Constraining the influence of natural variability to improve estimates of global aerosol indirect effects in a nudged version of the Community Atmosphere Model (CAM5)

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How do sub-micron particles suspended in the atmosphere affect clouds, climate, & life on Earth?

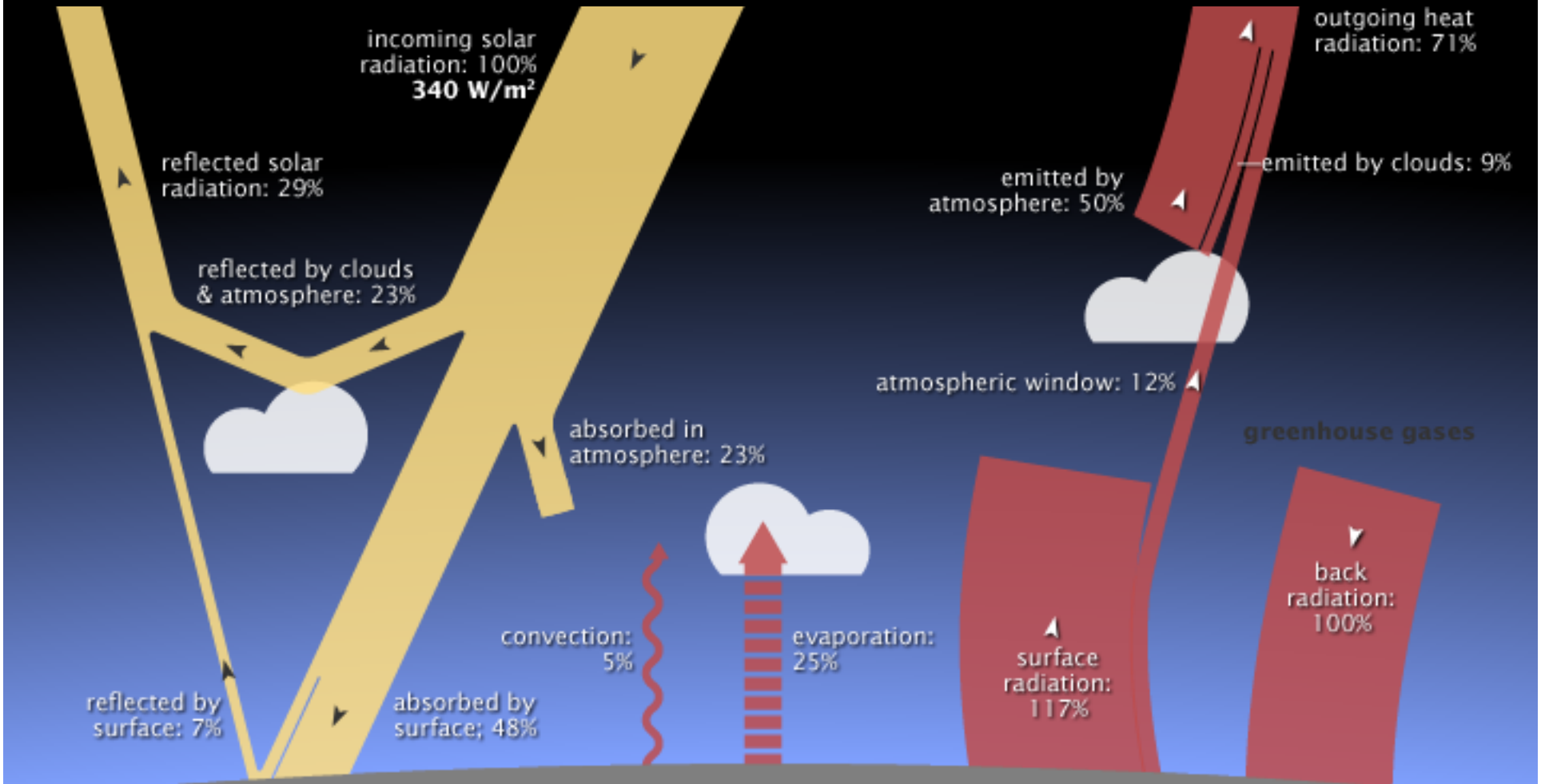
Background:

1. **How aerosol particles impact clouds and climate.**
2. **Representation of aerosol-cloud interactions in climate models.**

Improving global estimates of aerosol indirect effects by:

1. **Controlling for the influence of natural variability.**
2. **Explicitly resolving cloud scale aerosol interactions.**

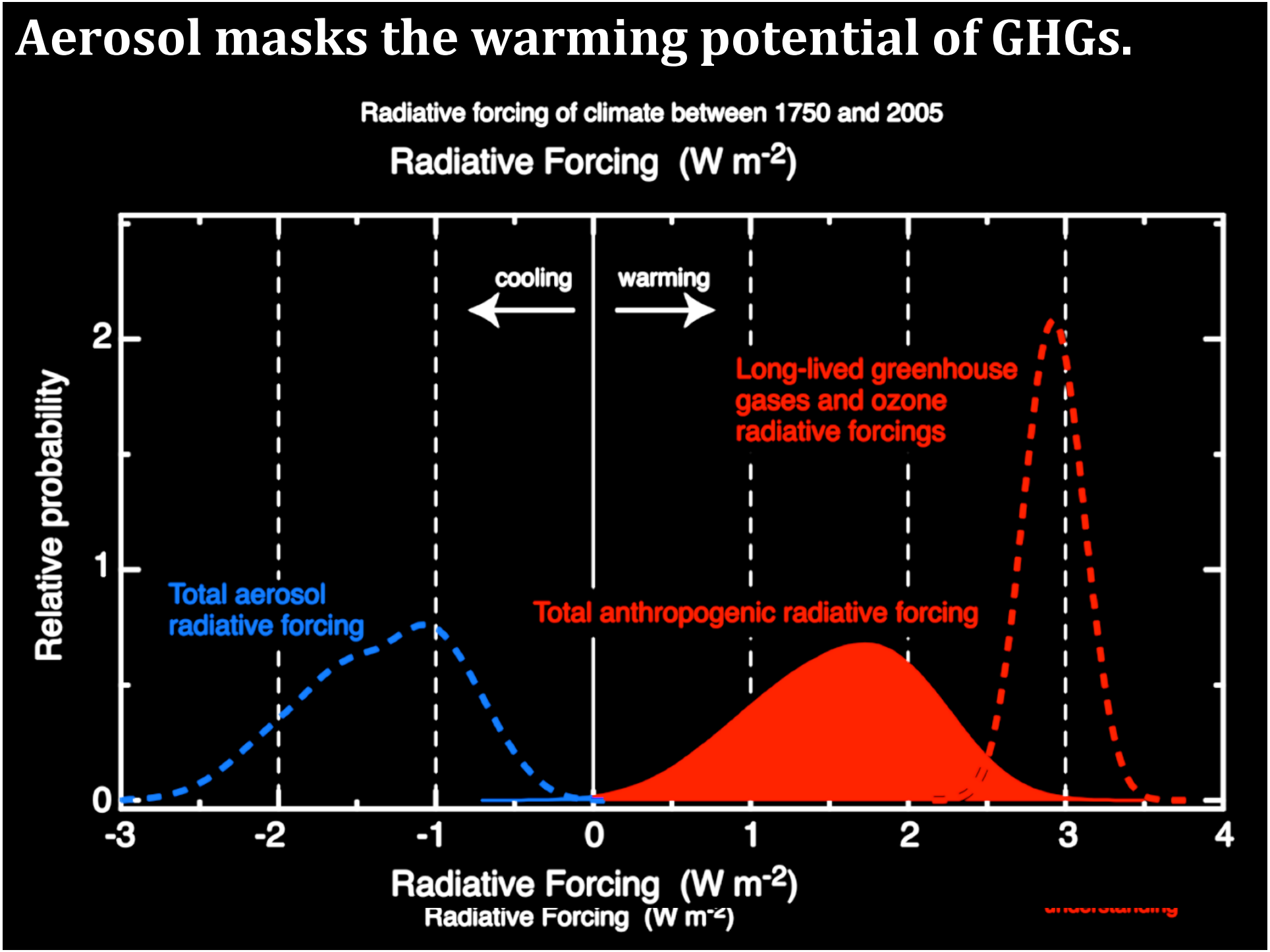
Clouds and aerosol particles reflect incoming solar radiation and trap longwave radiation.



Convective heating balances radiative equilibrium
Cloud shortwave albedo and longwave warming
Aerosol shortwave scattering and absorption

