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An Efficient Method for Discerning Climate-Relevant Sensitivities in AGCMs

Hui Wan, Phil Rasch, Kai Zhang, Yun Qian, Huiping Yan, Chun Zhao

Pacific Northwest National Laboratory

(Hui.Wan@pnnl.gov)

Thanks to Maoyi Huang, Qing Yang, Steve Ghan (PNNL), Cecile Hannay (NCAR) and the SciDAC Multiscale team for suggestions and technical help

Motivation

- We're interested in time step sensitivities and convergence properties in CAM5
- AMIP simulations need multiple years/decades to overcome natural variability
- Model with small time step is expensive to integrate

⇒ Need an alternative experimentation strategy

- **Our idea**

Replace serial-in-time long-term climate simulations by representative ensembles of shorter runs

- Utility of the method goes far beyond time step sensitivity
- An uncertainty quantification (UQ) example is shown later
- Very useful in efficient model tuning and sensitivity analysis, especially for high-resolution models

Comparison with CAPT

Similarities

- Both exploit the important role of fast processes in determining model sensitivities/uncertainties

Differences

- Model biases v.s. sensitivities as focus
- In this study we are interested in parametric and structural sensitivities close to the model's equilibrium state

We are trying to make use of the scientific basis of CAPT in more general ways

Evaluation Example (1): Time Step Sensitivity

- Reference simulations
  - 1+5-yr simulations, 2 degree FV dycore
  - 30-miniute and 4-minute time step
  - 5-yr mean DJF differences in clouds and precipitation

- Ensemble simulations
  - 50 members
  - Initial conditions sampled from DJF of a previously performed 20-yr simulation
  - 30-minute and 4-minute ensembles use the same set of initial conditions

- Compare 5-yr winter averages with 1-day 50-member ensemble averages

Global Averages

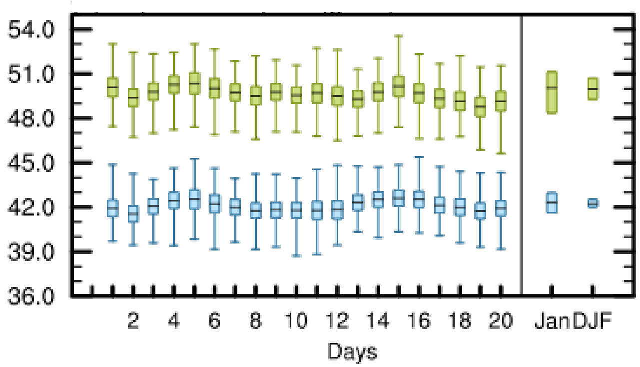
Global Mean Total Cloud Cover (%)

Daily mean ensemble averages

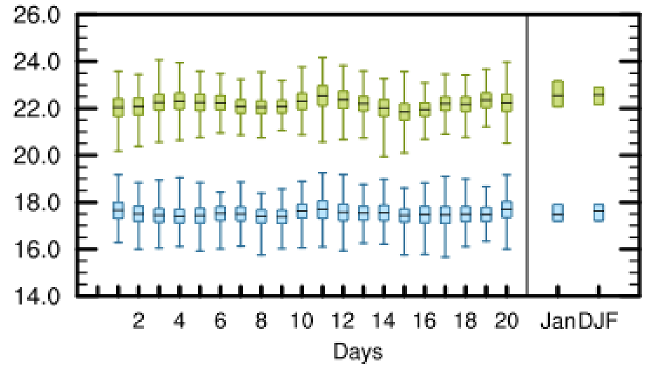
5-yr avg.

Some Other Fields

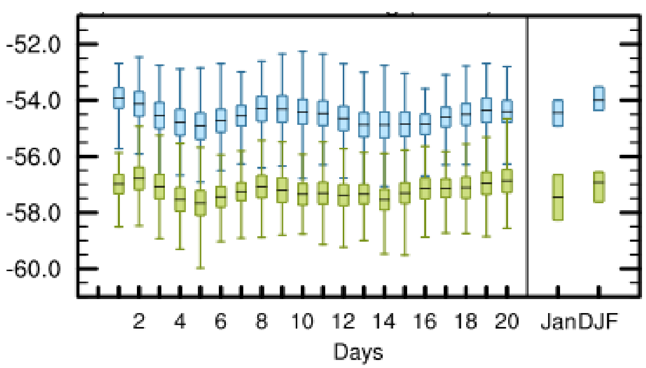
Liquid Water Path (g m^{-2})



