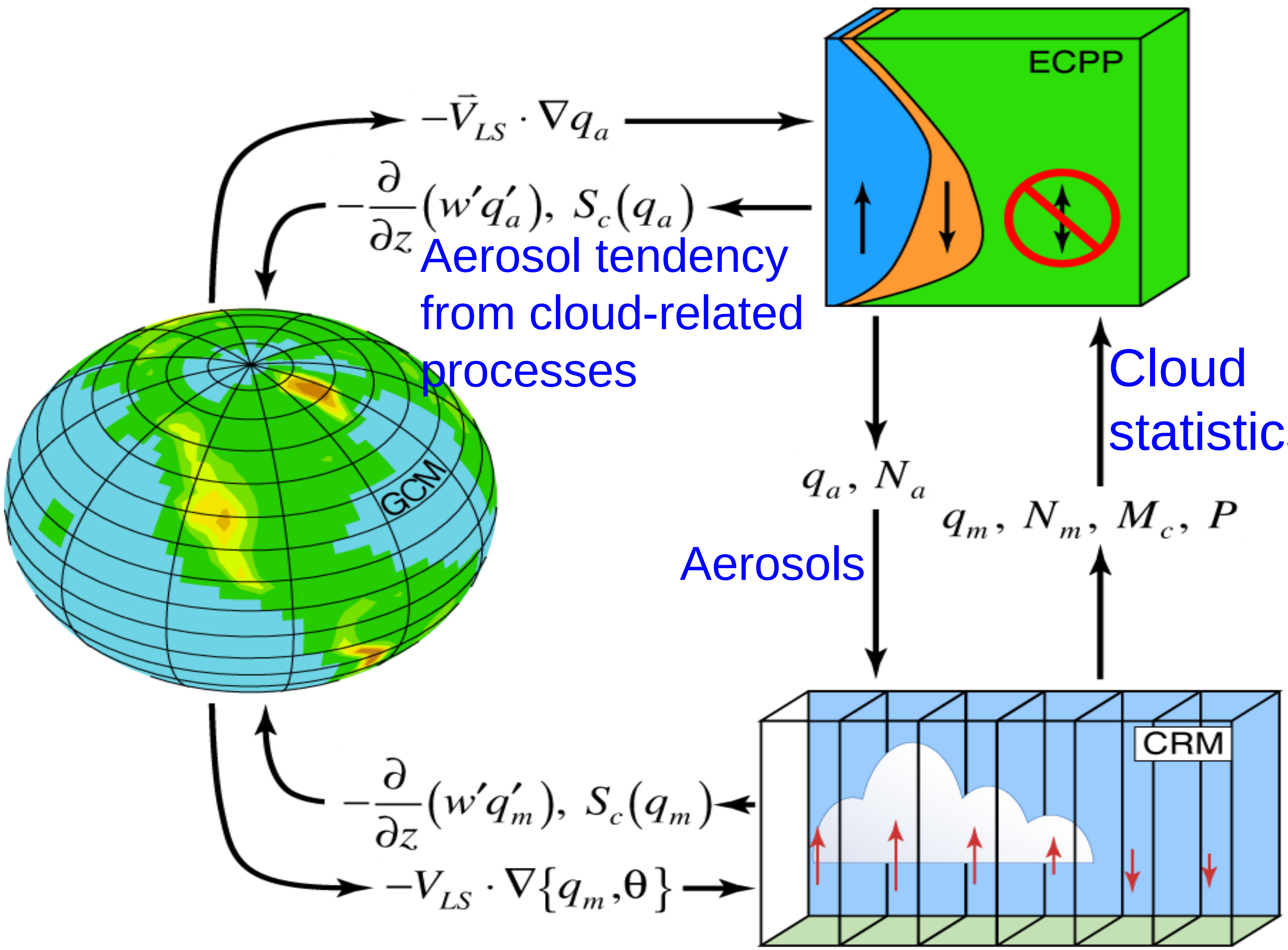
Aerosol lifetime

	MMF(PD/PI)	CAM5 (PD/PI)
Sulfate	1.01	1.12
BC	0.93	1.09

- ΔCCN in CAM5 is about 1.35 times that in the MMF.
- The larger ΔCCN in CAM5 is partly caused by larger increases in aerosol lifetime from PI to PD.