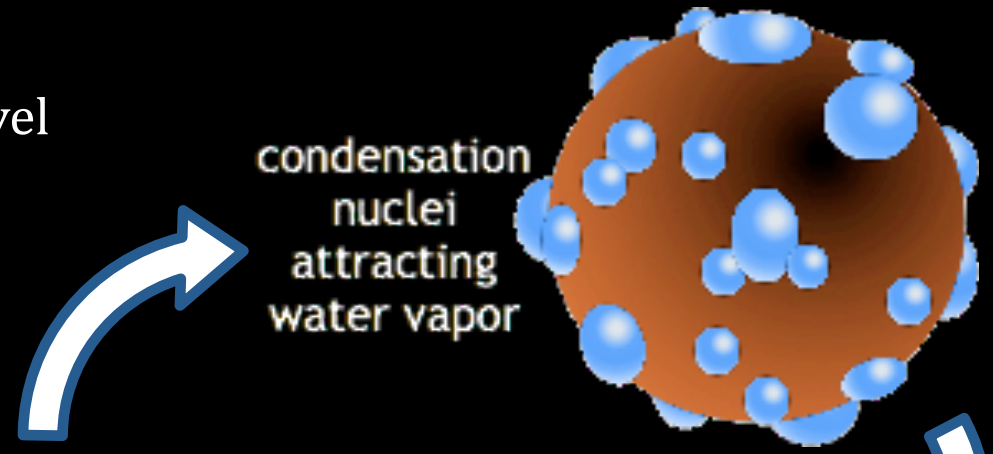
Trenberth et al. 2009

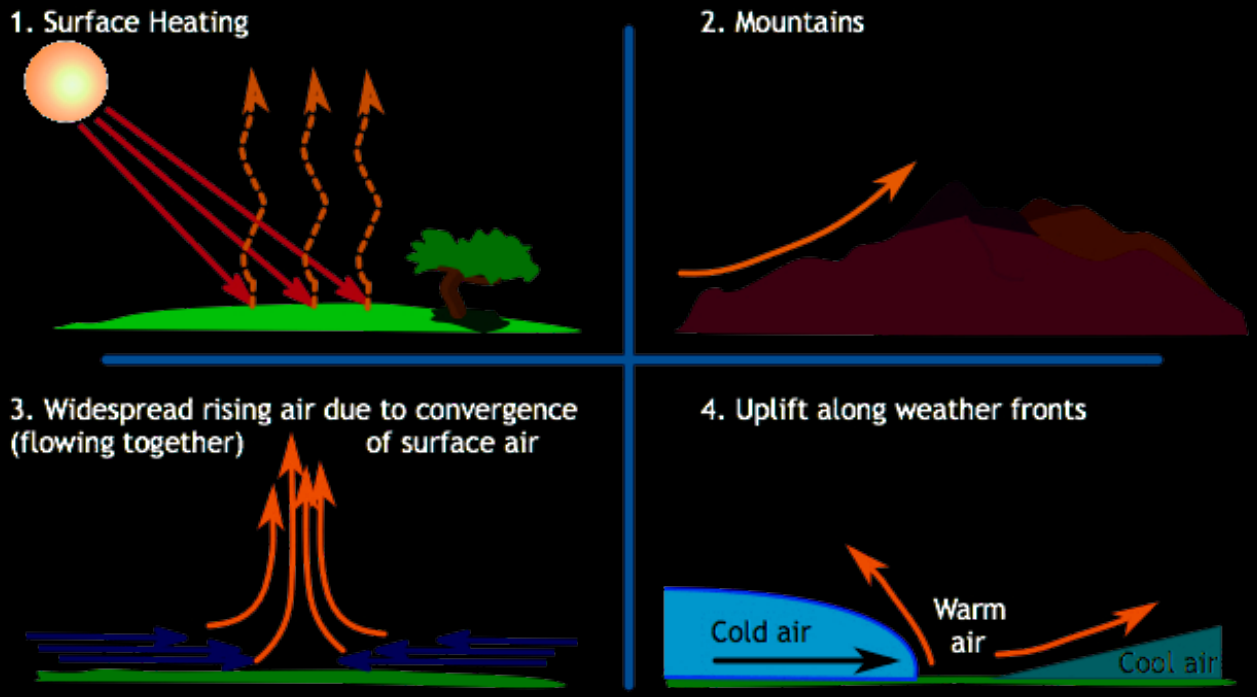
Aerosol masks the warming potential of GHGs.

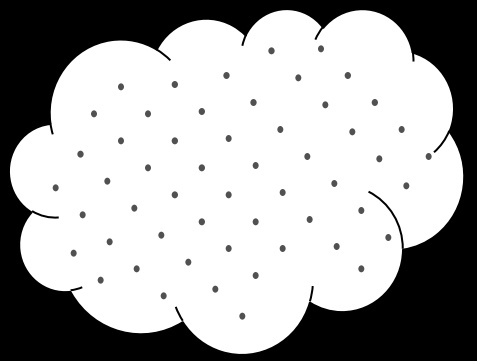


Cloud droplets form when water condenses onto aerosol particles.

- Warm-moist air rises
- Supersaturation reaches critical level
- Aerosol particles activate as cloud droplets
- Depends on SS, aerosol size, composition, & concentration

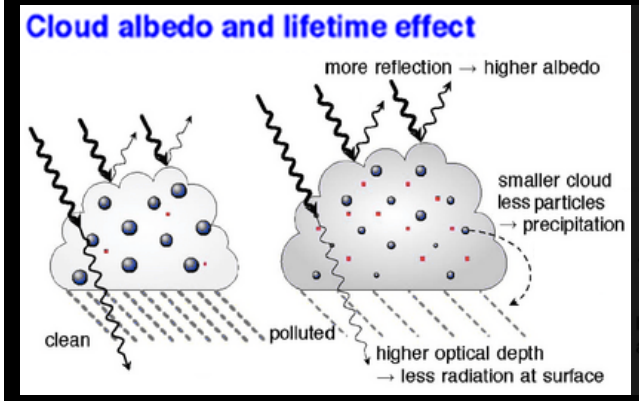


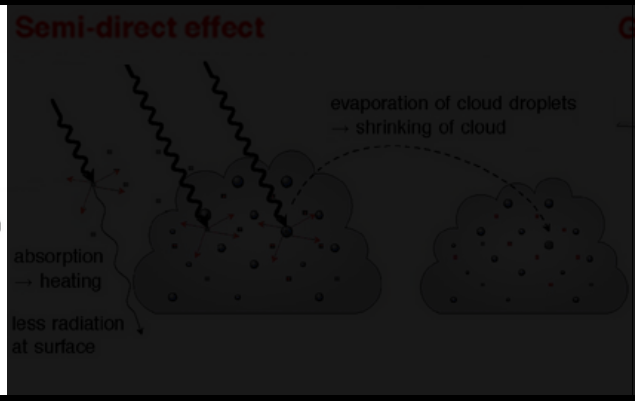


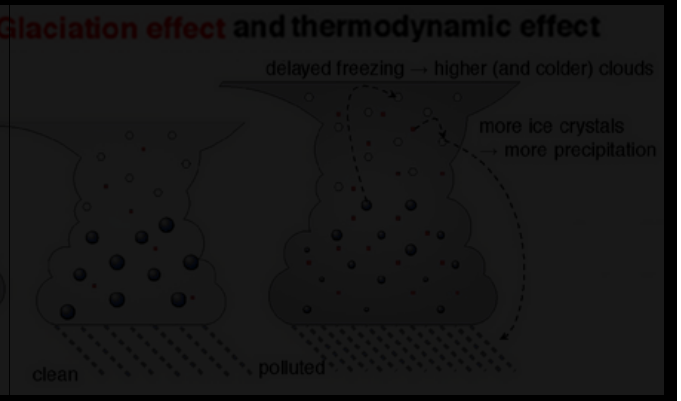


CMMAP

Human aerosol modifies cloud albedo & lifetime.



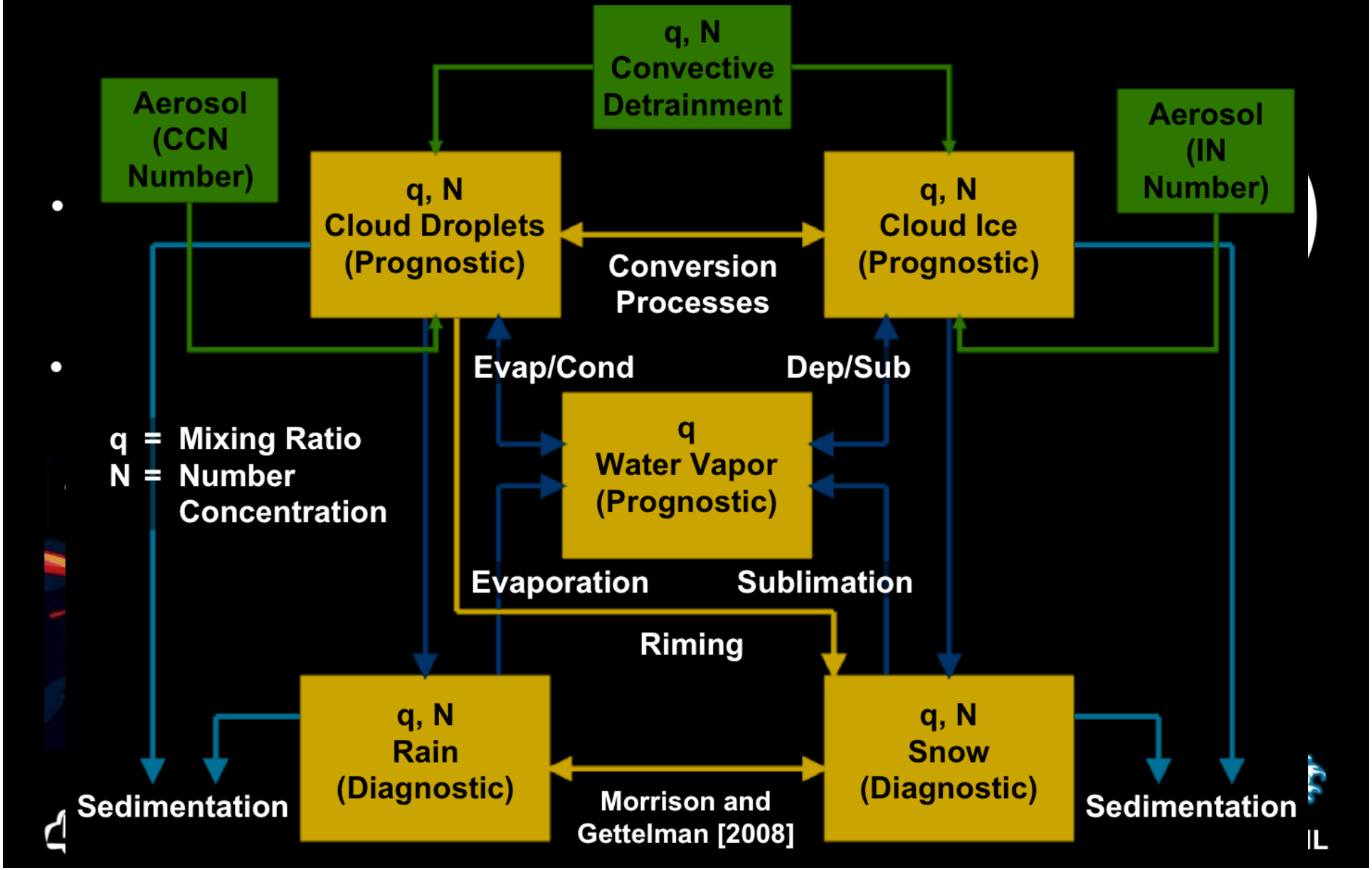




Effect	Clouds	Description	Sign	Understanding
1st effect albedo	All	For the same cloud water or ice content more but smaller cloud particles reflect more solar radiation	-	Low
2nd effect lifetime	All	Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime	-	Very low
Semi-direct	All	Absorption of solar radiation by absorbing aerosols affects static stability and the surface energy budget, and may lead to an evaporation of cloud particles	+	Very low
Glaciation	Mixed	An increase in IN increases the precipitation efficiency	+	Very low
Thermo-dynamic	Mixed	Smaller cloud droplets delay freezing causing super-cooled droplets to extend to colder temperatures	+/-	Very low
Convective invigoration	Deep	Smaller drops reach super-cooled levels, freeze onto ice and melt at lower levels, releasing more heat aloft and absorbing more heat below --> Greater upward heat transport, invigorating convection and rainfall.	+	Very low

IPCC AR4

Since the IPCC AR4 new aerosol and cloud physics have been added to GCMs (CAM5).



Cloud lifetime effects involves changes in the cloud lifecycle and can't be estimated in one simulation.

Aerosol Indirect Effects = Present-Day – Pre-Industrial

Cloud Forcing = All-Sky – Clear-Sky

NASA

Quasi Forcing

vs.