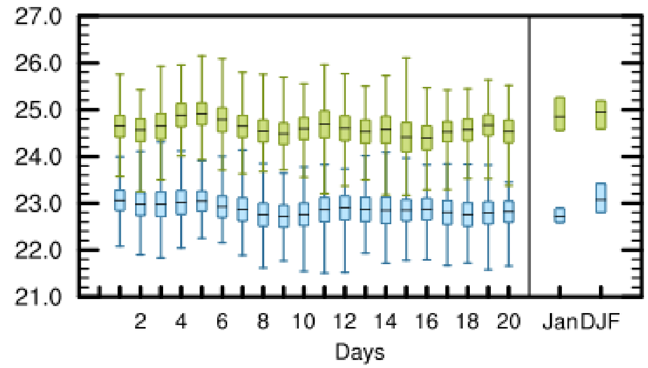
Ice Water Path (g m^{-2})



Shortwave Cloud Forcing (W m^{-2})



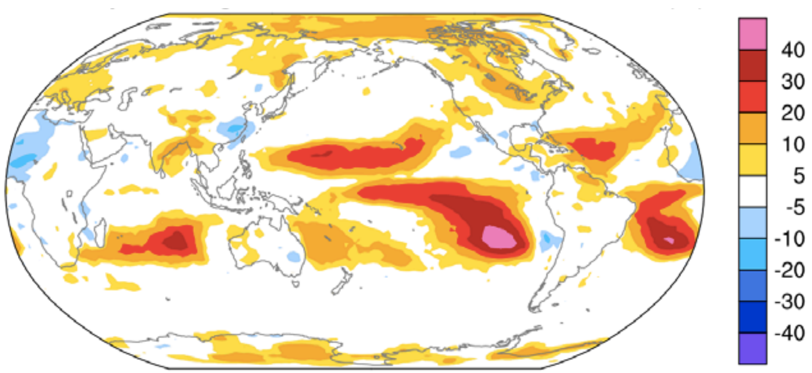
Longwave Cloud Forcing (W m^{-2})



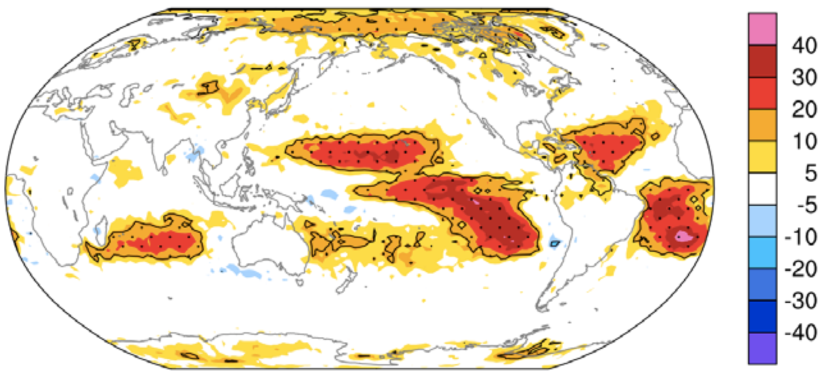
Geographical Distribution

Total Cloud Cover Difference (%)
4-minute minus 30-minute time step

5-yr DJF Average



50-member Average at Day 3



Stippling in the right panel indicates differences
significant at the 95% confidence level according to the local t-test.

Vertical Structure

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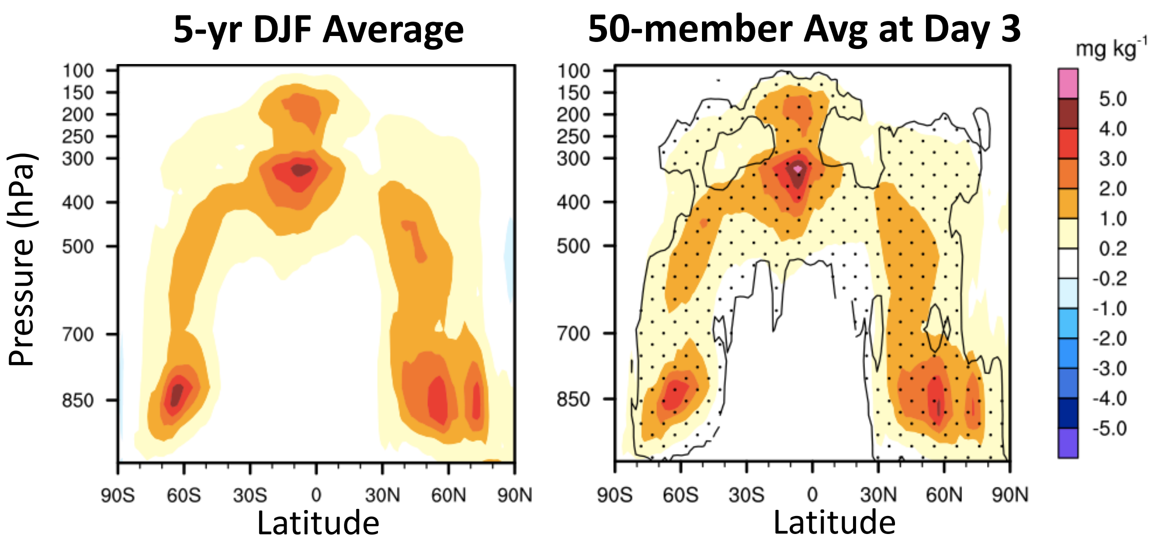
Δ Cloud Ice
4-minute minus 30-minute time step



