Towards Process-level Evaluation of Aerosol Effects on Ice Clouds in Global Aerosol-Climate Models

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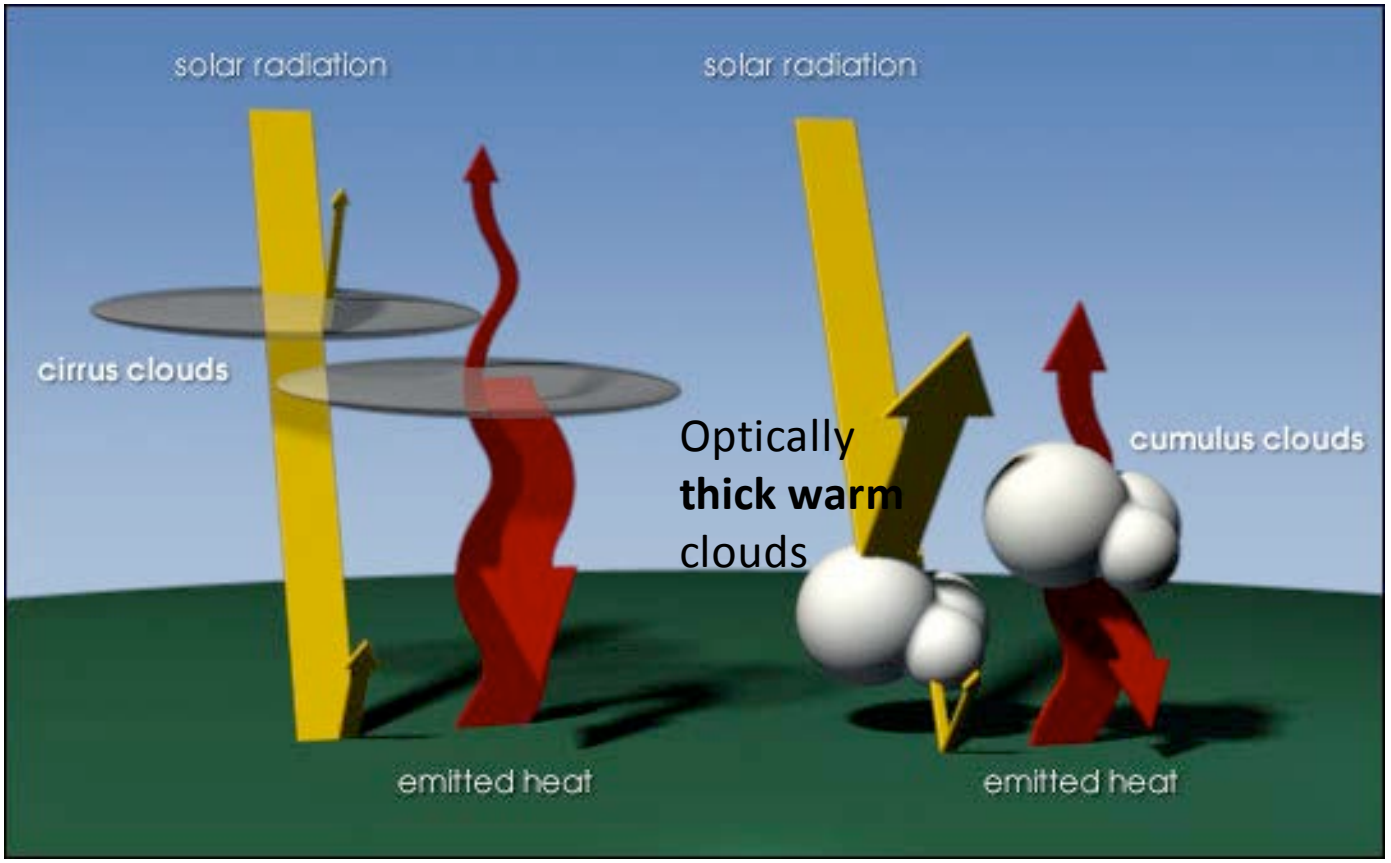
Typical pure ice phase clouds (cirrus)

Why do we care about ice clouds?

Source: https://earthobservatory.nasa.gov/Features/DelicateBalance

Optically **thin ice** clouds



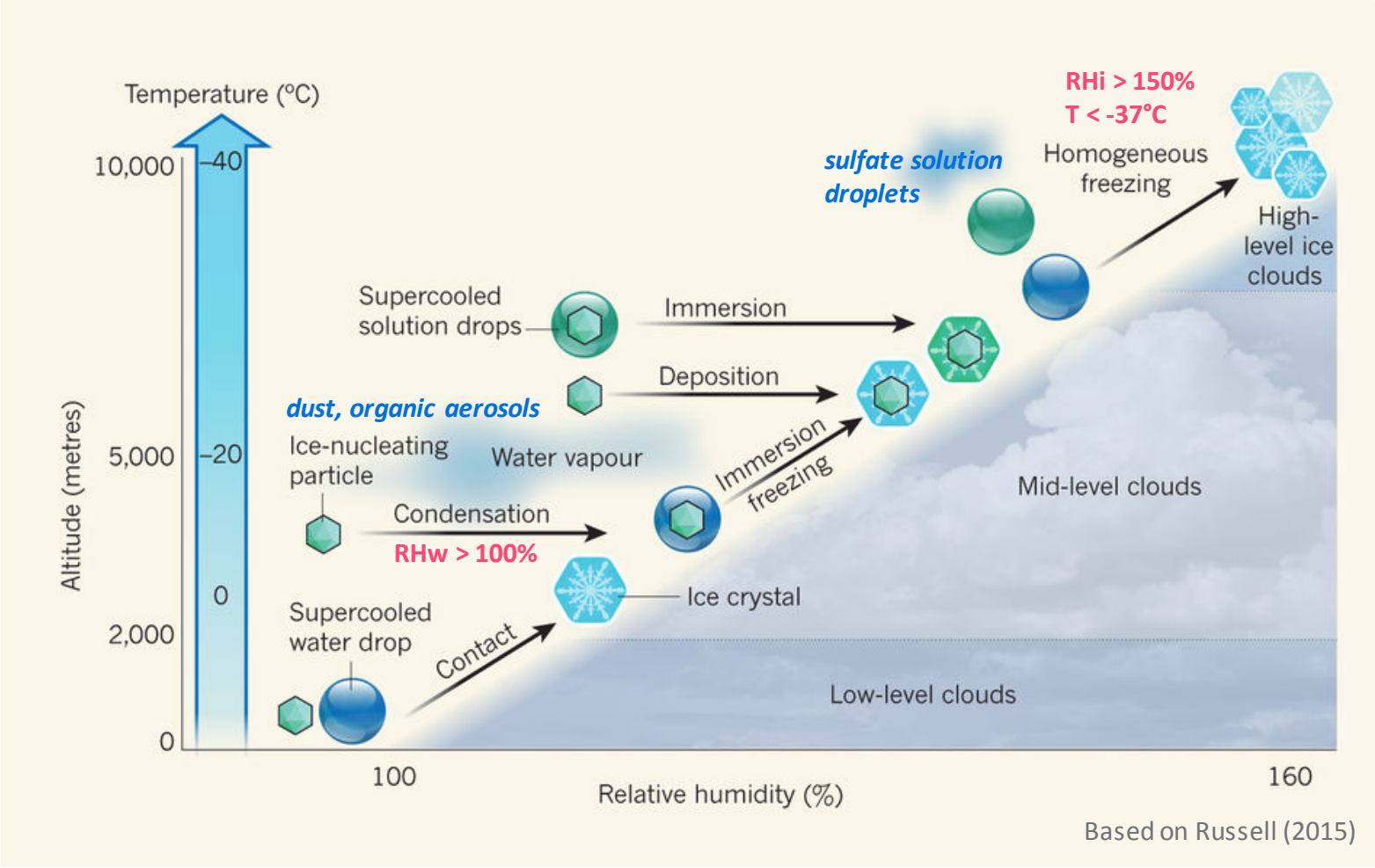
Optically **thick warm** clouds

Optically **thick liquid and ice** clouds

Absorb **longwave** radiation
heat the atmosphere

Reflect **shortwave** radiation
cool the atmosphere

Ice formation mechanisms

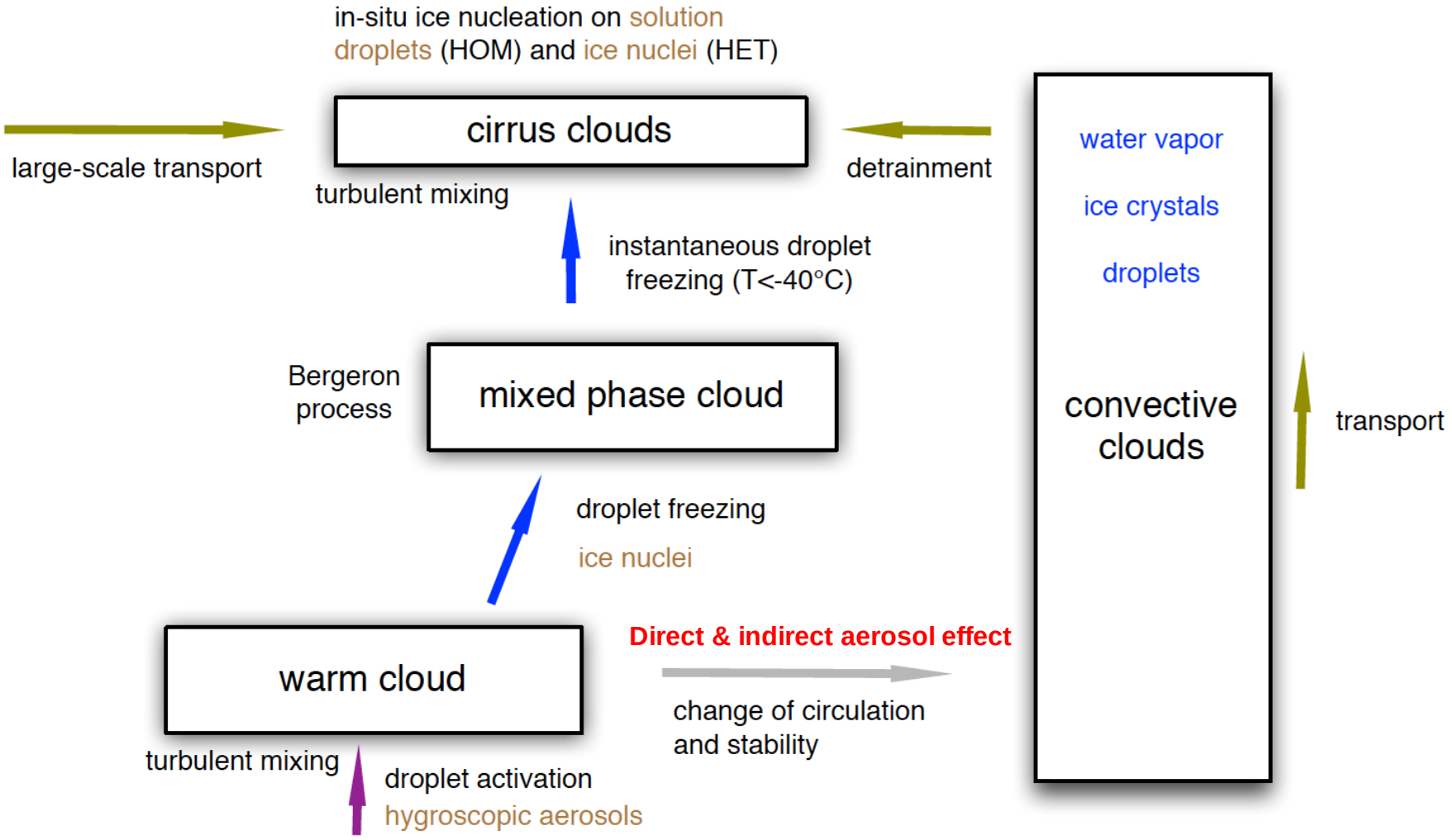


Based on Russell (2015)

Which dynamical processes are important for ice cloud formation?