Pure Forcing

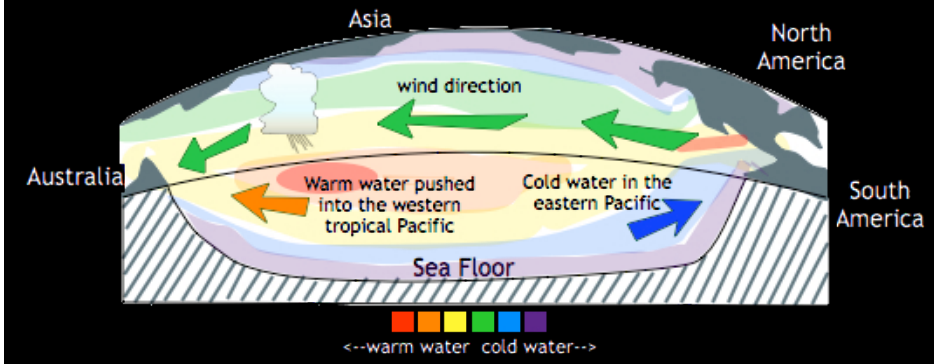
"This approach gives a 'quasi forcing,' which differs from a pure forcing in that fields other than the initially perturbed quantity have been allowed to vary."

- Rotstayn and Penner, 2001

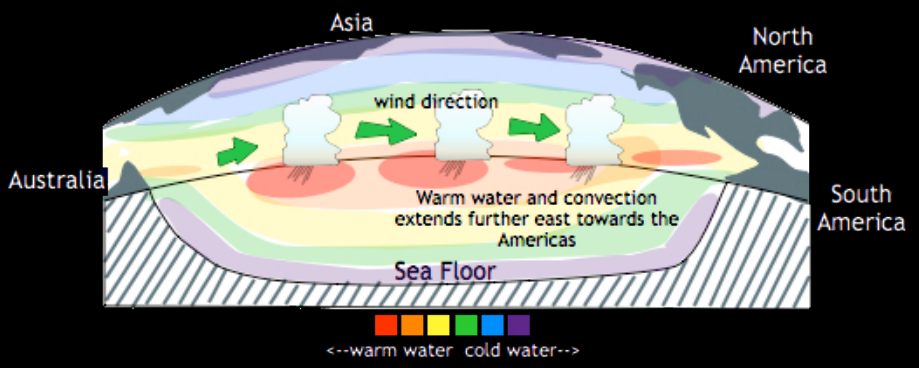
Estimates of cloud forcing are complicated by unconstrained natural variability.

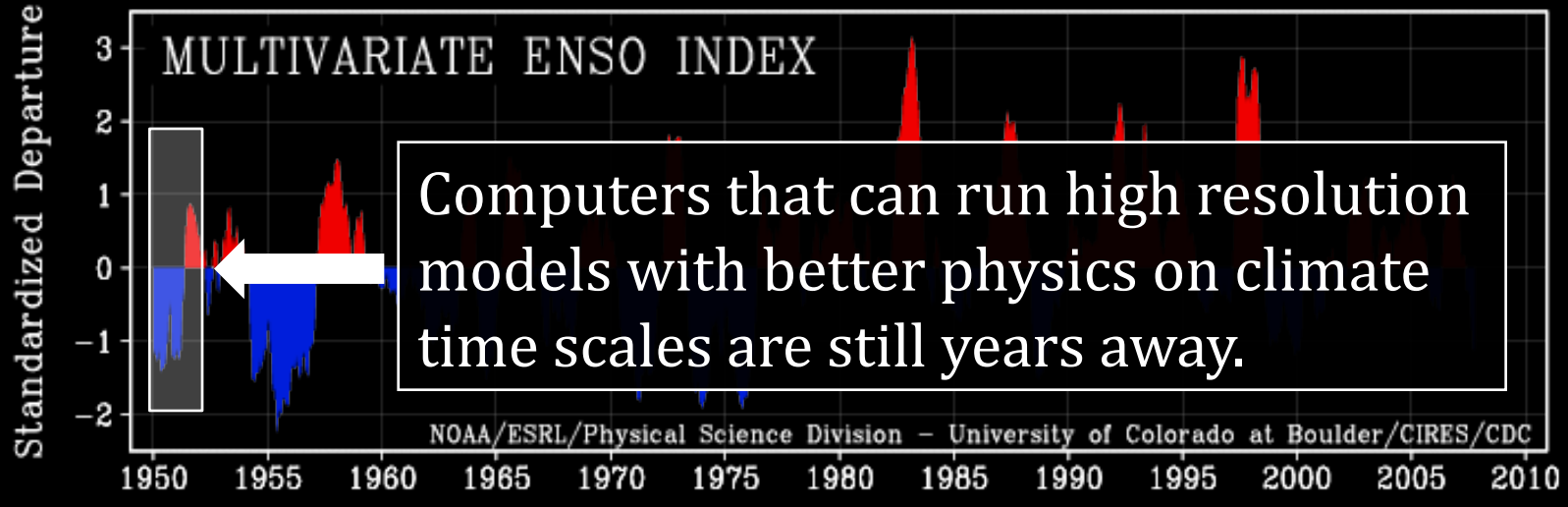
Inter-annual variability:

Normal Conditions



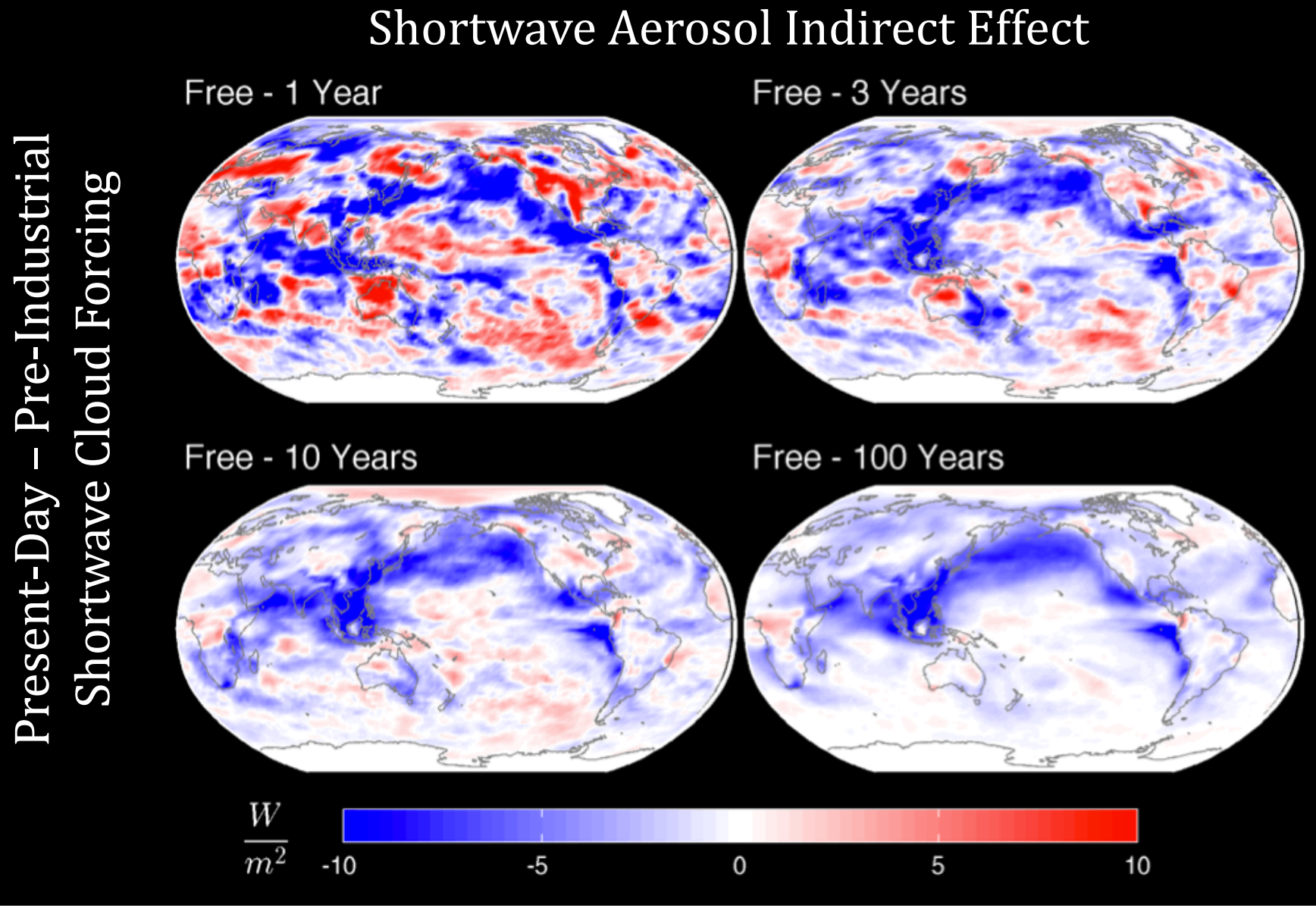
El Nino Conditions





Computers that can run high resolution models with better physics on climate time scales are still years away.

Even with prescribed SSTs, we still need to average over many years to reduce internal variability.