Stippling in the right panel indicates differences significant at the 95% confidence level according to the local t-test.

Summary of Example (1)

Effectiveness

- Ensembles of 20 to 50 three-day simulations are sufficient for clouds and precipitation
- The method can detect global mean differences AND identify climate regimes
- Ensembles can be combined with nudging to help understand the role of physics-dynamics interaction (not shown here)

Computational efficiency

- 50 x 3-day simulations *v.s.* 1+5-yr climate run
- Total CPU time: 150 *v.s.* 2190 days, a factor of 15
- Throughput time: 20 minutes v.s. 4-7 days on Yellowstone, a factor of several hundred
- Contrast can be even stronger for certain variables and domain averages

Evaluation Example (2): Uncertainty Quantification

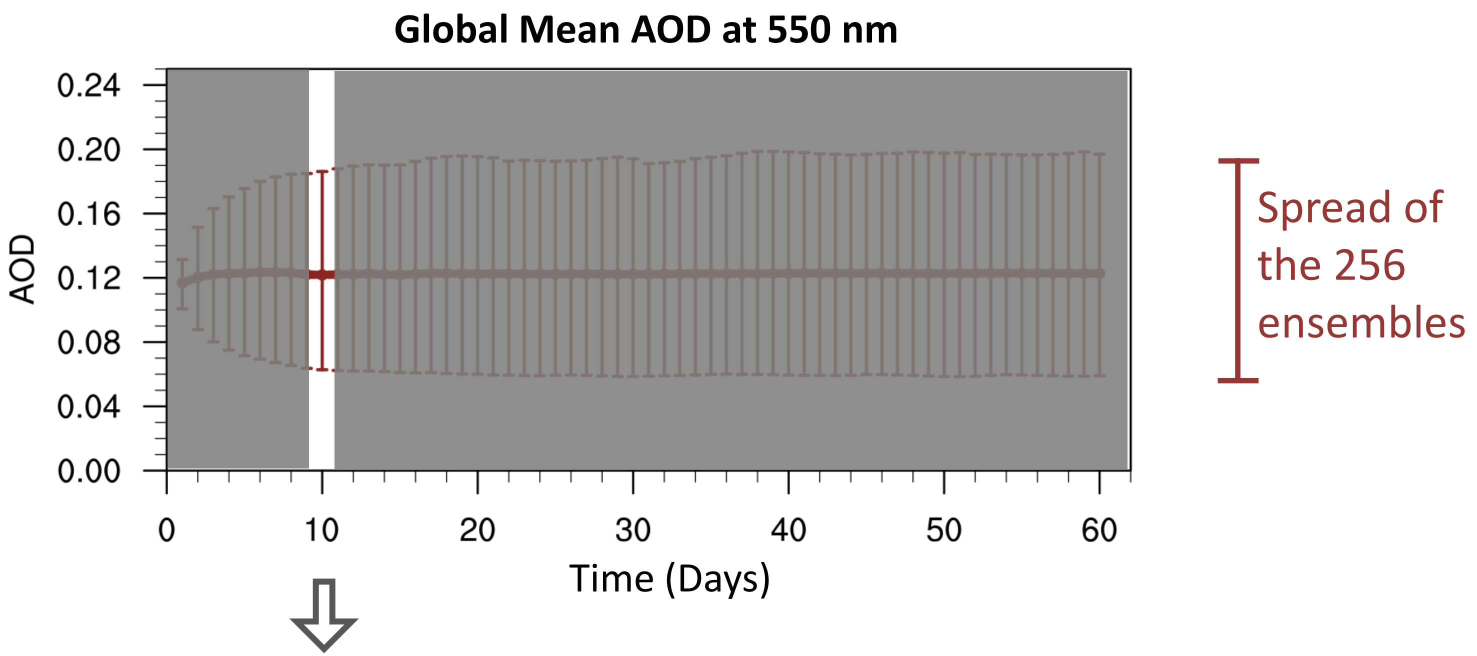
- Zhao et al. (2013, doi:10.5194/acp-13-10969-2013)
  - Parametric sensitivity of TOA radiatiative balance
  - Perturbed 16 empirical parameters in CAM5
  - Quasi-Monte Carlo sampling, 256 simulations, 1+4-yr AMIP