Explicit-Cloud Parameterized-Pollutant (ECPP) Approach (Gustafson et al., 2008)

Use cloud statistics to drive a physically-based treatment of aerosol and trace gas processing by clouds, which replaces conventional treatment of these processes in CAM5.



Model configuration

The PNNL-MMF:

- GCM component: NCAR CAM5

  - finite volume dynamical core;

  - 1.9x2.5 horizontal resolution and 30 vertical levels.

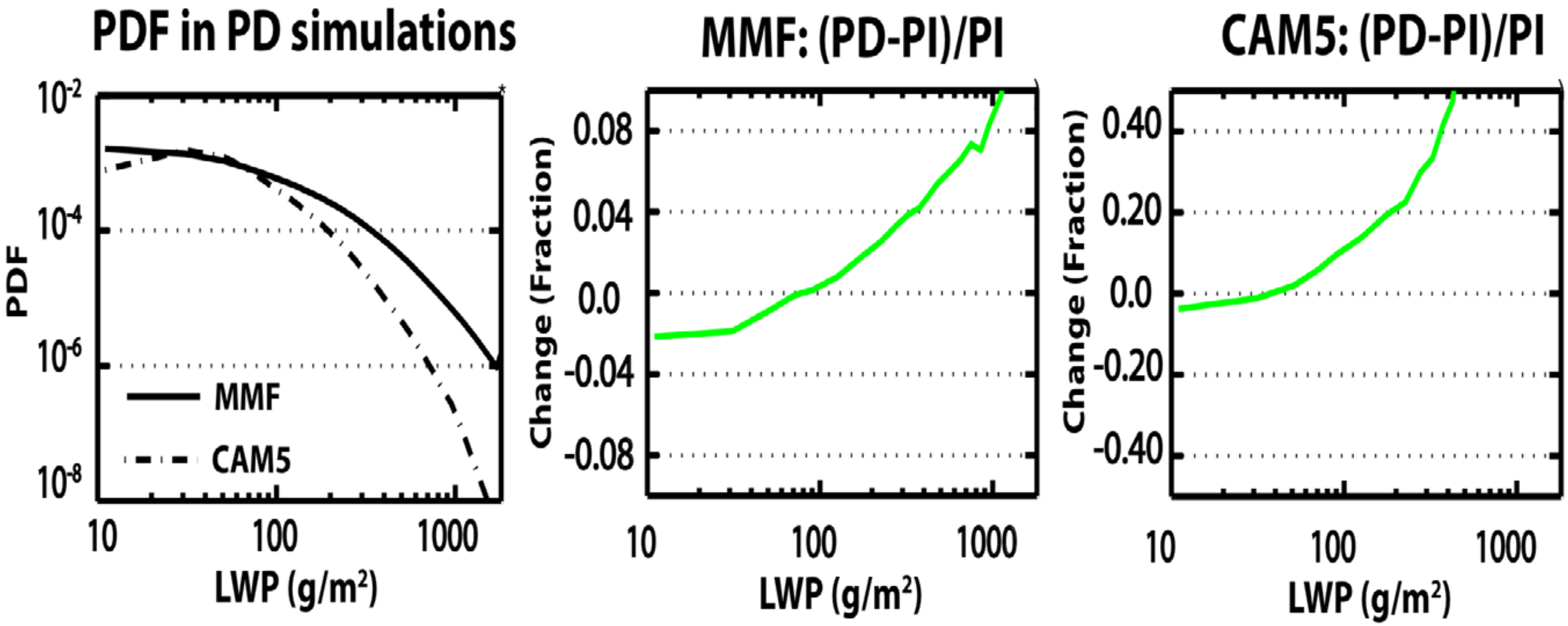
  - IPCC AR5 emissions: present day (PD) and preindustrial emissions (PI), 3-year simulation each;

- CRM component: SAM

  - 32 CRM columns at 4 km resolution.