- Large scale advection of moist air and ice nucleating aerosols to cold places
  - moisture source for high relative humidity
- Strong convection
  - Moisture / aerosol transport; forms and detrains ice crystals at upper levels
- Strong turbulence
  - sustains the supersaturation in ice clouds

Effect of aerosols on ice clouds



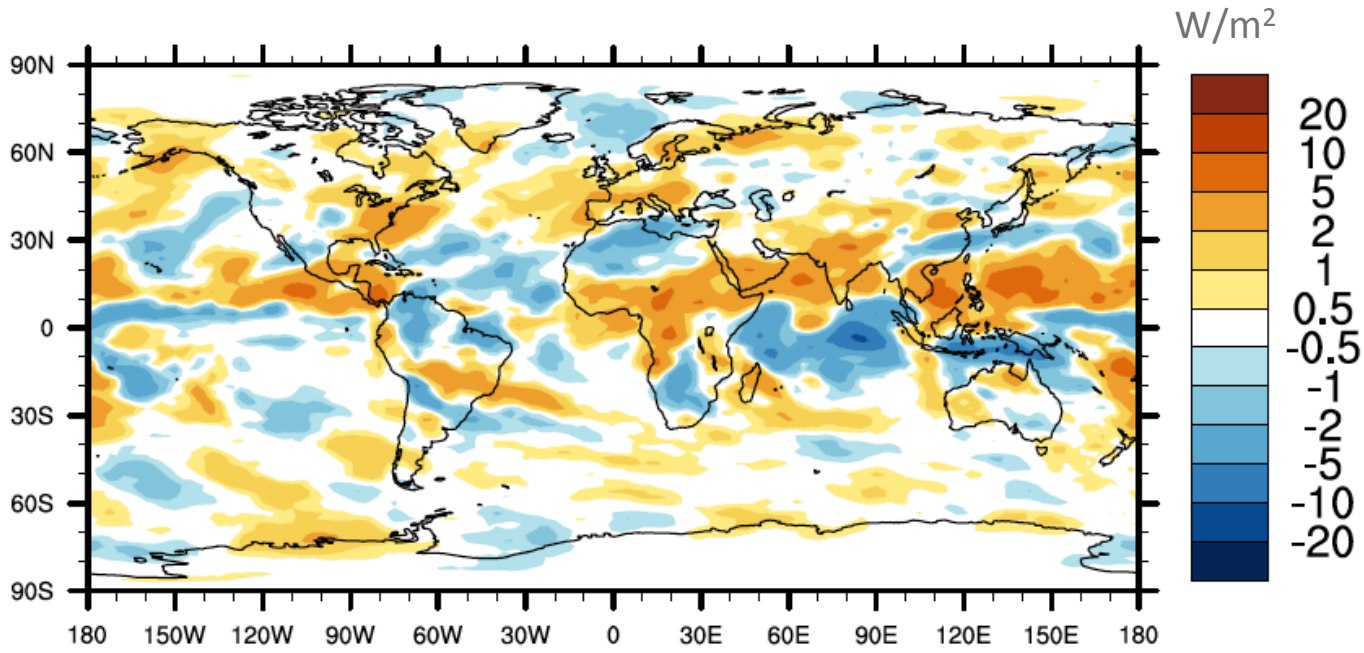
Difficulty in identifying the aerosol effect

- Cloud forcing is often 1-2 orders of magnitude larger than aerosol forcing
  - A small buffering effect by cloud and convection processes can override the aerosol effect
  - Due to the complicated microphysical and dynamical processes that affecting ice cloud formation, it's more difficult to quantify the aerosol effect on ice clouds.
- Noises caused by the chaotic behavior of the atmosphere can hinder signal detection (between the simulations with pre-industrial and present-day emissions)
- Very long simulations are needed to get statistically robust results
  - A big effort for developing high resolution models

Signal vs. noise

Longwave Cloud Forcing, PD – PI Difference (5-yr mean)

Free-running

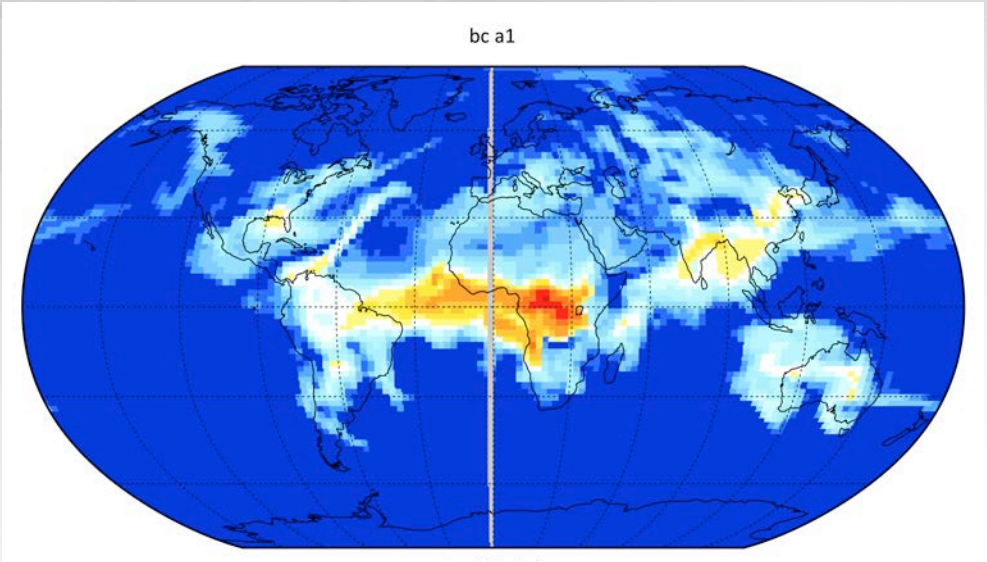


Solution

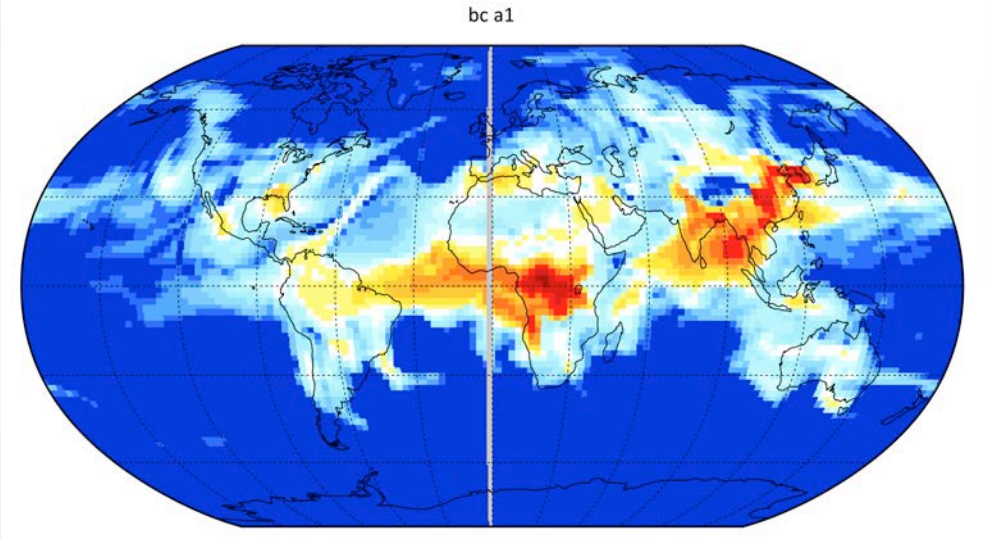
- Nudged simulations (Kooperman et al, 2012; Zhang et al. 2014)
  - Simple assimilation technique, easy to implement
  - Only dynamical variables are nudged, other fields (clouds) can still freely evolve.
  - Only provide a single estimate if not combined with ensembles
  - Caution needed when selecting nudged variables
- Short hindcast ensemble simulations (based on Wan et al., 2014 and Phillips et al., 2004)
  - Fast; can be done in parallel
  - Nudged or initialized ensembles
  - Can provide an estimate on when and where the aerosol effect (or any other perturbation) is significant

PD and PI daily mean aerosol concentrations

PI



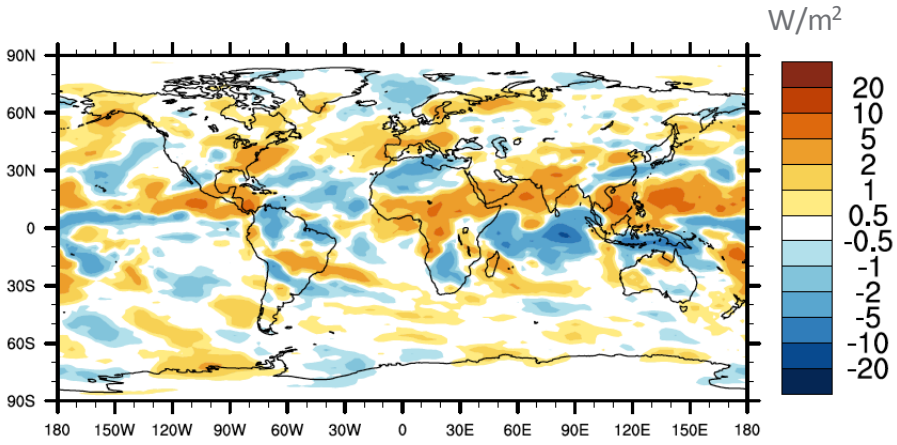
PD



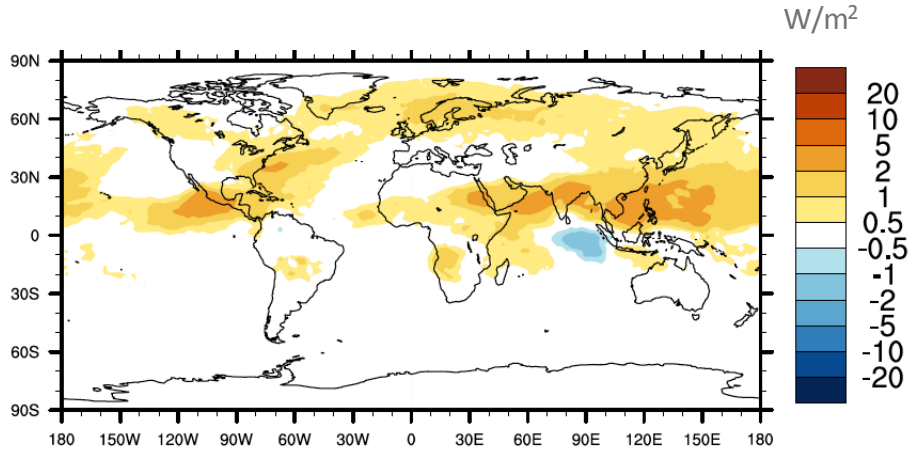
Impact of Nudging

Longwave Cloud Forcing, PD – PI Difference (5-yr mean)