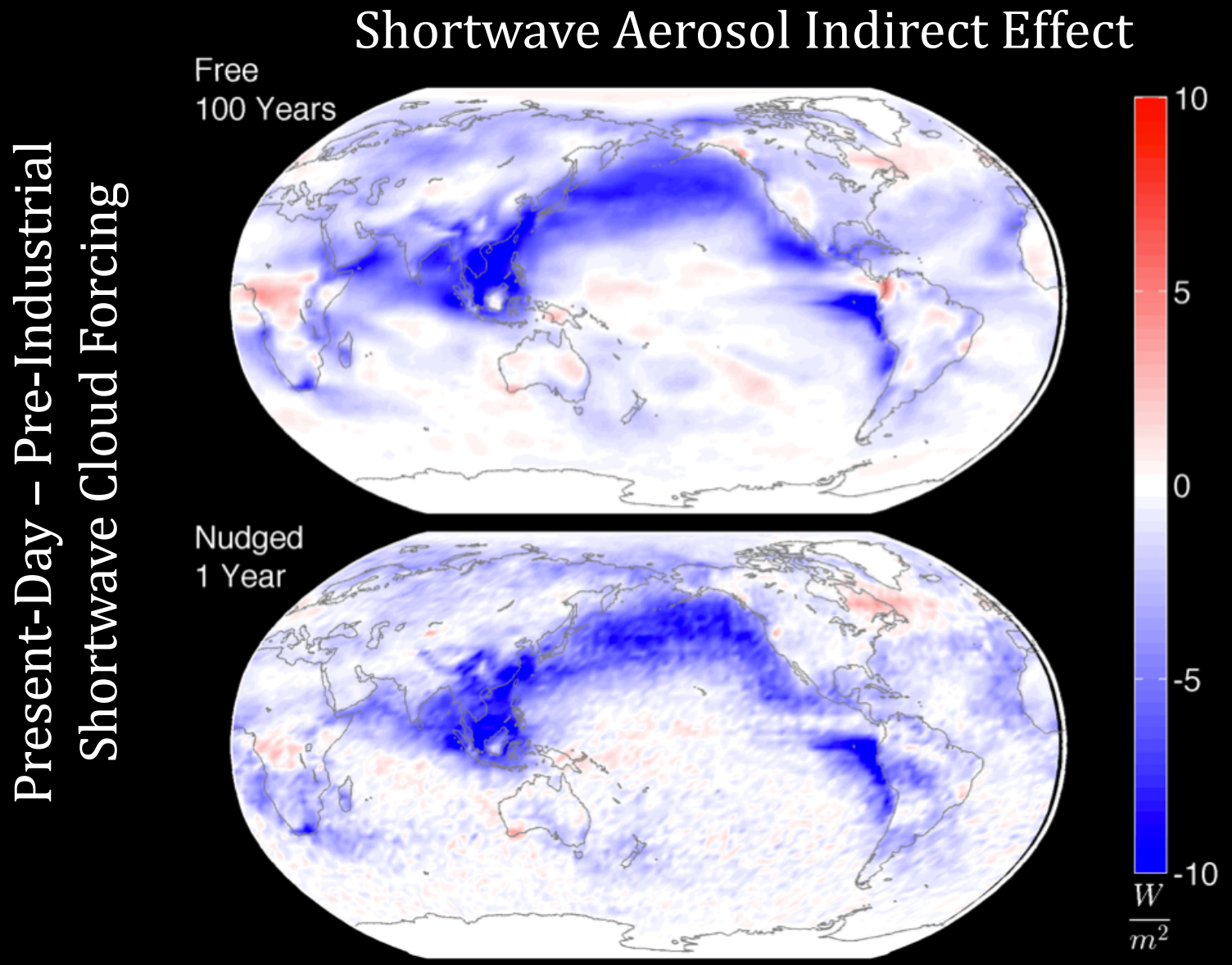


Improving global estimates of aerosol indirect effects by:

1. **Controlling for the influence of natural variability.**

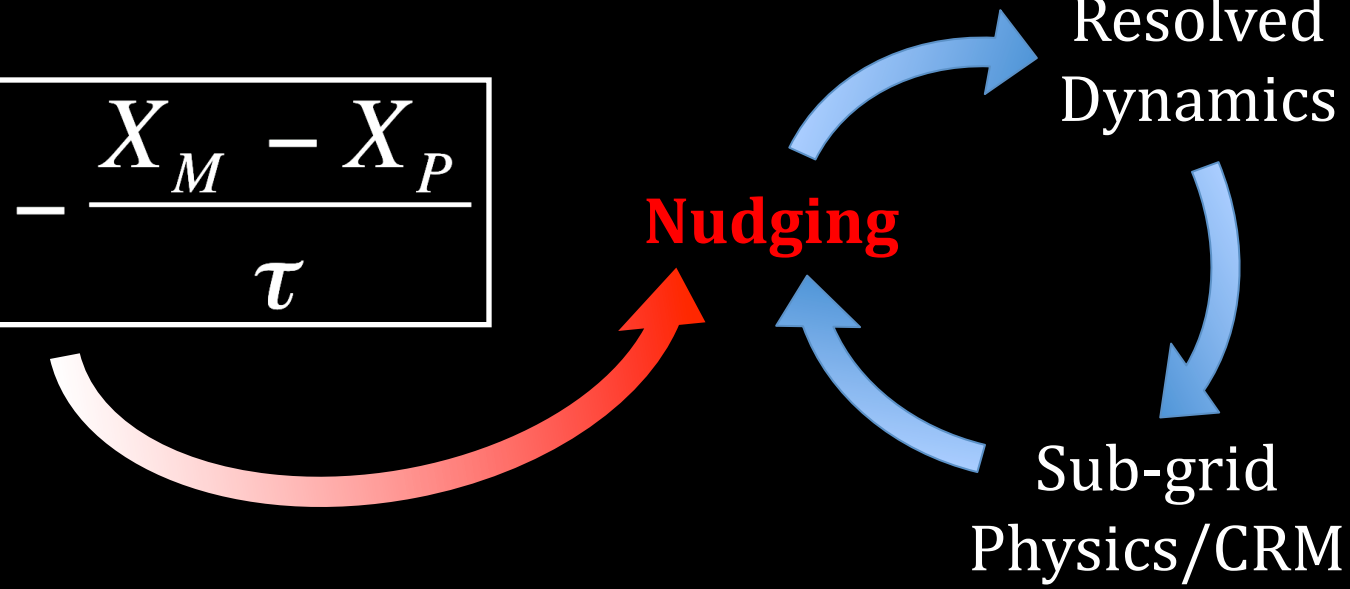
2. **Explicitly resolving cloud scale aerosol interactions.**

But constraining variability can bring out the 100 year signal in only one year simulations.

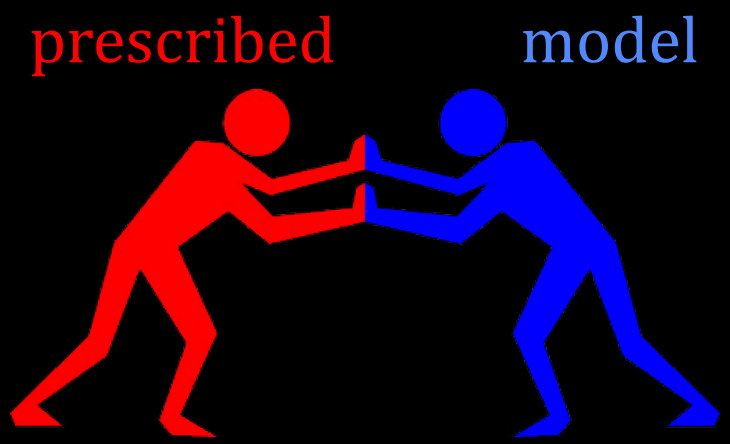


Nudging forces the pre-industrial and present-day simulations to have the same variability.

$$\frac{\partial X_M}{\partial t} = \ldots - \frac{X_M - X_P}{\tau}$$



X = horizontal winds
temperature
M = model values of variables
P = prescribed values
τ = relaxation time constant



Also controls temperature change and feedback responses.

Nudging constrains large-scale meteorology and feedback responses.

What variables should be constrained?

Meteorological variability & circulation: Horizontal Wind

Aerosol effects as "instantaneous" forcing: Temperature

Sensitivity tests indicated that the model was over constrained when also nudging: Humidity

And how strongly should they be constrained?

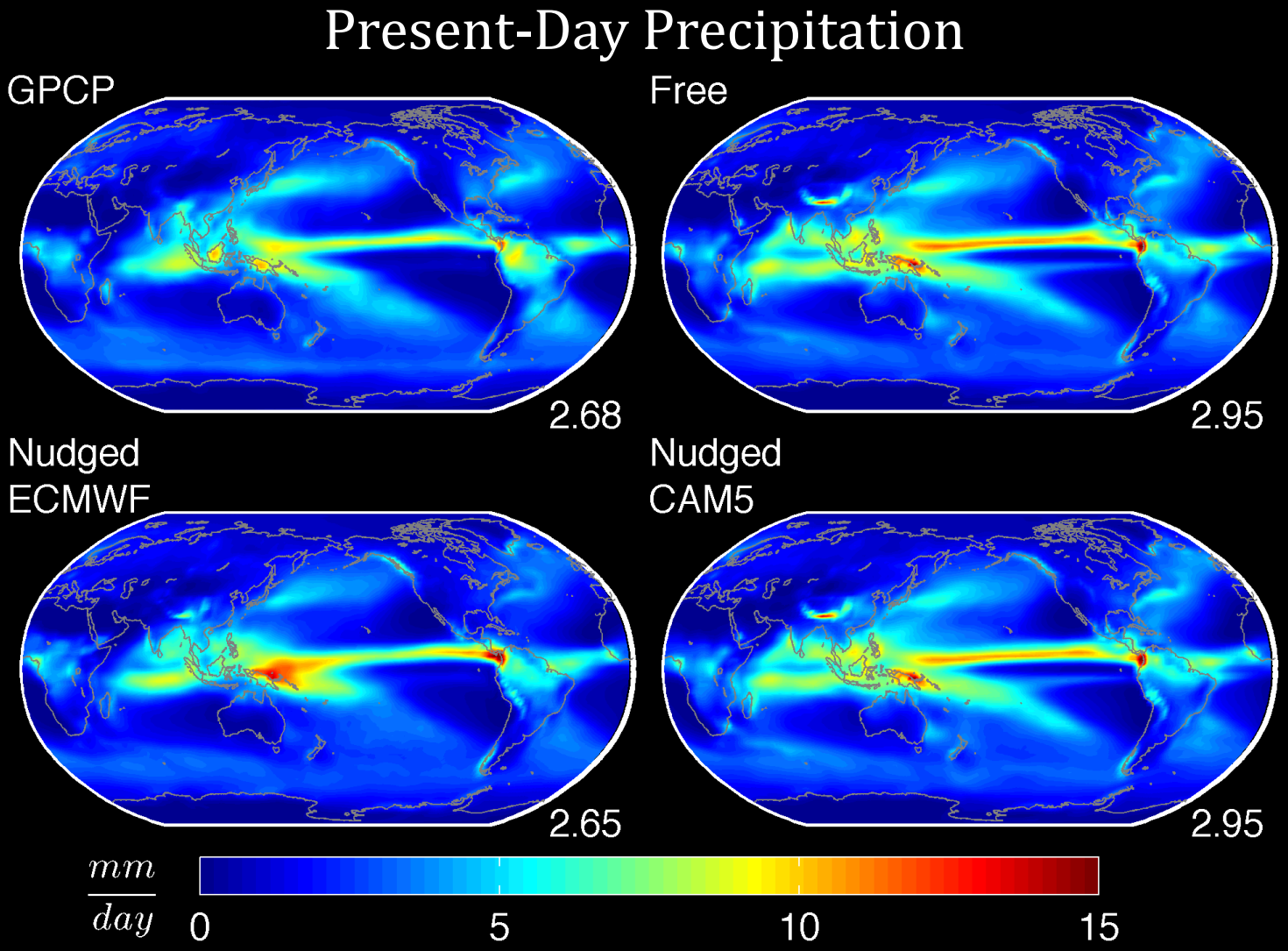
Aerosol Effects on Cloud: Synoptic Albedo → Lifetime → Meteorology → Circulation

The relaxation time allows aerosol changes to cloud properties on different time scales.

Pure Forcing with prescribed SSTs

Full Feedbacks with interactive ocean

Unconstrained fields are not impacted by nudging.