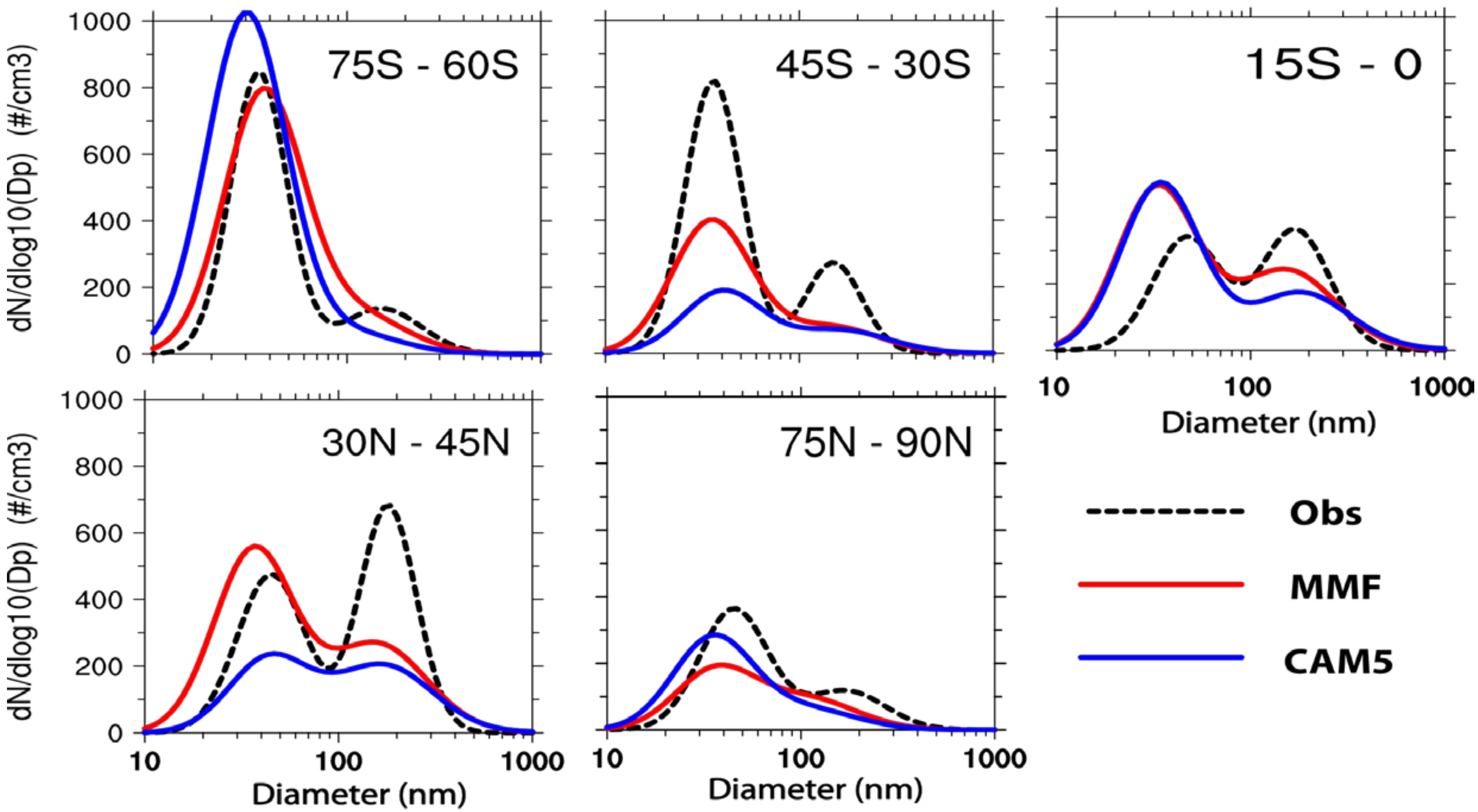
CAM5 : the same as the MMF, but using its own cloud parameterizations (no aerosol indirect effect on convective clouds), 5-year simulation each.