Free-running



Nudged

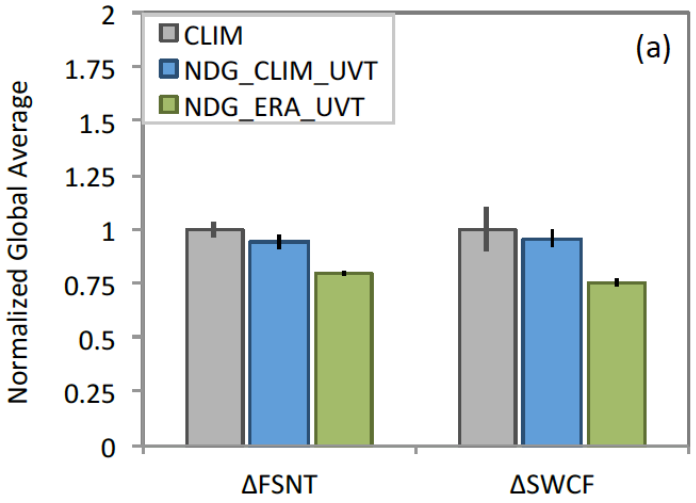


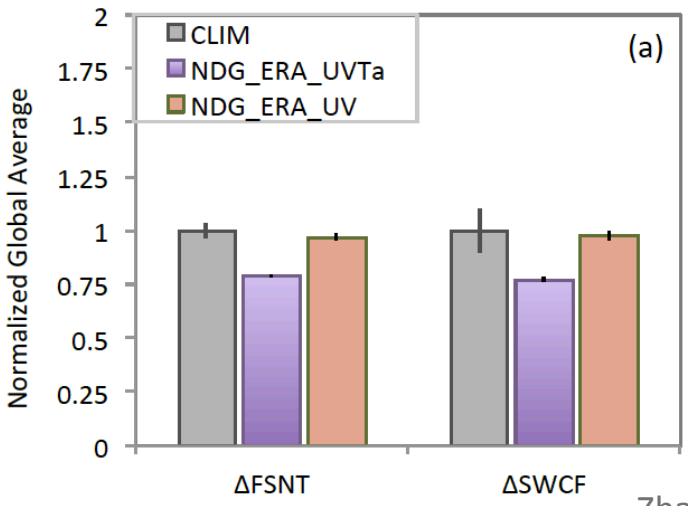
Identify the best nudging strategy

Impact of UVT Nudging

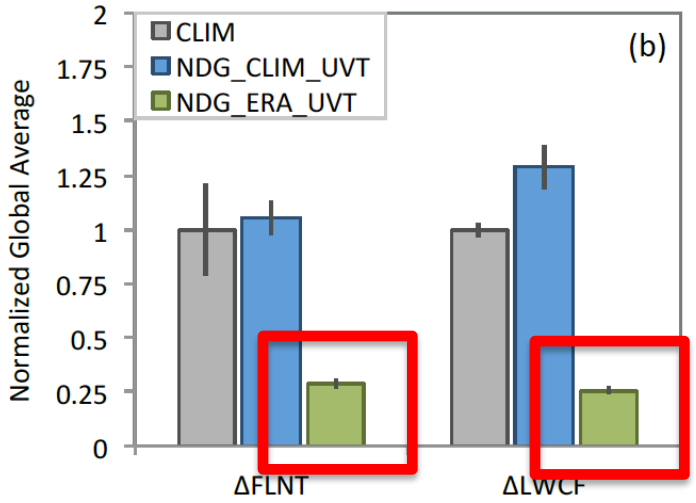
Impact of UV Nudging

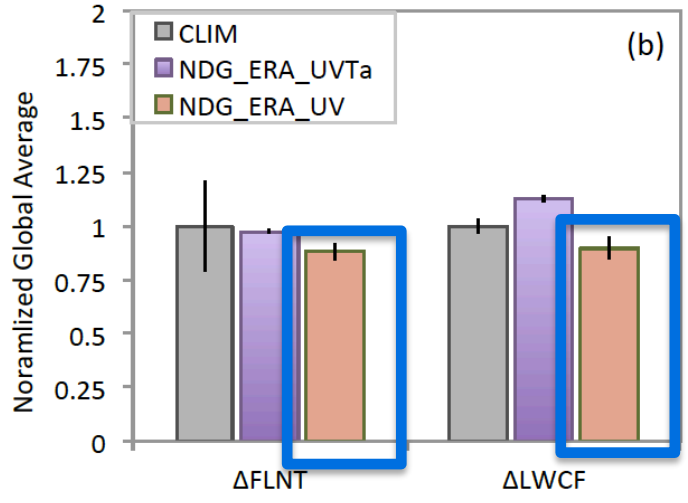
SW





LW





Zhang et al. (2014)

Convective precipitation reduced by 30%.

AeroCom inter-comparison of aerosol indirect effect through cirrus clouds

- Global climate models have started to include the treatment of aerosol effect on ice nucleation
- Assess the impact of aerosols on cirrus clouds more systematically
- Improve the model and reduce the uncertainty in the AIE estimation

CTRL

- Reference model. Both homogeneous and heterogeneous ice nucleation in cirrus clouds are considered. Direct aerosol effect and aerosol indirect effect through warm clouds are also included.

FIX as CTRL, but

- For T<-37 C° , using a constant ice number
- Aerosol effect on ice nucleation in cirrus clouds is not considered.

HOM as CTRL, but

- Only homogeneous nucleation is considered for cirrus cloud condition.

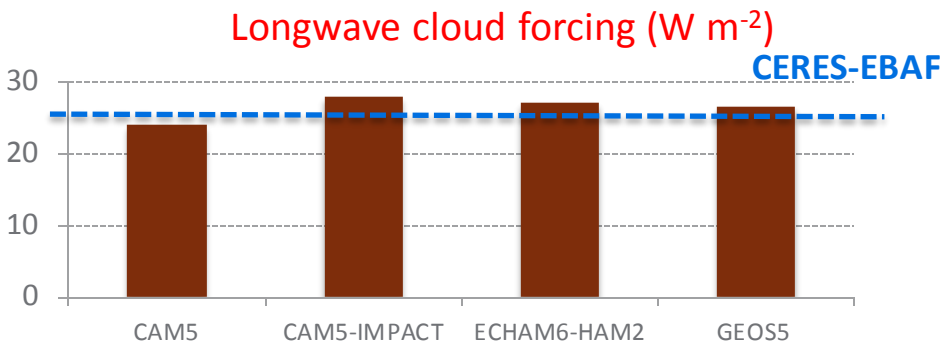
Participating models and groups

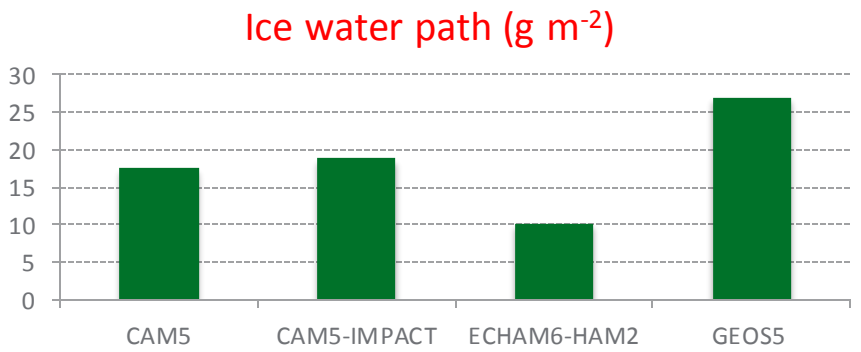
- CAM5 (2º x 2.5º)
- CAM5-IMPACT (2º x 2.5º)
- ECHAM6-HAM2 (1.9º x 1.9º)
- GEOS5 (2º x 2º)

- Prescribed SST
- Nudged towards re-analysis data (wind)
- Present-day and pre-industrial emissions

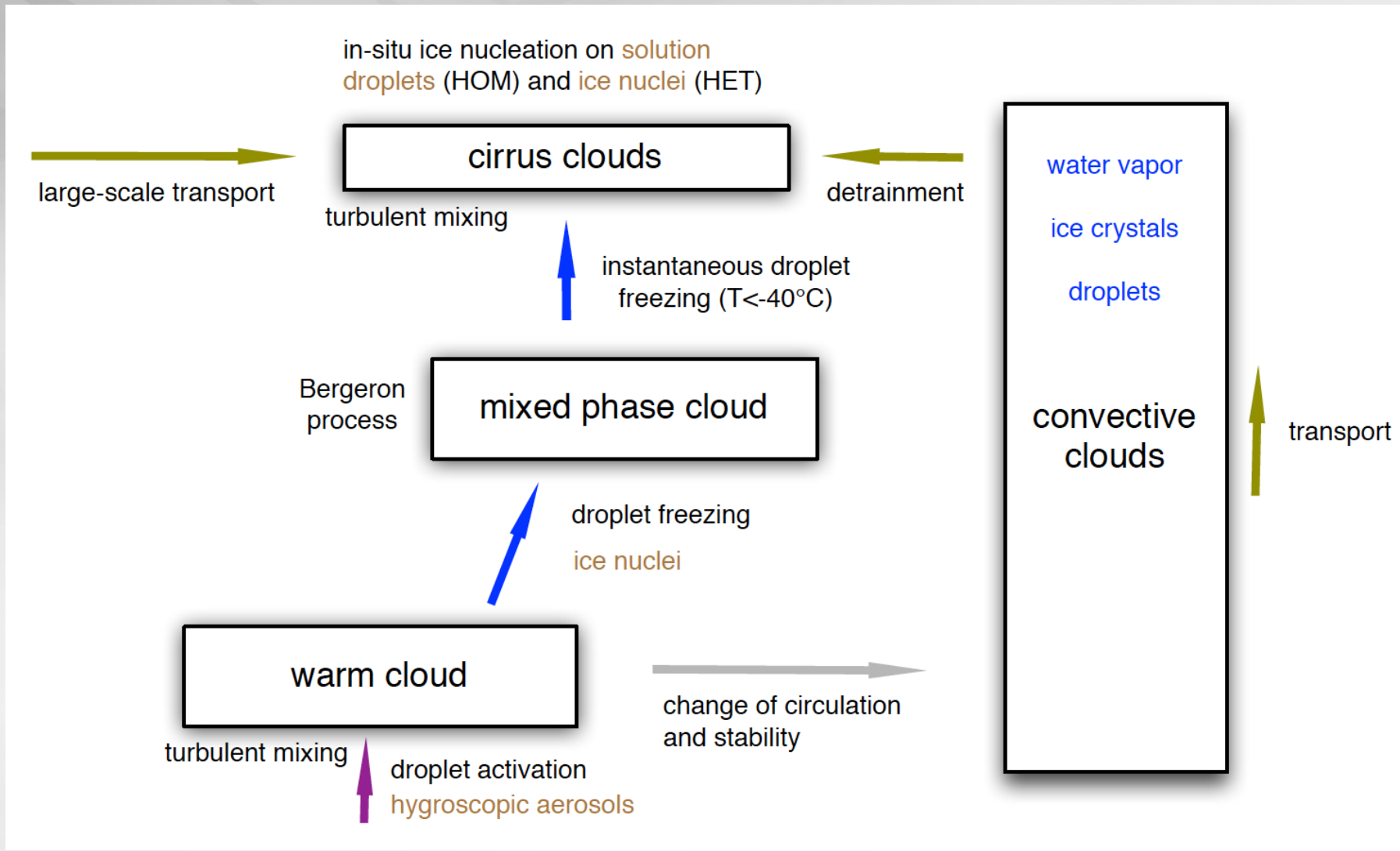
What did we learn?