- Our ensemble experiments
  - Same 256 parameter combinations
  - 12 ensemble members representing 12 months of a year

- Compare 4-yr averages with 1-day 12-member averages

Spin-up Time

- 11 out of 16 parameters directly affect aerosols (e.g., tuning factors for emissions)
- Global mean aerosol life cycle is ~4 days in CAM5-MAM3 (Liu et al., 2012, GMD)
- Expect longer spin-up than in the 1st example



Day-10 averages are used in figures shown on the next slides

Global Mean TOA Net Radiative Flux (FNET)

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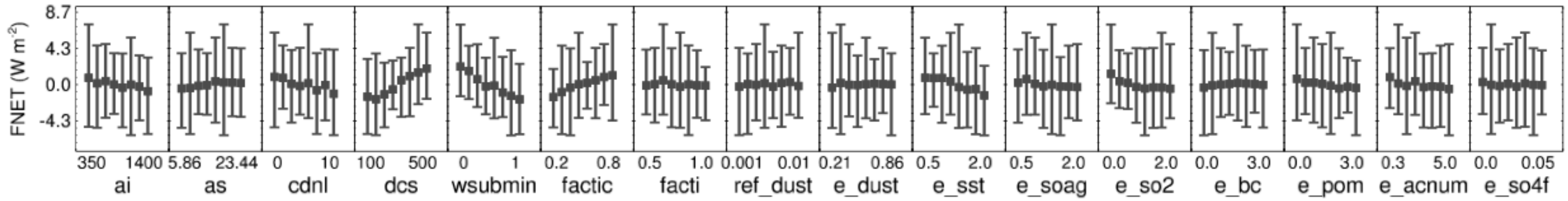
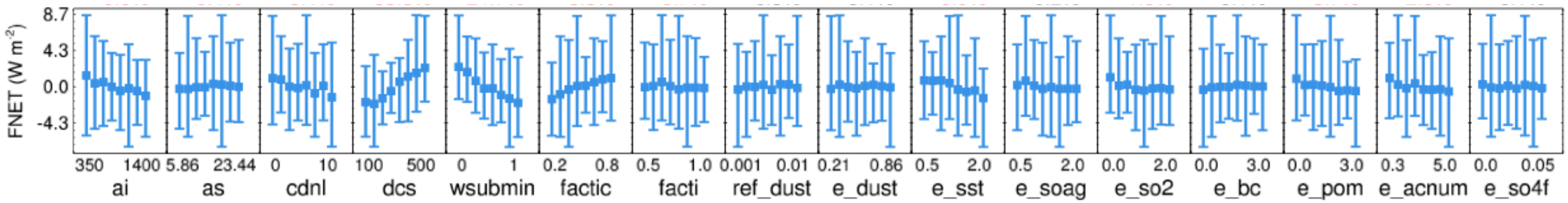
- Sensitivity of FNET to individual parameters