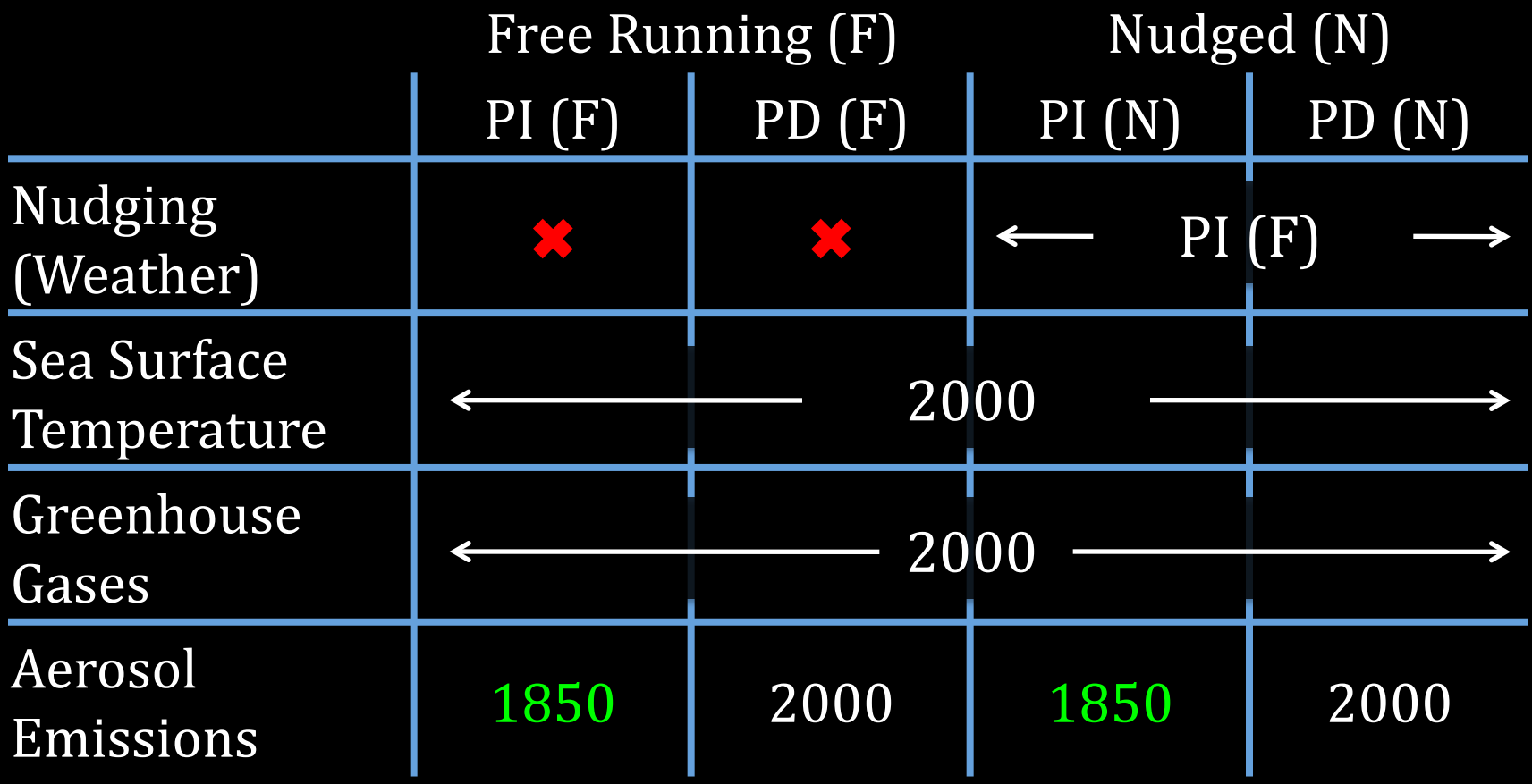
Heating tendencies (W/m^2): Deep/Shallow Convection = 42.6/41.8, Radiation = -81.3, and Nudging = 0.3

Constraining simulations with both PI and PD aerosol toward identical meteorological.

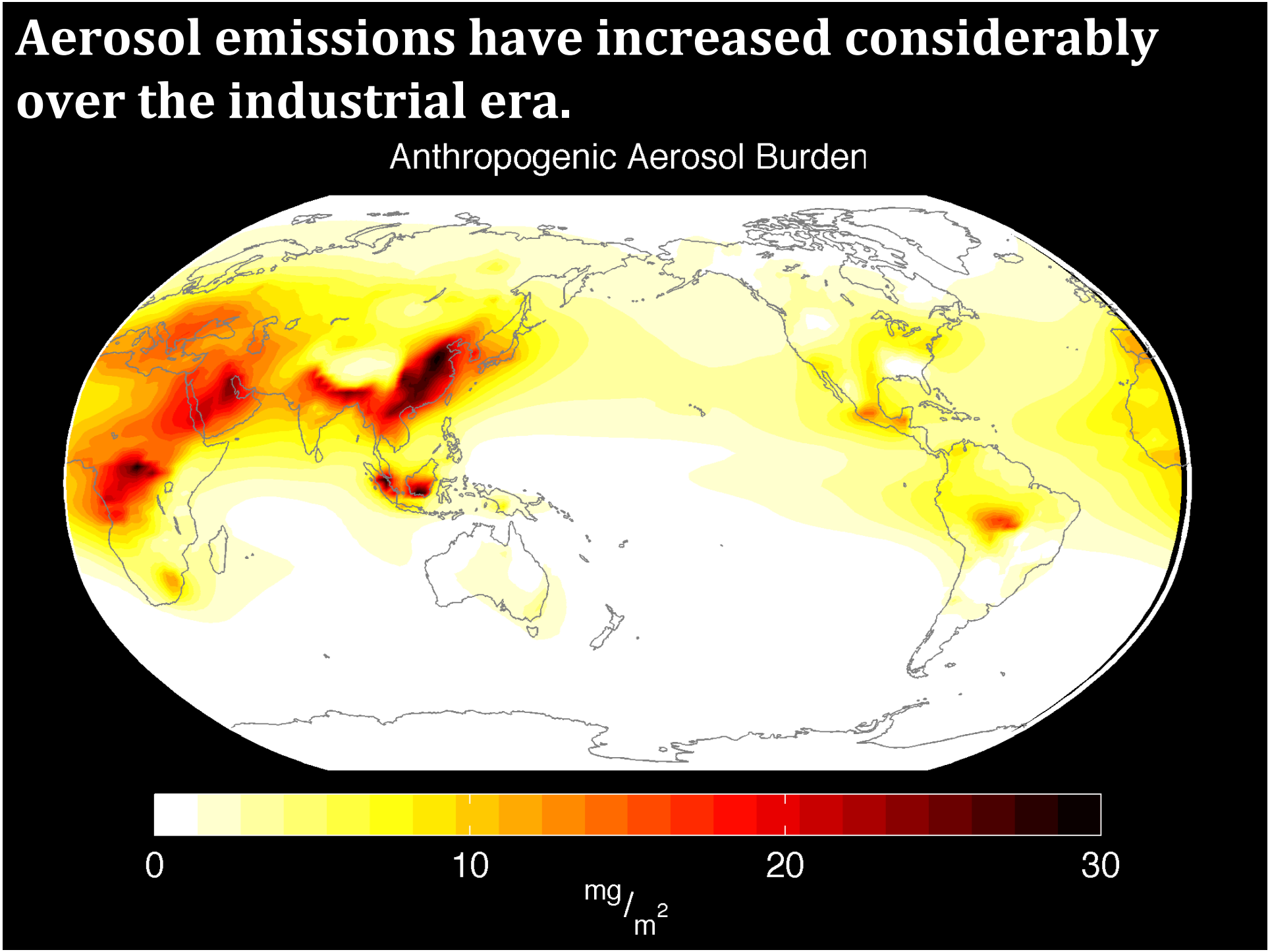
Experiment Design: Four 10 year simulations with CAM5

Four 1 year simulations with the MMF

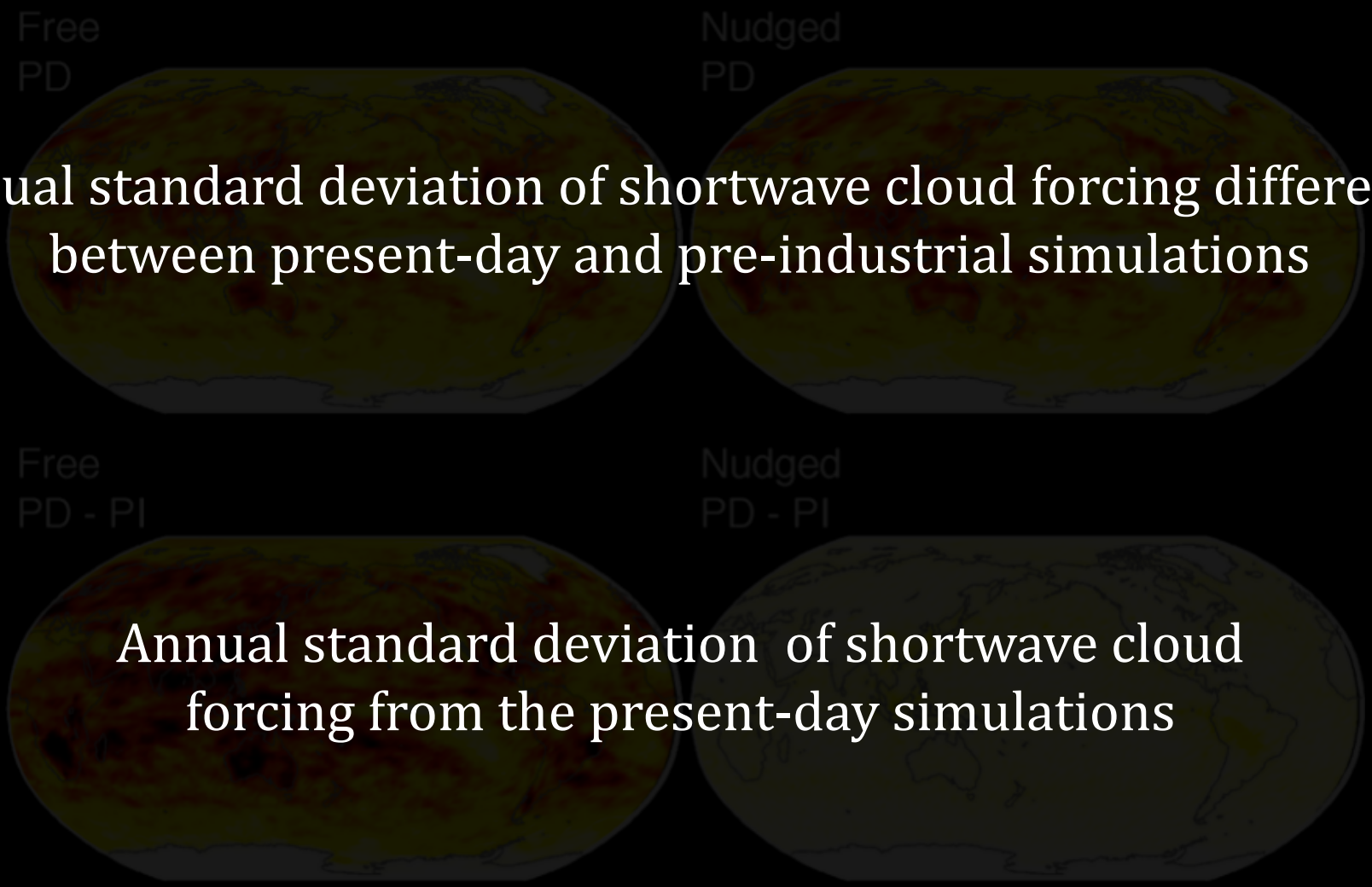
PI = Pre-Industrial PD = Present-Day



Aerosol emissions have increased considerably over the industrial era.