- Models have similar longwave cloud forcing, but very different ice water path and ice crystal sizes – indicates compensating errors exist
- With nudging, the simulated daily global pattern of ice cloud distribution (ice water path) in all four models are similar.
- The global annual mean anthropogenic aerosol effect through cirrus clouds is estimated to be 0.5-0.6 W m^{-2} for the longwave, and 0.1-0.3 W m^{-2} for the net effect (SW+LW). The contributions from changes of individual cloud types are very different.





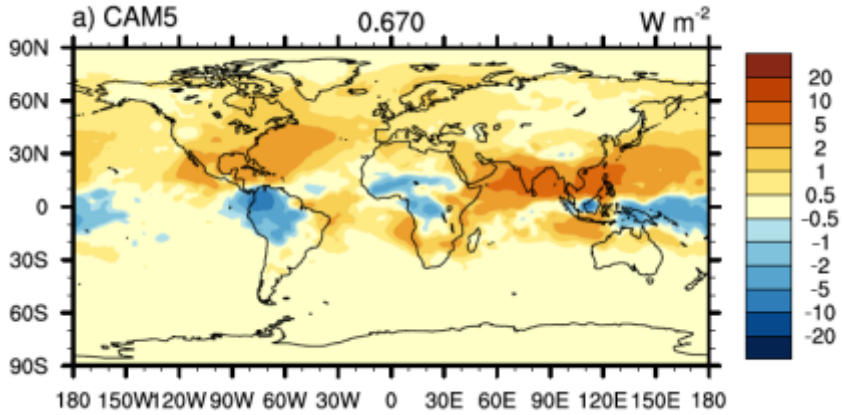
Experiment CTRL



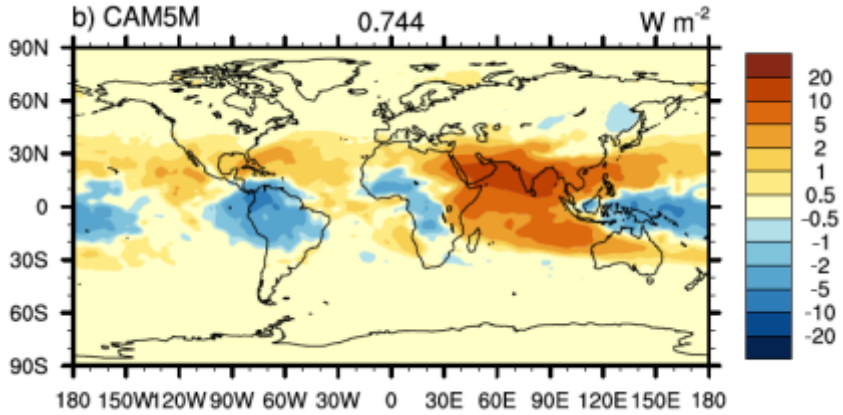
TOA LW Flux Change (PD-PI) total ant. aerosol effect

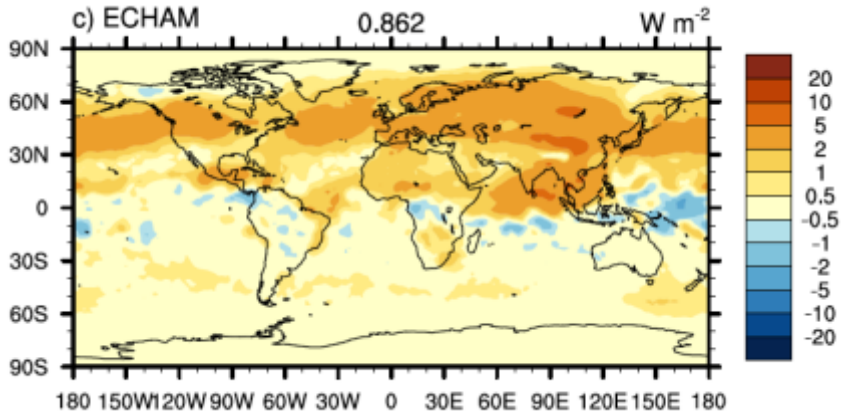
ΔFLNT

CAM5

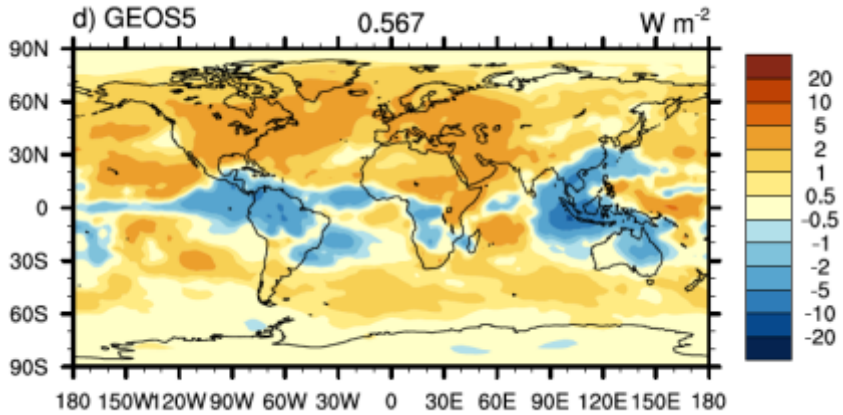


CAM5-IMPACT





ECHAM6-HAM2



GEOS5

Liu et al. (in preparation)

New endeavors

- For existing AeroCom model simulations, use high-frequency (3h) data to conditionally sample data for certain cloud types

- New model simulations using short hindcast ensembles

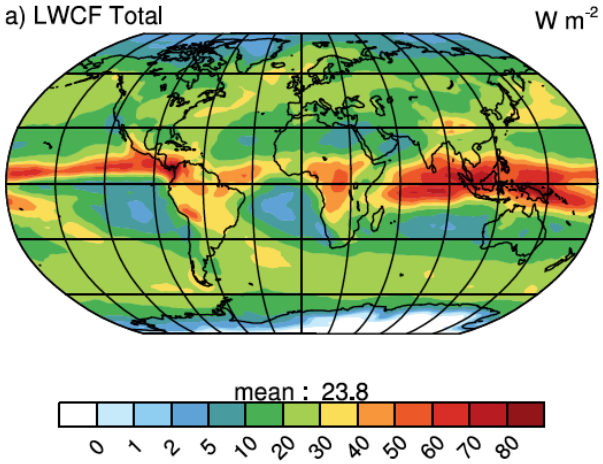
Isolate the impact on ice / liquid / overlapped (including mixed-phase) clouds

- Conditional sampling of high frequency data (e.g. 3h)
  - Pure ice clouds (IWP > ε, LWP < ε)
  - Pure warm clouds (IWP < ε, LWP > ε)
  - Co-existing ice and warm clouds in column (IWP > ε, LWP > ε)
  - Vertical profiles of IWC and LWC are needed for diagnosing mixed-phase cloud forcing
- Compare PD and PI results

Conditional sampling (cloud phase) - CAM5

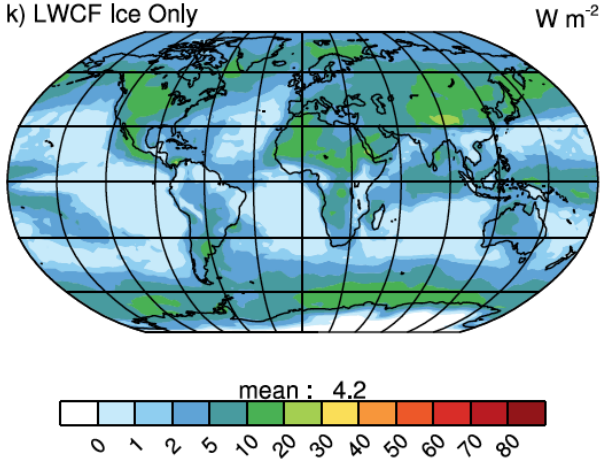
Present-day

Total

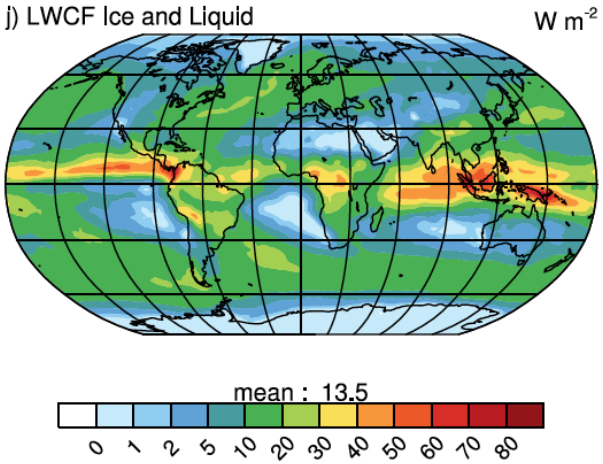


Zhang et al. (in preparation)

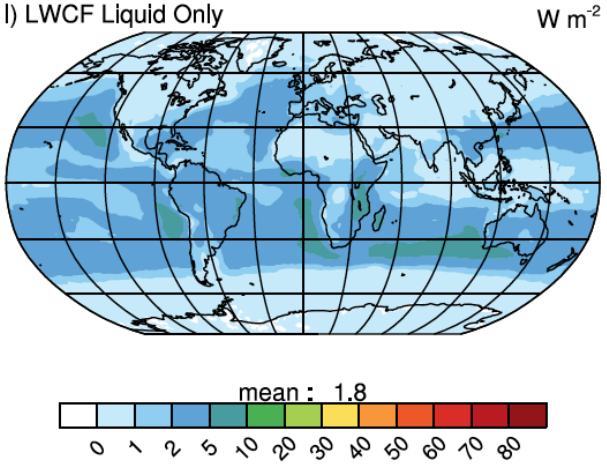
Pure Ice



Liquid and Ice (>threhold)