4-yr Annual Mean



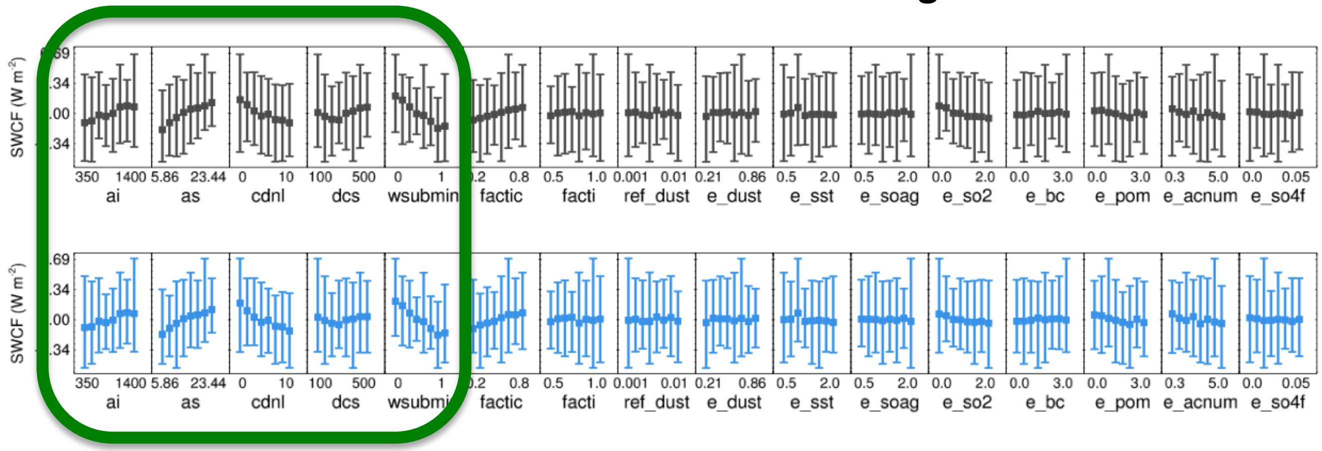
12-member Ensemble Average at Day 10



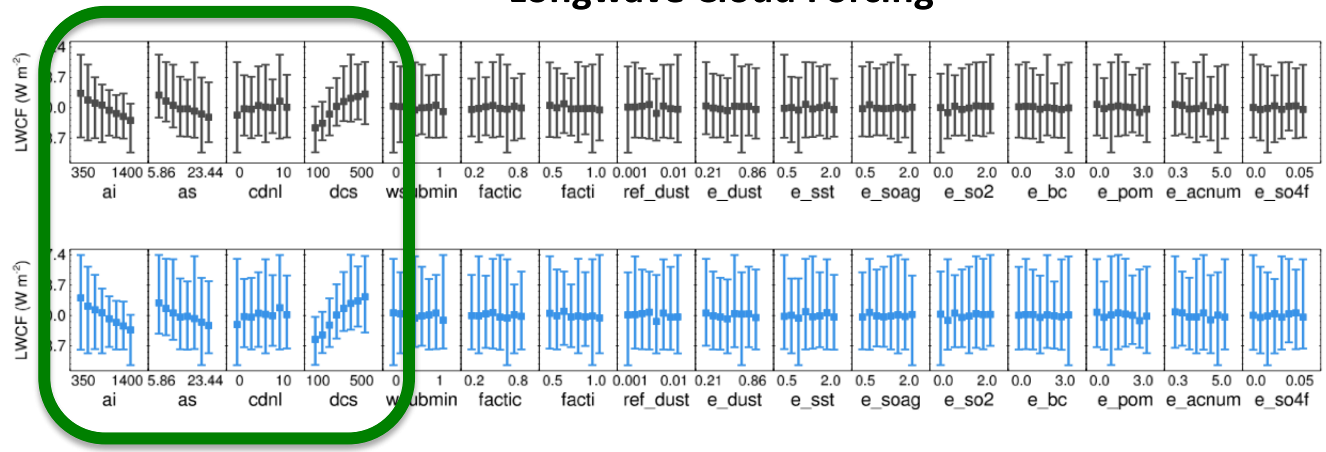
Cloud Forcing

Black: 4-yr mean; Blue: 12-member ensemble average at day 10

Shortwave Cloud Forcing



Longwave Cloud Forcing



Summary of Example (2)

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Effectiveness

- Short ensembles correctly reproduces parametric sensitivities of the TOA radiative budget

Computational efficiency

- 12 x10-day simulations *v.s.* 1+4-yr AMIP run
- Total CPU time: 120 *v.s.* 1825 days, a factor of 15
- Throughput time: 12 x 256 simulations finished overnight on Yellowstone
- If more nodes had been available to allow 3000+ simulations to run simultaneously, the entire ensemble UQ experiment could have been completed within 15 minutes!

Conclusions

The ensemble method

- Exploits the fact that **fast processes** are an important source of model sensitivities and uncertainties
- Is very **effective** and **efficient**
- Does not address slow modes or slow feedbacks, but
- Can provide a first-order assessment of model sensitivity at substantially reduced computational cost
- Can be very useful for speeding up investigations, especially for expensive models/studies

We plan to test and use the ensemble strategy in other applications

(e.g., aerosol lifecycle and climate effects)