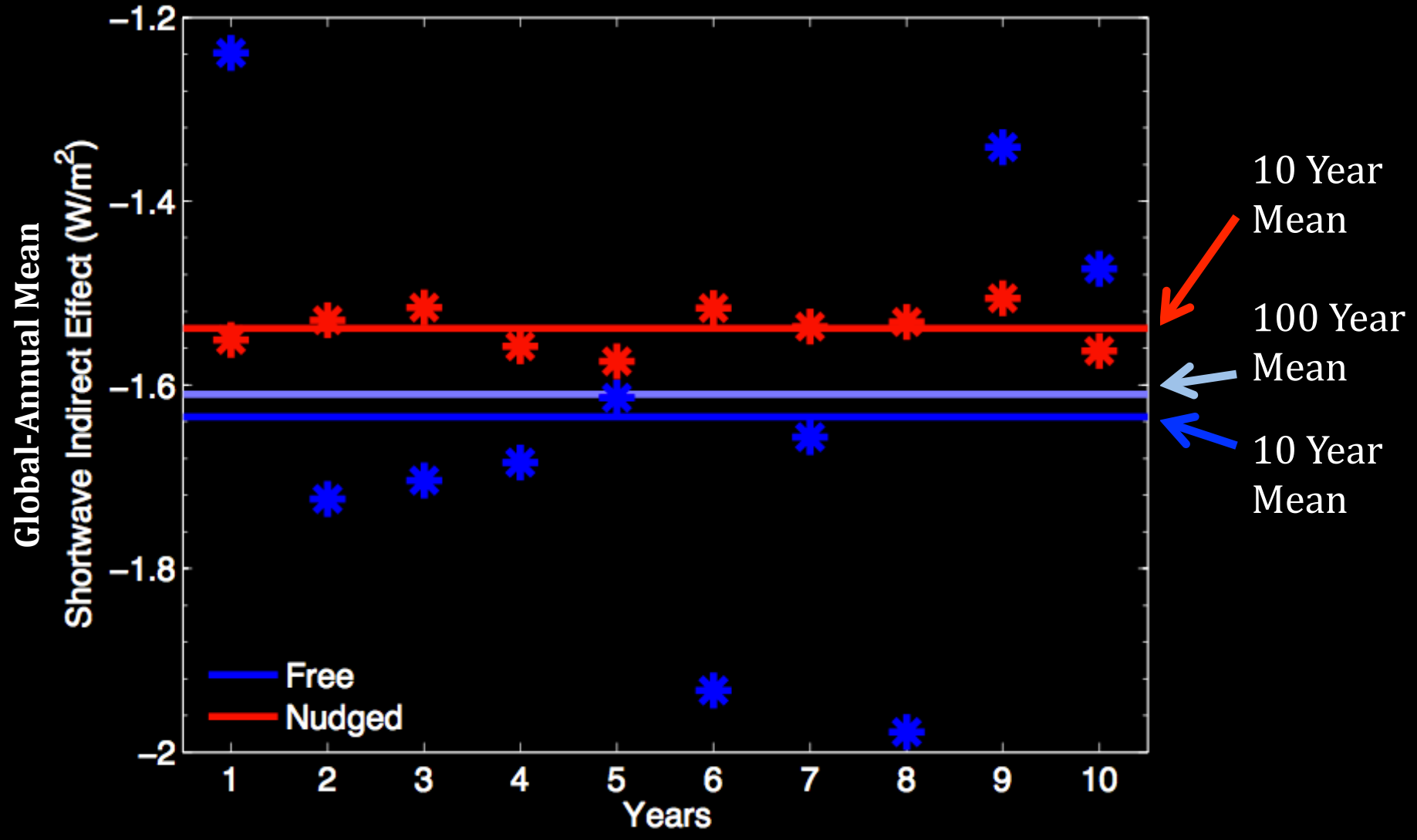
Pre-industrial and present-day simulations have the same shortwave cloud forcing variability.



Annual standard deviation of shortwave cloud forcing difference between present-day and pre-industrial simulations

Annual standard deviation of shortwave cloud forcing from the present-day simulations

So a more stable estimate of the shortwave aerosol-cloud forcing is produced.



Mean and 95% Confidence Intervals: -1.54 ± 0.02 W/m^2 and -1.63 ± 0.17 W/m^2

The forcing results from increased liquid water and droplet number concentration.

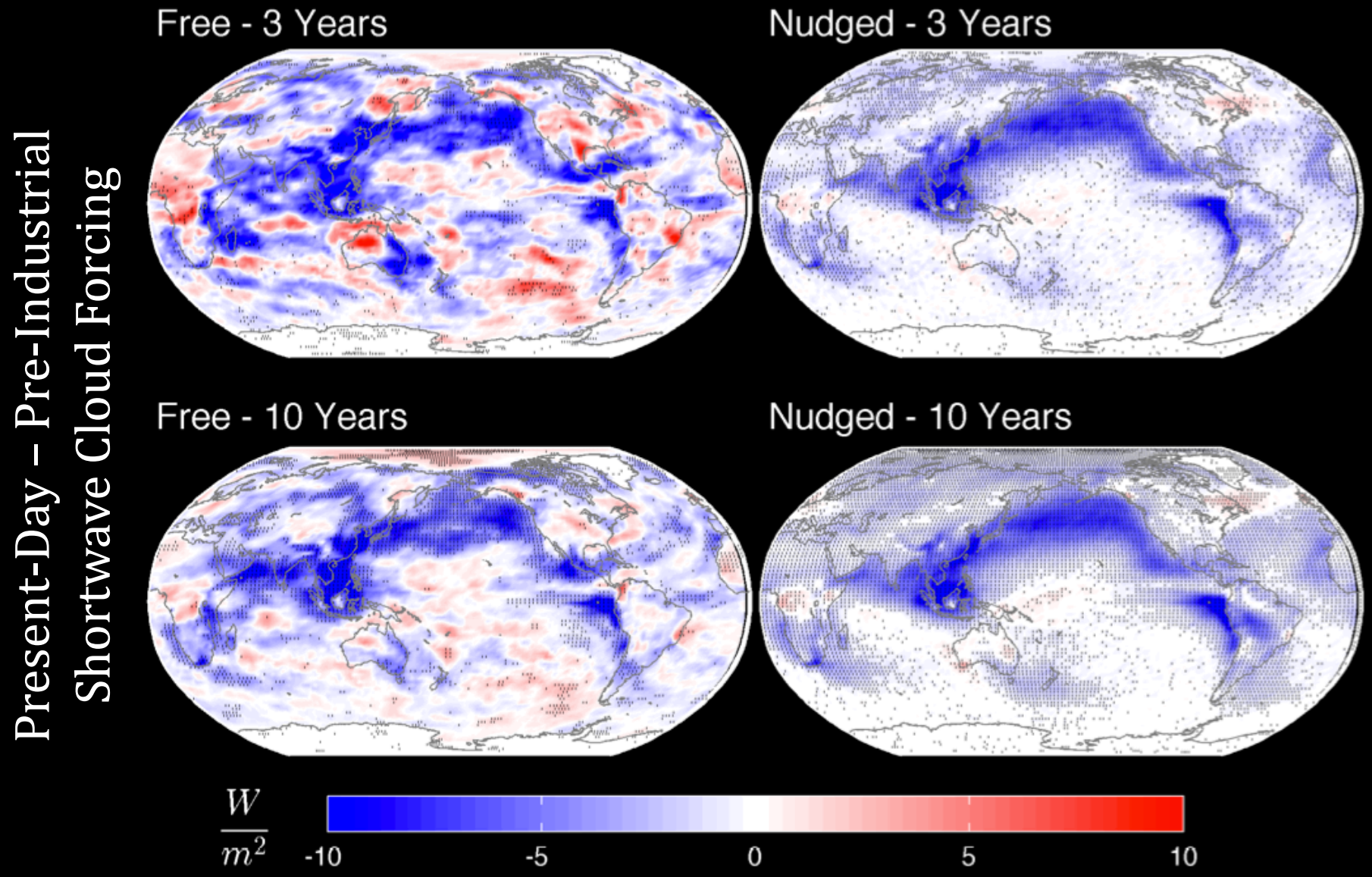
	Global Mean		Standard Deviation		Pattern Correlation 1 year with 10 year	
	Nudged 10 years	Free 10 years	Nudged 10 years	Free 10 years	Nudged 10 years	Free 10 years
SW Cloud-forcing	-1.54	-1.63	0.02	0.23	0.95	0.52
LW Cloud-forcing	0.35	0.27	0.02	0.13	0.94	0.44
SW Clear-sky	-0.44	-0.49	0.01	0.07	0.91	0.50
LW Clear-sky	0.08	0.21	0.00	0.16	0.92	0.38
Liquid water path	3.84	3.88	0.05	0.38	0.98	0.76
% Droplet number	38.7	40.6	0.55	2.01	0.99	0.96
Ice water path	0.10	-0.05	0.01	0.13	0.89	0.40
% Ice number	3.84	2.48	0.39	1.16	0.95	0.56
Precipitation	-0.27	-0.54	0.01	0.22	0.92	0.37

TOA radiative forcing (W/m^2)
Liquid/ice water path (g/m^2)
Column droplet/ice number (% increase)
Precipitation (cm/yr)

Change from Pre-Industrial to Present-Day

Nudging improves spatial statistical significance.