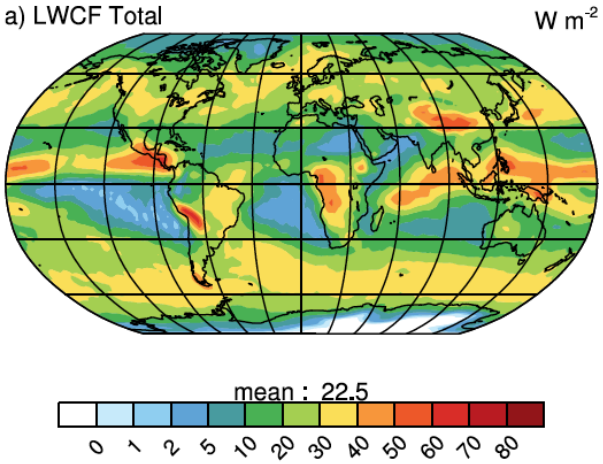
Pure Liquid



Conditional sampling (cloud phase) – ECHAM6-HAM

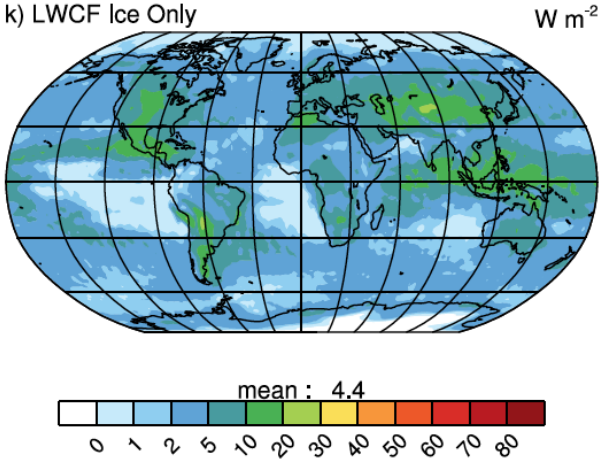
Present-day

Total

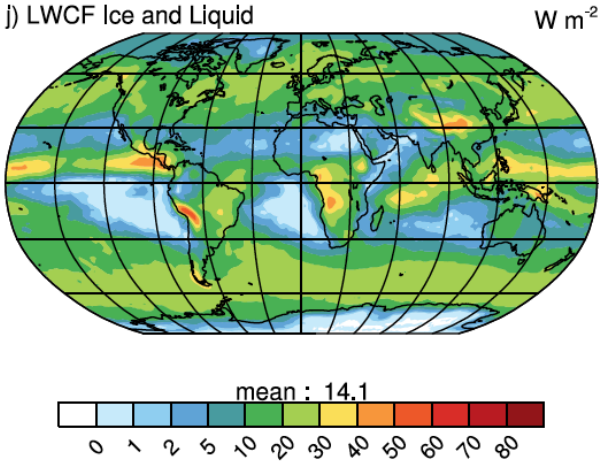


Zhang et al. (in preparation)

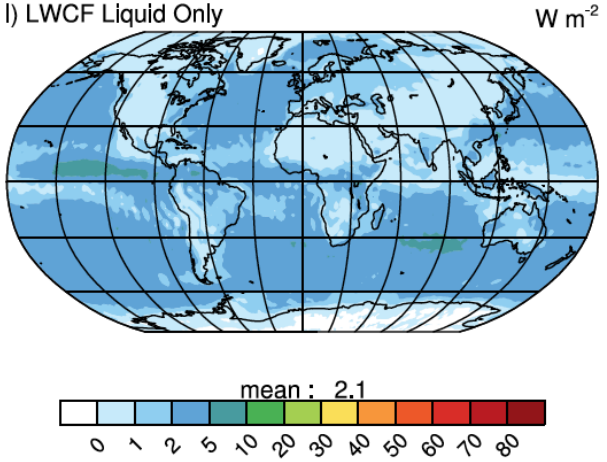
Pure Ice



Liquid and Ice (>threhold)



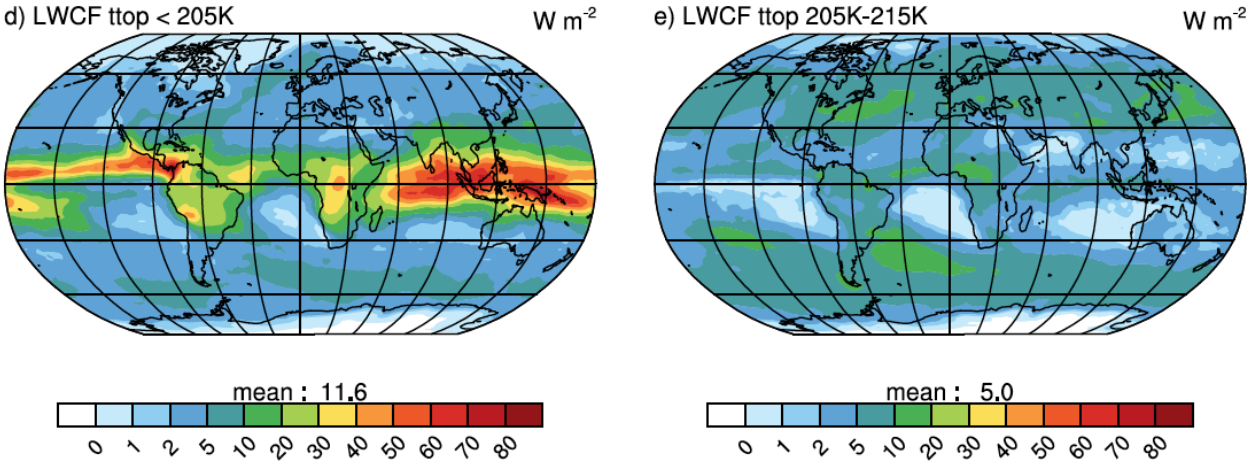
Pure Liquid



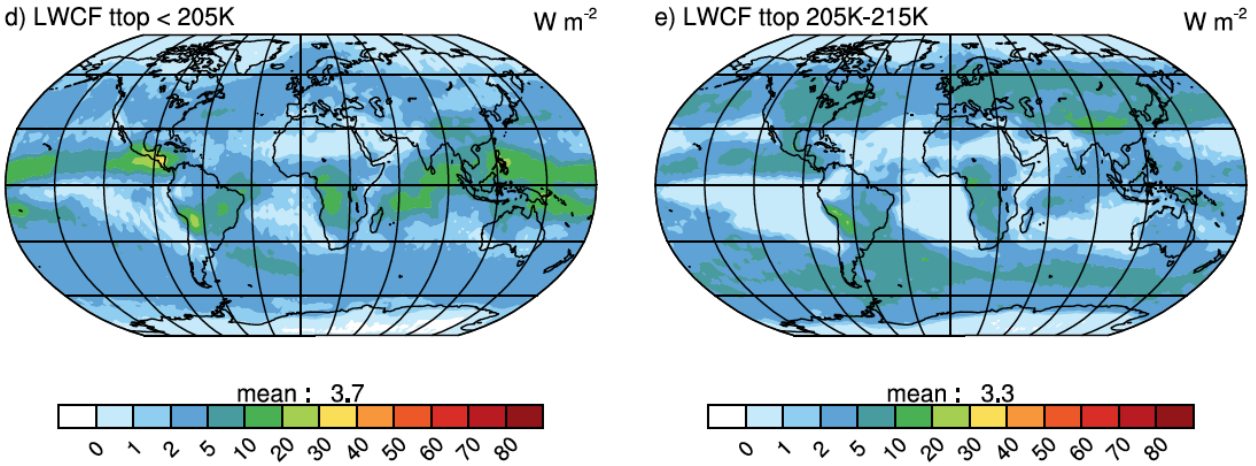
Conditional sampling (Cloud top temperature)

Present-day

CAM5



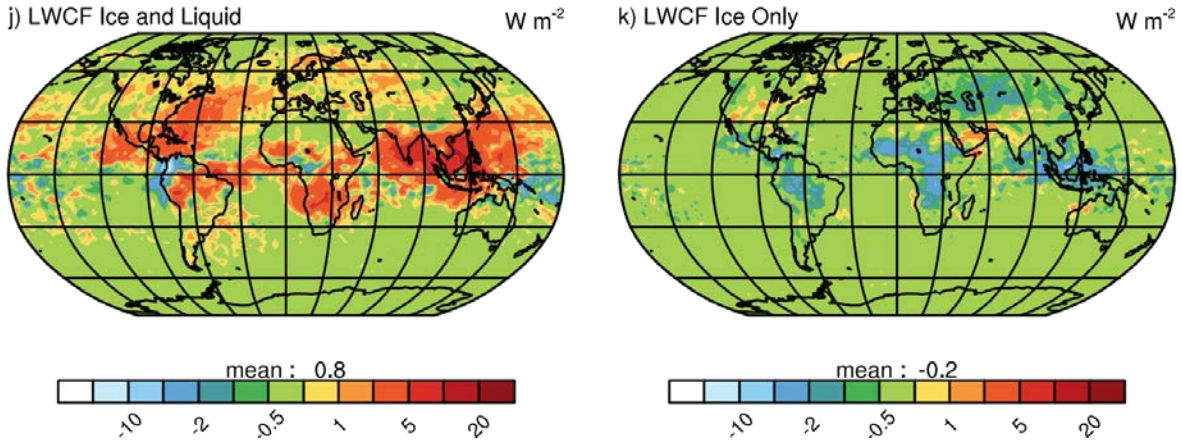
ECHAM6-HAM2



Zhang et al. (in preparation)

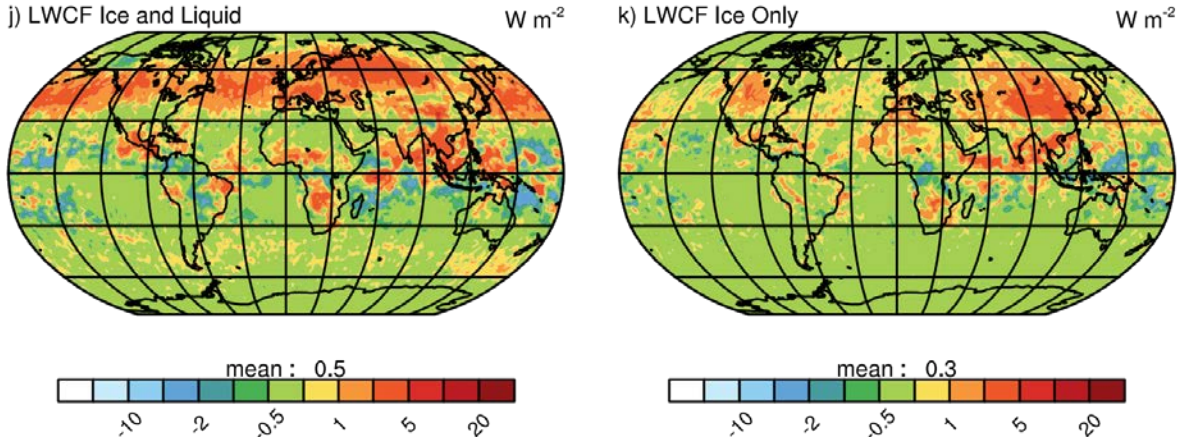
Conditionally sampled LWCF (PD – PI)