Relative changes in the probability distribution of LWP: (PD – PI)/PI



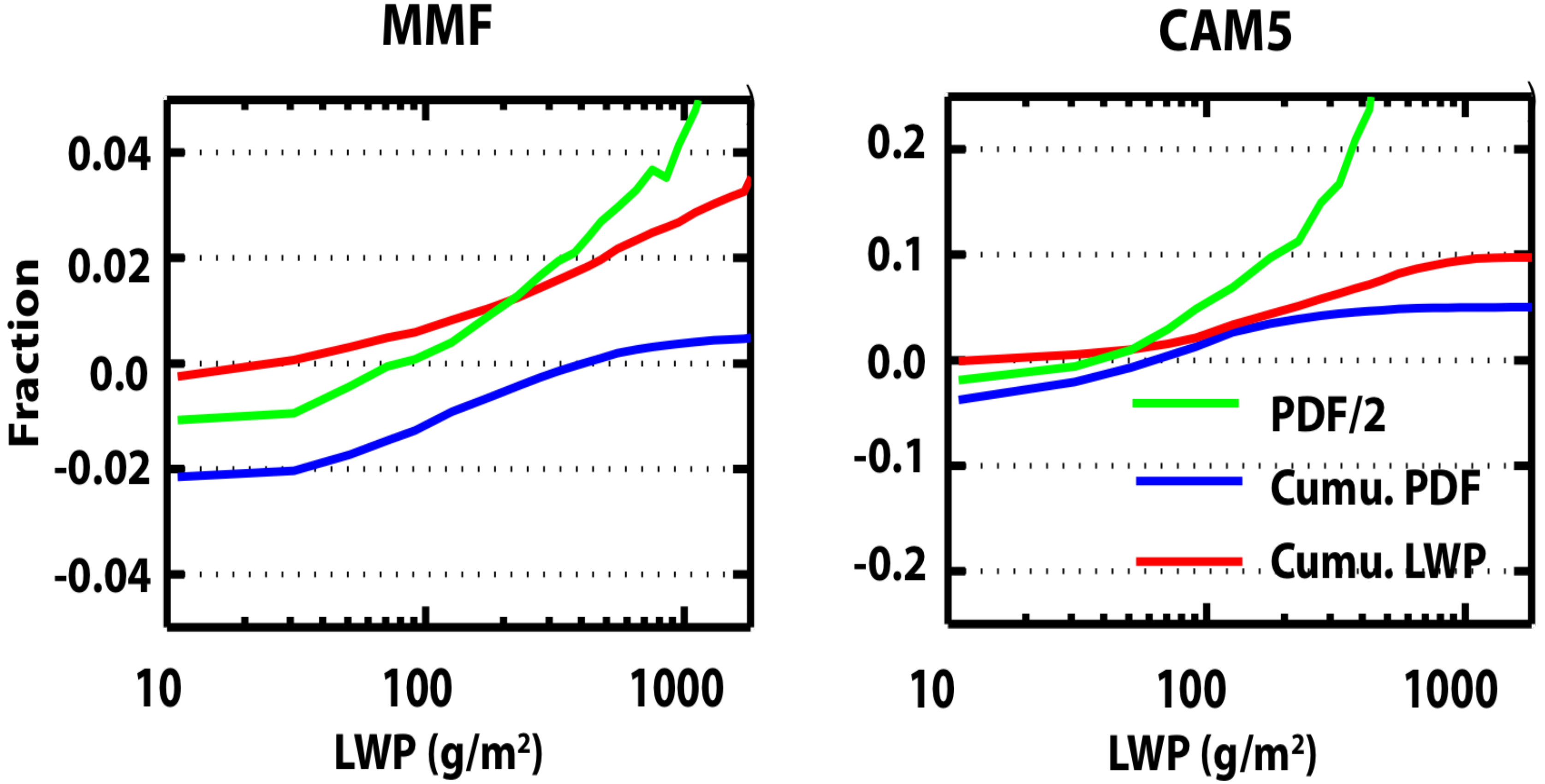
- ➢ Cloud fraction of thin clouds decreases, while that of thick clouds increases.
- ➢ The MMF produces much smaller change in LWP than CAM5.

Aerosol size distributions in the marine boundary layer (Observations: Heintzenberg et al., 2001)



MMF results are similar with those in CAM5, and both are in qualitative agreement with observations.

Relative changes in the probability distribution of liquid water path: (PD – PI)/PI



MMF produces a weaker change in liquid water path.

Changes in Cloud top droplet effective radius changes (PD –PI)