Shortwave Aerosol Indirect Effect



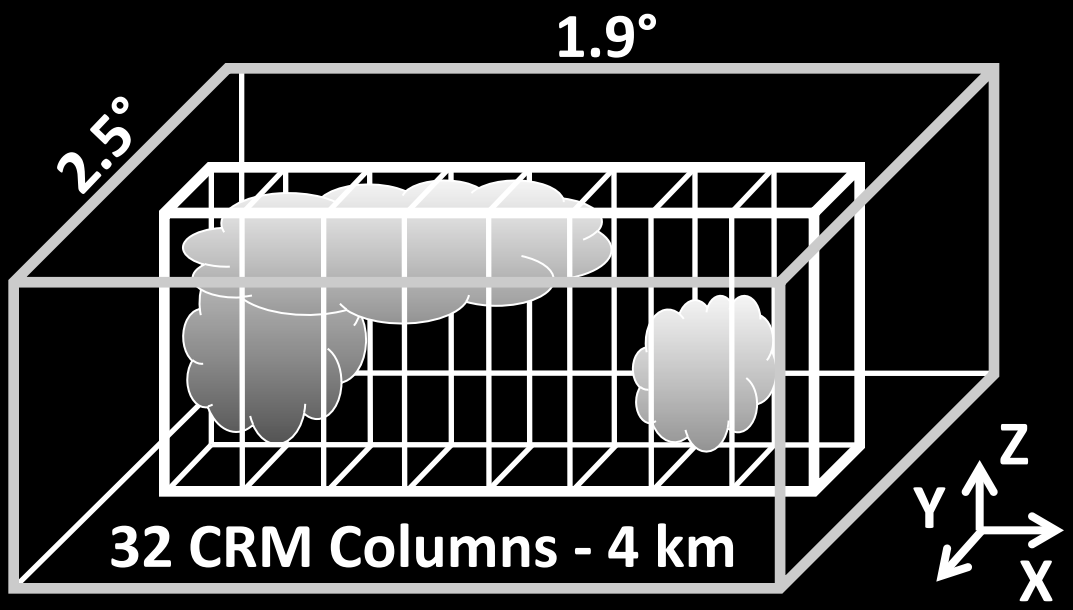
Fraction of area that is statistically significant : 68% for nudged and 25% free.

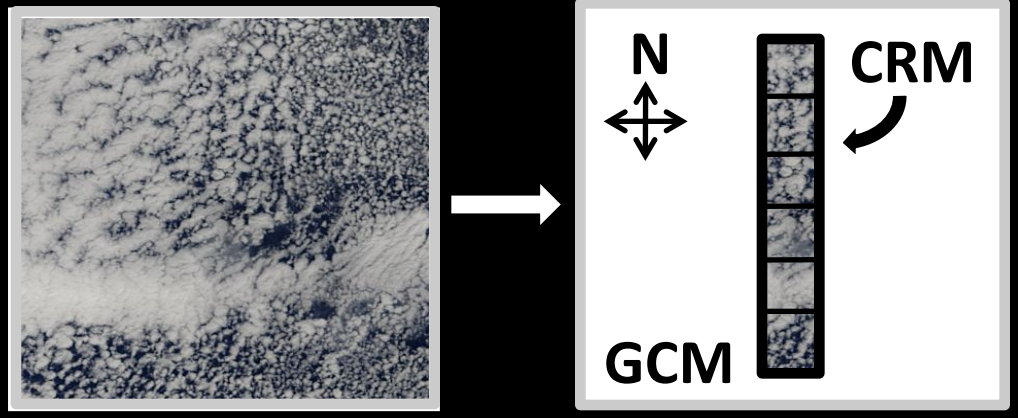
Improving global estimates of aerosol indirect effects by:

1. **Controlling for the influence of natural variability.**

2. **Explicitly resolving cloud scale aerosol interactions.**

Multiscale climate models (MMFs) realize the scale interface in a new way.





a.k.a.
"super-parameterization"

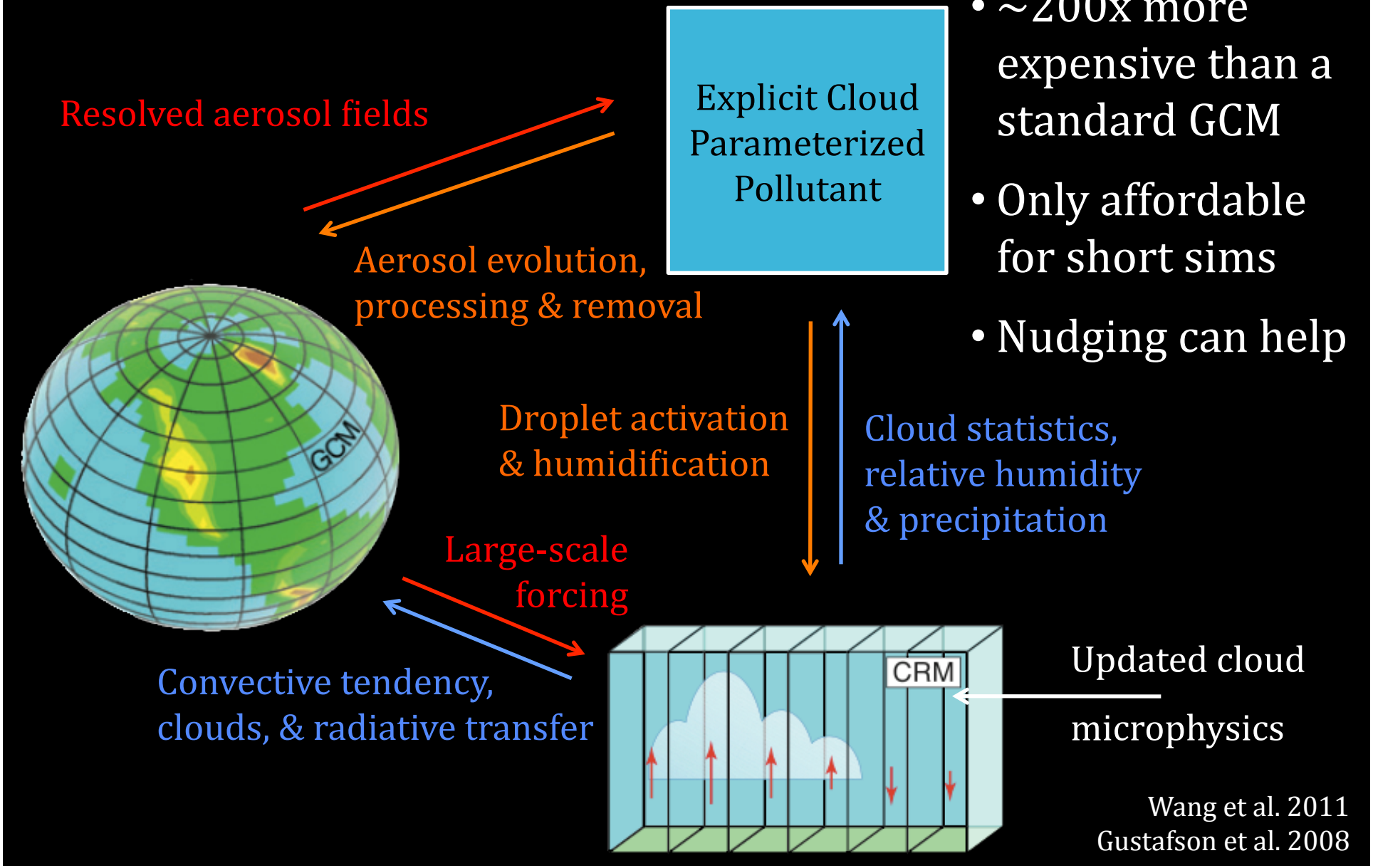
Idealized 2D cloud resolving models (CRMs) are embedded in each grid column of a GCM to replace conventional cloud parameterizations and explicitly represent sub-grid convection.

MMFs are 200x more expensive computationally than GCMs, but scale efficiently with increasing number of processors, providing an interim strategy until global-climate CRMs are affordable.

Multiscale Modeling Framework

CMMAP
Reach for the sky

A new MMF connects CAM5 aerosol physics with resolved cloud dynamics.



- ~200x more expensive than a standard GCM
- Only affordable for short sims
- Nudging can help

Wang et al. 2011
Gustafson et al. 2008

Weaker indirect effects in the MMF result from smaller global mean changes in LWP and CDNC.

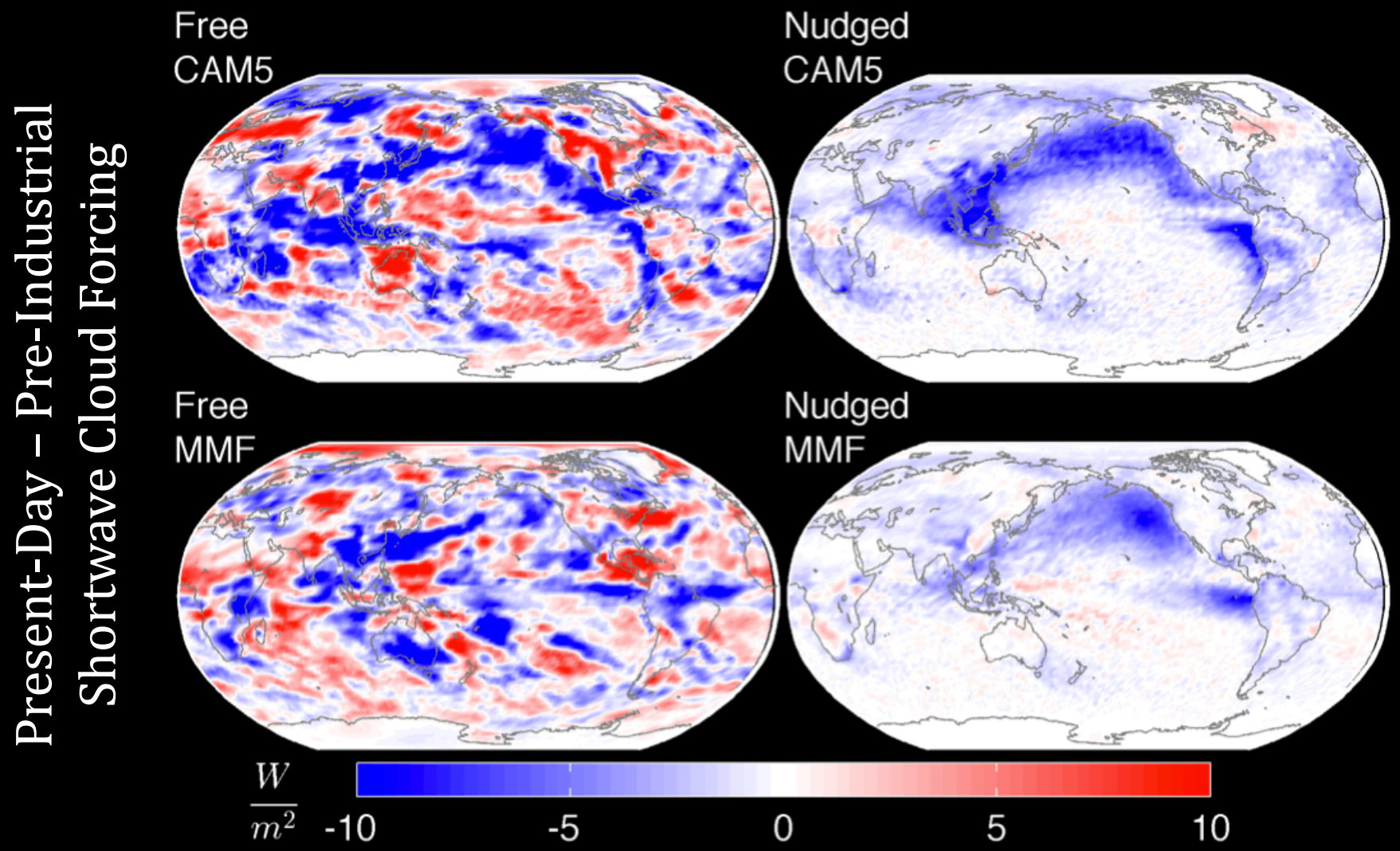
	CAM5 Global Mean			MMF Global Mean		
	Nudged 10 years	Free 10 years	Free 100 years	Nudged 1 year	Free 1 year	* Free 3 years
SW Cloud-forcing	-1.54	-1.63	-1.61	-0.80	-0.56	-0.77
LW Cloud-forcing	0.35	0.27	0.26	-0.01	-0.27	-0.06
SW Clear-sky	-0.44	-0.49	-0.48	-0.57	-0.66	-0.54
LW Clear-sky	0.08	0.21	0.15	0.11	-0.04	0.31
Liquid water path	3.84	3.88	3.80	2.12	2.16	2.11
% Droplet number	38.7	40.6	39.8	25.3	24.9	26.7
Ice water path	0.10	-0.05	-0.07	-0.03	-0.10	0.00
% Ice number	3.84	2.48	2.38	-0.72	-2.47	-0.93
Precipitation	-0.27	-0.54	-0.53	-0.32	-0.06	-0.37

TOA radiative forcing (W/m^2)
Liquid/ice water path (g/m^2)
Column droplet/ice number (% increase)
Precipitation (cm/yr)

* 3 year MMF results are from Wang et al. [2011].