CAM5



Weakened upward motion

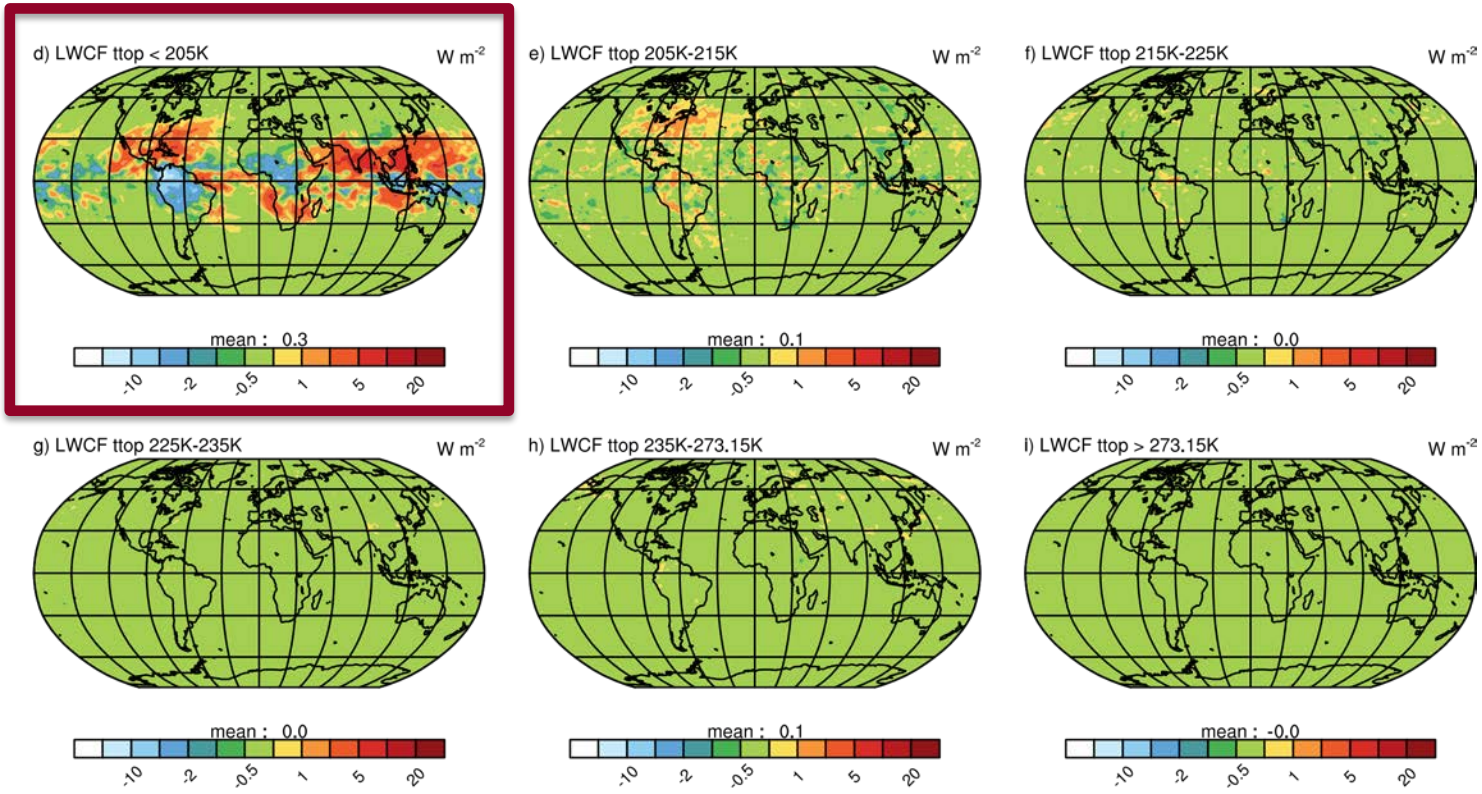
ECHAM6-HAM2



Zhang et al. (in preparation)

PD – PI Conditionally sampled for each TTOP range

CAM5

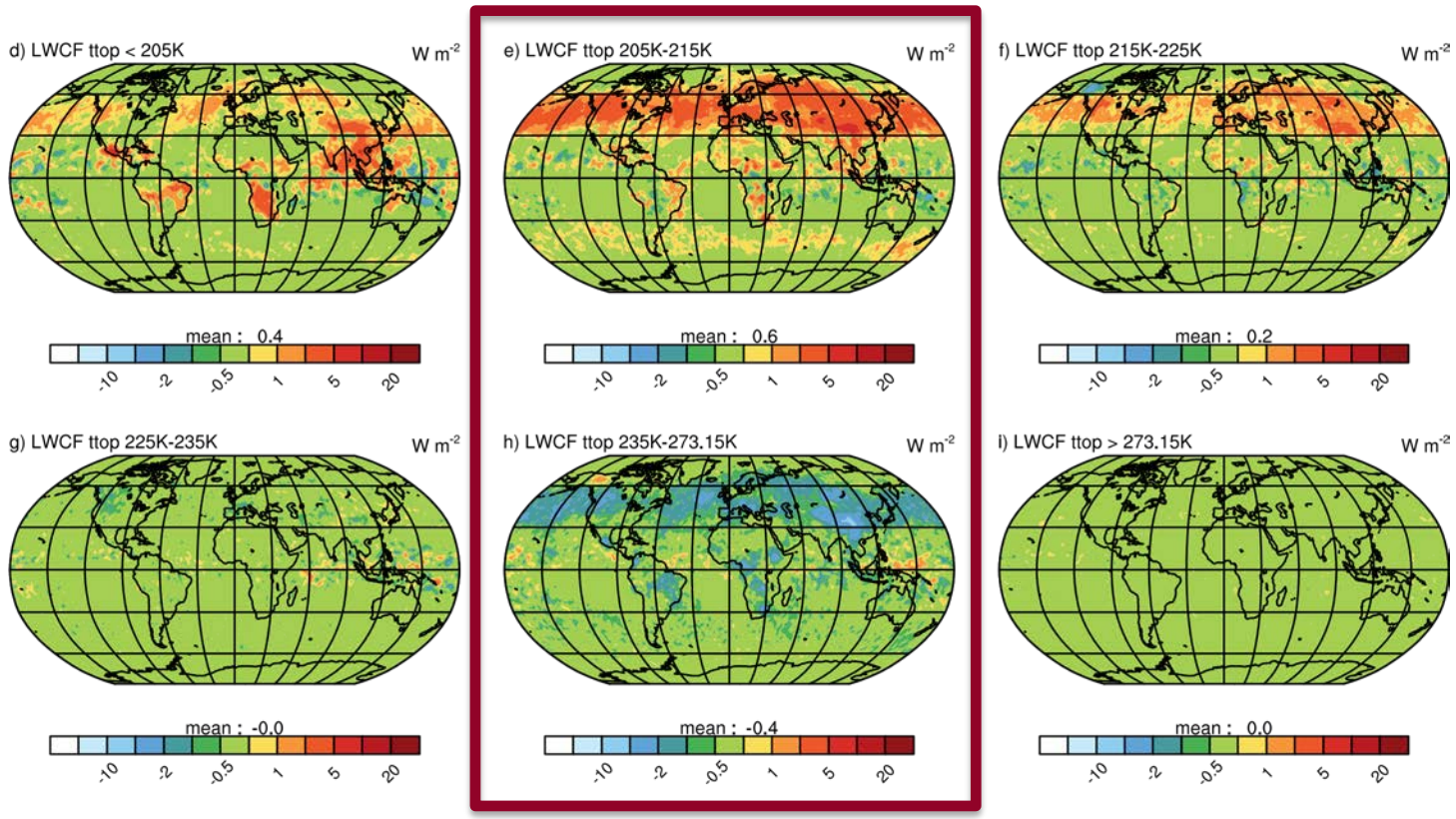


Most changes in CAM5 are associated with deep convective clouds.

Zhang et al. (in preparation)

PD – PI Conditionally sampled for each TTOP range

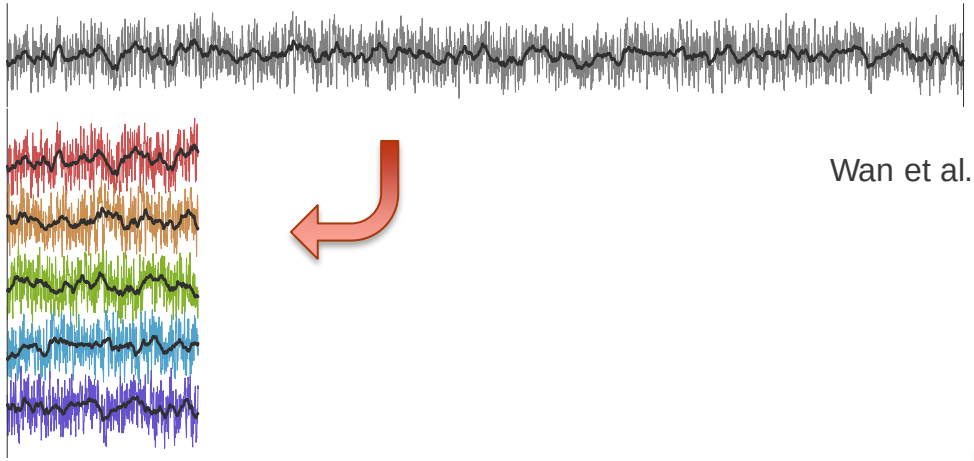
ECHAM6-HAM2



Zhang et al. (in preparation)

Changes in heterogeneous ice nucleation and its competition with homogenous ice nucleation in ECHAM6-HAM2 leads to differences in different cloud types.

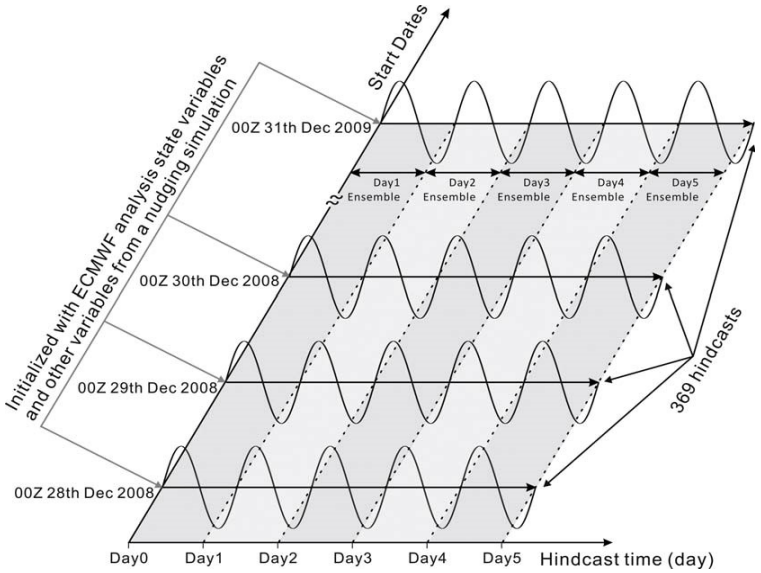
Short nudged or initialized ensemble hindcast simulations



Wan et al. (2014)

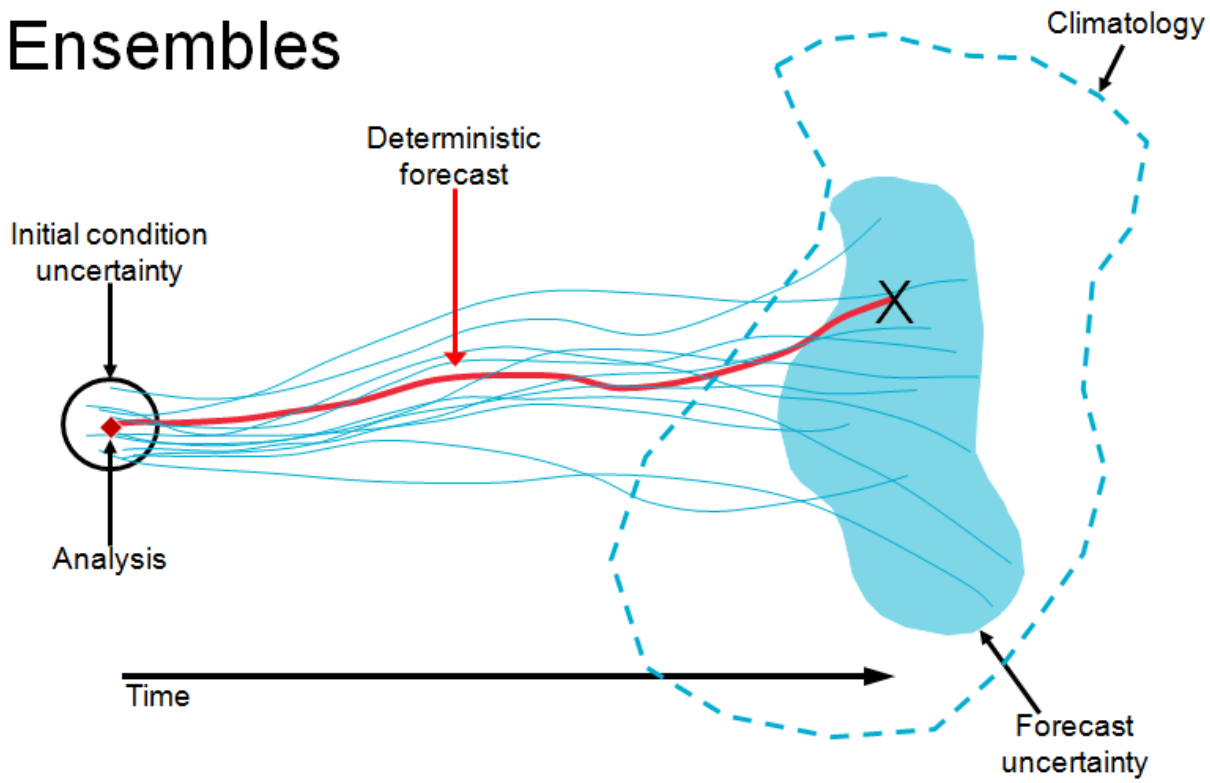
Methods to create ensembles

1. Perturbing nudging coefficients in nudged simulations - **nudged hindcast ensembles**
2. Perturbing initial conditions in transpose-AMIP type (free-running) simulations - **initialized hindcast ensembles**



Ma et al. (2015)

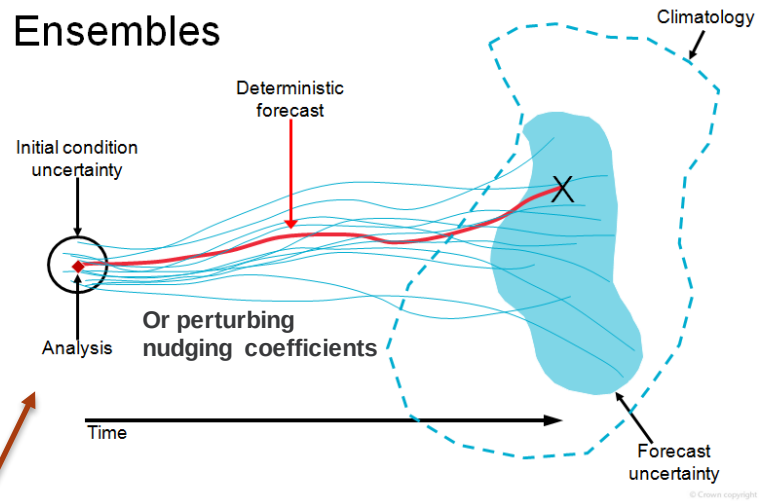
Ensemble forecast in weather models



Source: MetOffice

Nudged or initialized hindcast ensembles (e.g. PD vs. PI)

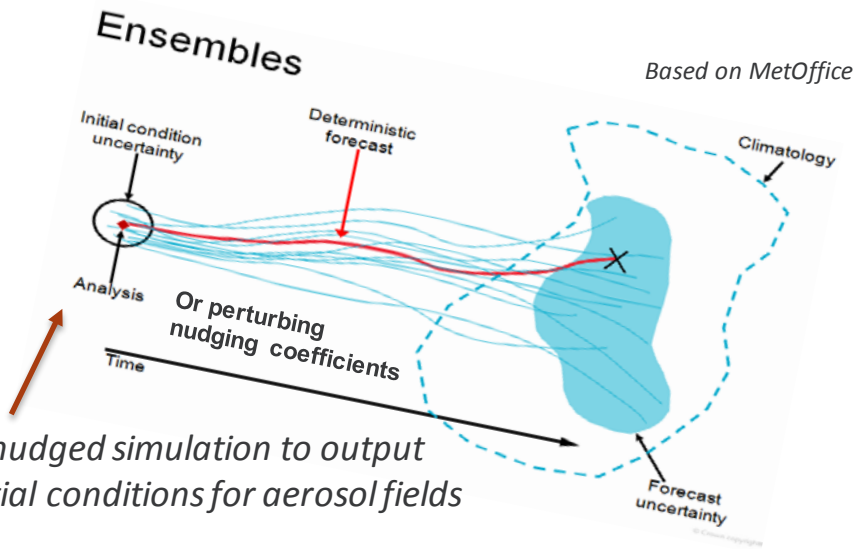
With present-day emissions



PD nudged simulation to output initial conditions for aerosol fields

With pre-industrial emissions

Based on MetOffice

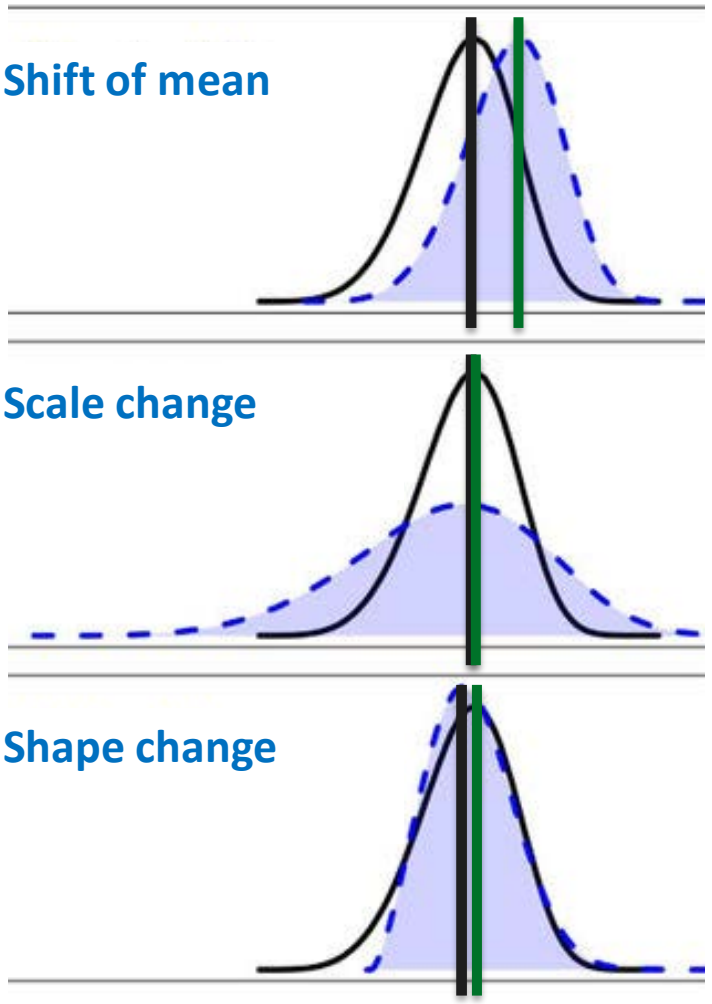


PI nudged simulation to output initial conditions for aerosol fields

Compare both mean and distribution (e.g. PD vs. PI)