Change from Pre-Industrial to Present-Day

Nudging enables the evaluation of spatial features in computationally expensive climate models.



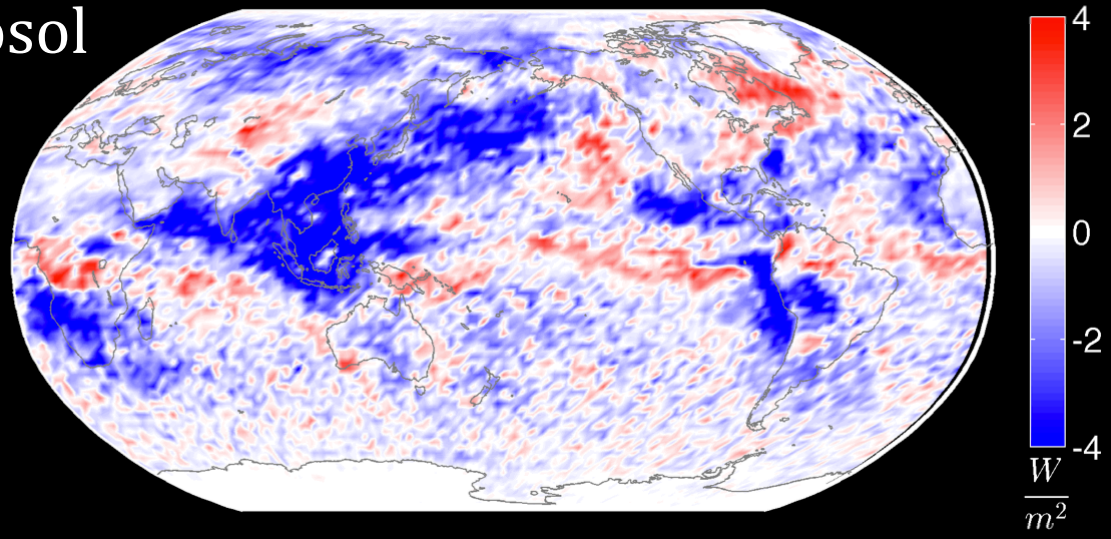
MMF means are -0.80 W/m^2 and -0.56 W/m^2 for nudged and free, respectively.

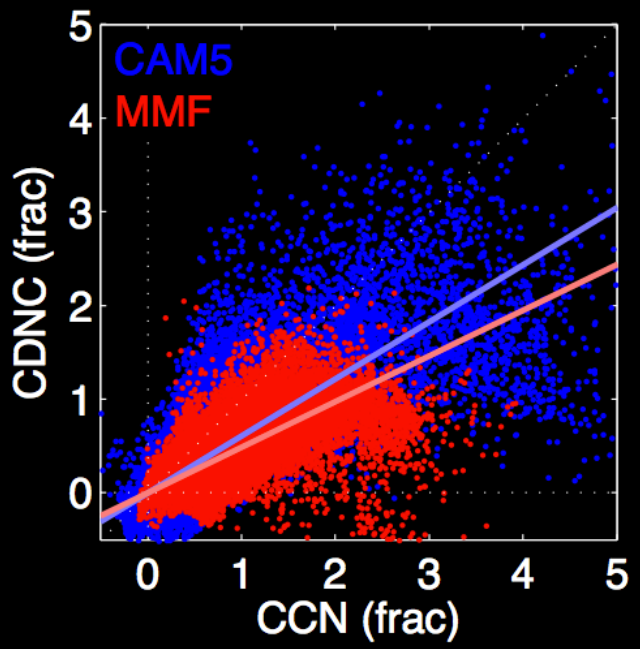
Smaller global mean changes in the MMF result from weaker relationships with CCN.

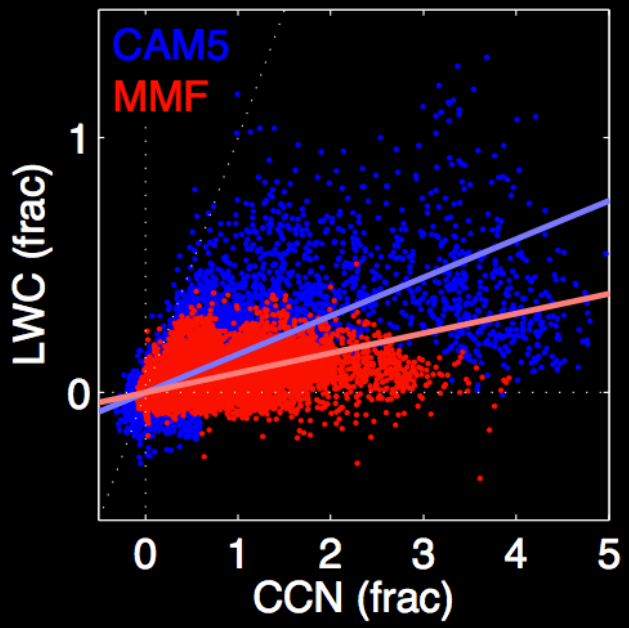
Shortwave Aerosol Indirect Effect

CAM5 – MMF

Nudged







CCN = Cloud Condensation Nuclei (Aerosol)

CDNC = Cloud Droplet Number Concentration

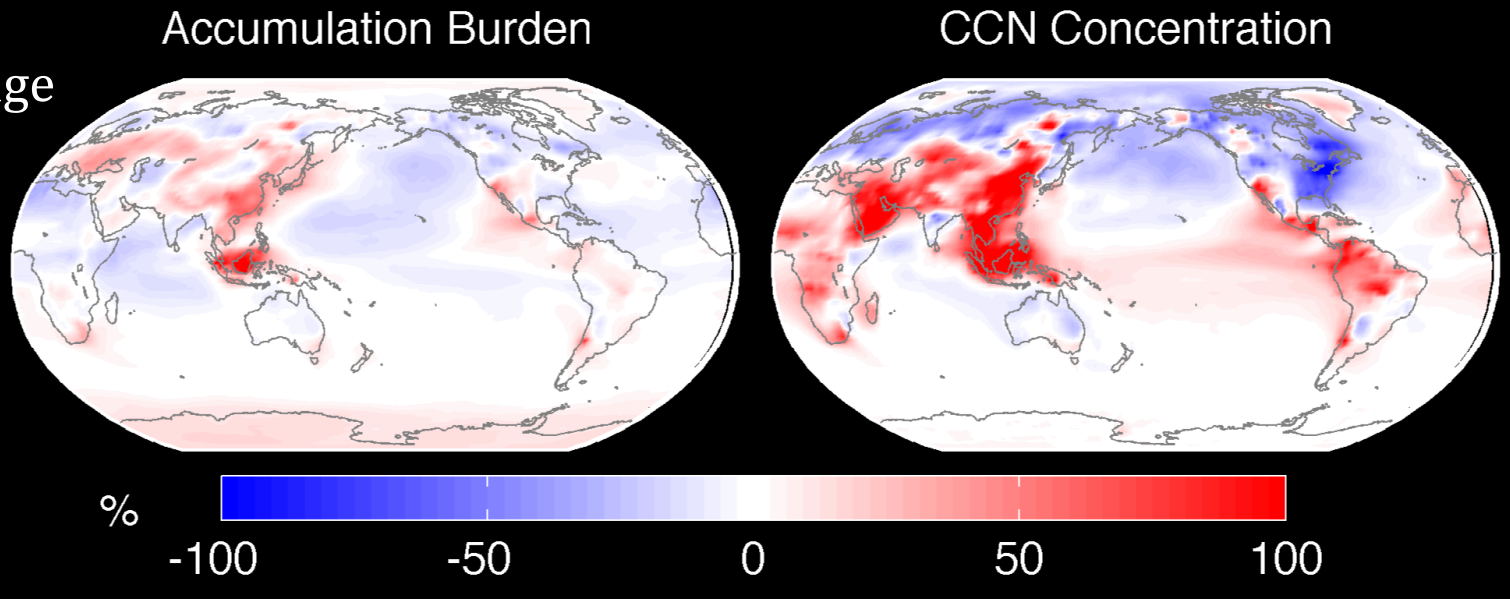
LWC = Liquid Water Content

Cloud changes feedback on aerosol fields and contribute to larger aerosol burdens in the CAM5.

Relative Change in Aerosol Burden

Percent change		Sulfate	BC	POM	SOA	Dust	Sea Salt
CAM5	Nudged	232	150	67	17	-1	1
	Free	226	150	64	16	-4	1
MMF	Nudged	118	133	53	15	0	2
	Free	120	133	53	14	0	3
CAM5 - MMF	Nudged	114	17	14	2	-1	-1
	Free	106	17	11	3	-4	-2

Relative Change
CAM5 – MMF



Summary

- Nudged estimates of shortwave aerosol indirect effects are more stable, with mean and 95% confidence intervals of:
  Nudged: -1.54 ± 0.02 W/m^2
  Free: 1.63 ± 0.17 W/m^2

- Nudging increases the fraction of the world's area in which the aerosol indirect effect is statistically significant:
  Nudged: 68%
  Free: 25%

- The MMF produces a weaker aerosol indirect effect with global-annual mean values of:
  Nudged: -0.80 W/m^2 (consistent with 3 year results)
  Free: -0.56 W/m^2

- The MMF has smaller global mean changes from PI to PD and smaller increases in CDNC and LWC with CCN.