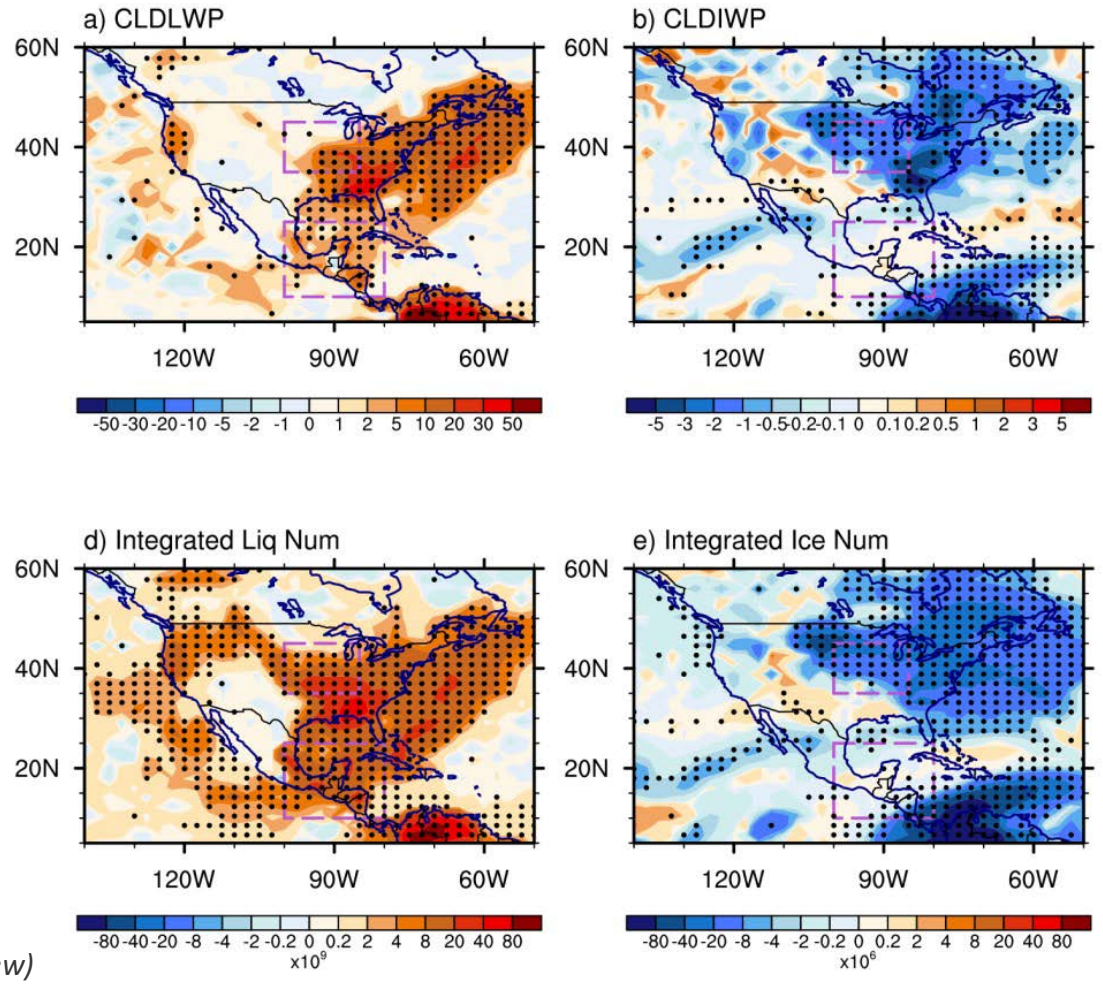
Single estimate

Ensemble estimate



Impact of fire aerosols on liquid and ice clouds

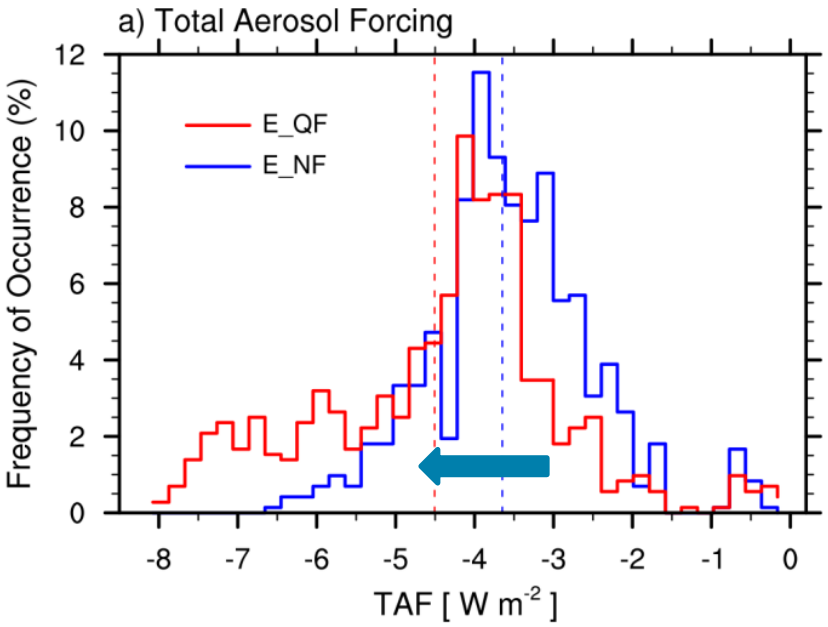
Difference between two group of 10-day **nudged hindcast ensemble** simulations (with and w/o fire aerosol emissions).

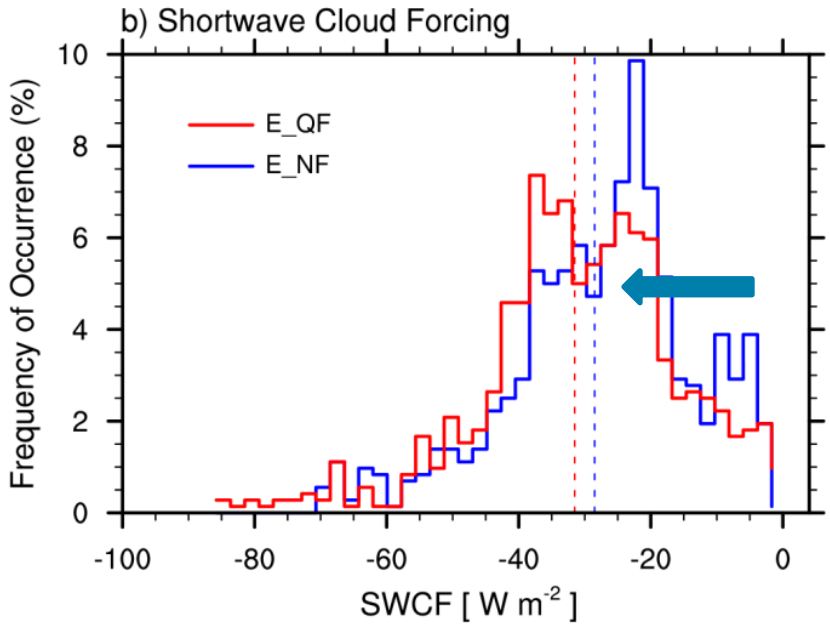


Liu et al. (2017, under review)

Changes in probability distribution (No fire vs. with fire)

Southern Mexico





72 grid boxes, 10 ensemble members, 720 samples

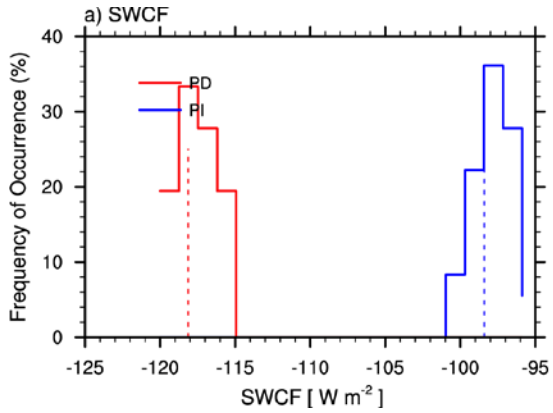
Liu et al. (2017, under review)

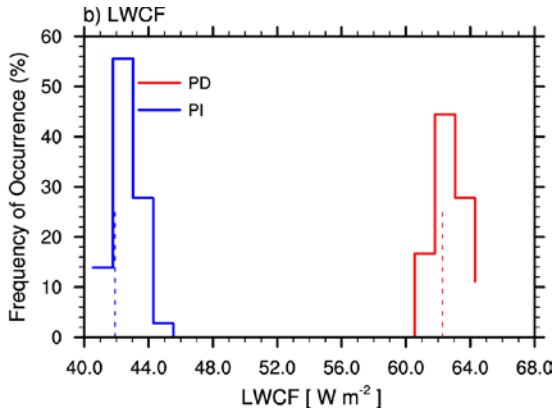
Initialized ensemble hindcast (PD vs. PI)

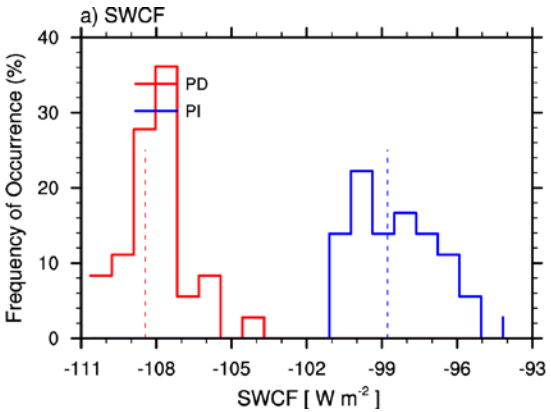
GMT 00:00 Dec 31, 2005

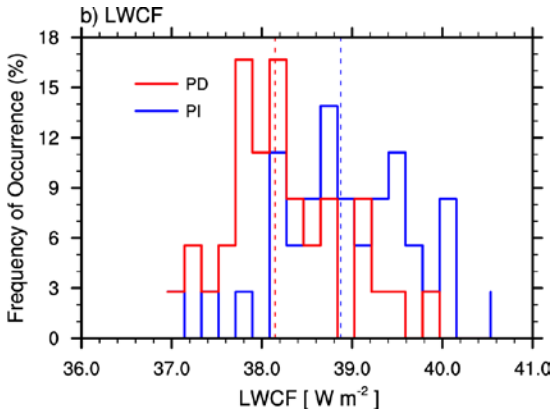
GMT 00:00 Jan 1, 2006

Day 2 ensemble hindcast







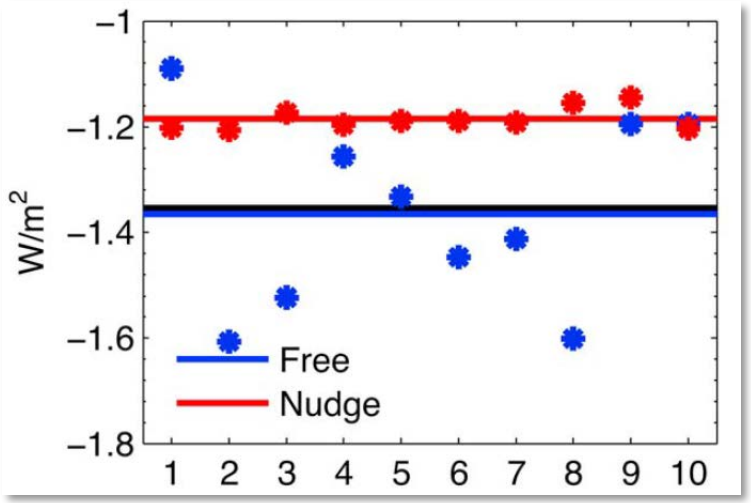


Summary

- With nudging and short hindcast ensembles, it is much easier to detect the aerosol-effect signal from the noise.
- Conditional sampling helps isolate the impact on ice, liquid, and overlapped clouds and look at aerosol effects on different types of clouds.
- Short hindcast ensembles can provide an uncertainty estimate and help us evaluate whether the aerosol effect is robust.
- Both the microphysical and dynamical effects of aerosols are important for the impact on ice clouds.

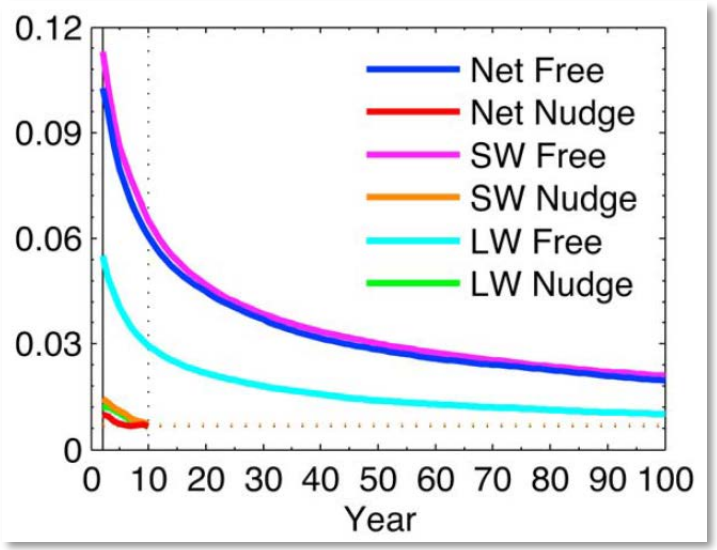
Assessing the anthropogenic aerosol effect

Net Indirect Effect



Year

Standard Error



Year

Kooperman et al. (JGR2012)