School of Earth and Environment
INSTITUTE FOR CLIMATE & ATMOSPHERIC SCIENCE

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Model sensitivity and uncertainty analysis
Towards AeroCom MMPPE

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National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

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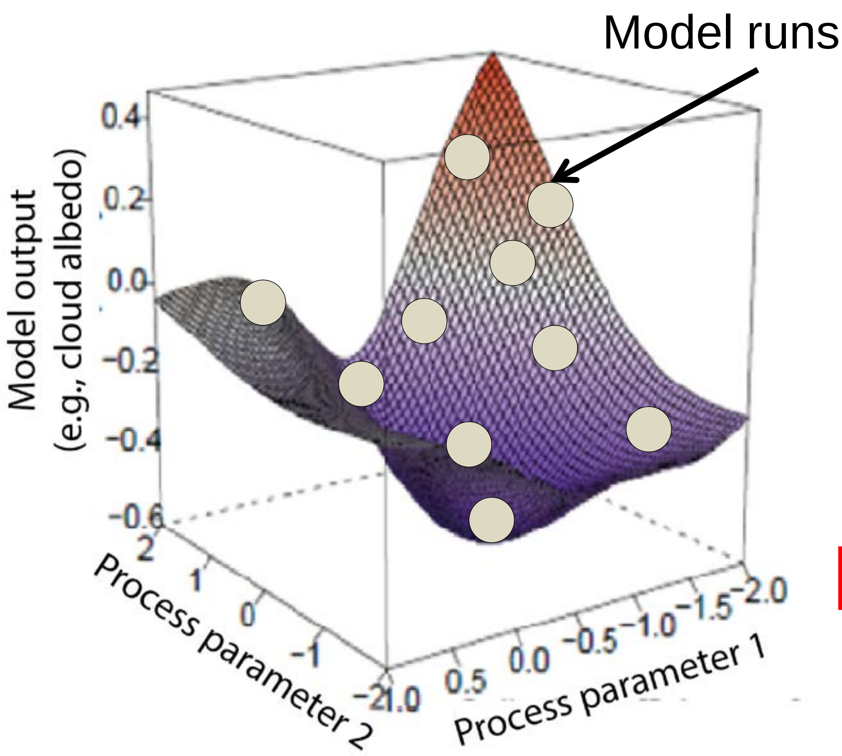
THE ROYAL SOCIETY

What is a PPE?

A *Perturbed Parameter Ensemble* designed in such a way that we can ***map the response surface*** of a model using emulators



An emulator is a fast surrogate model that defines model output in terms of variations in model parameters

Extend to *N* dimensions for *N* important uncertainties

Lee, L.A. et al., Emulation of a complex global aerosol model to quantify sensitivity to uncertain parameters, ACP 2011.

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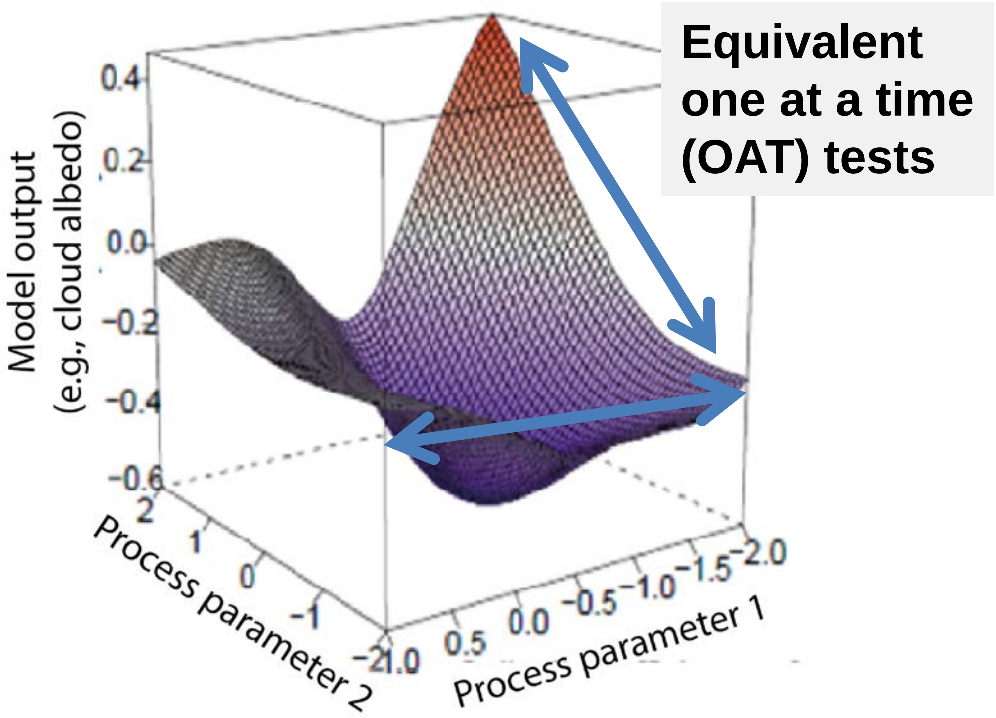
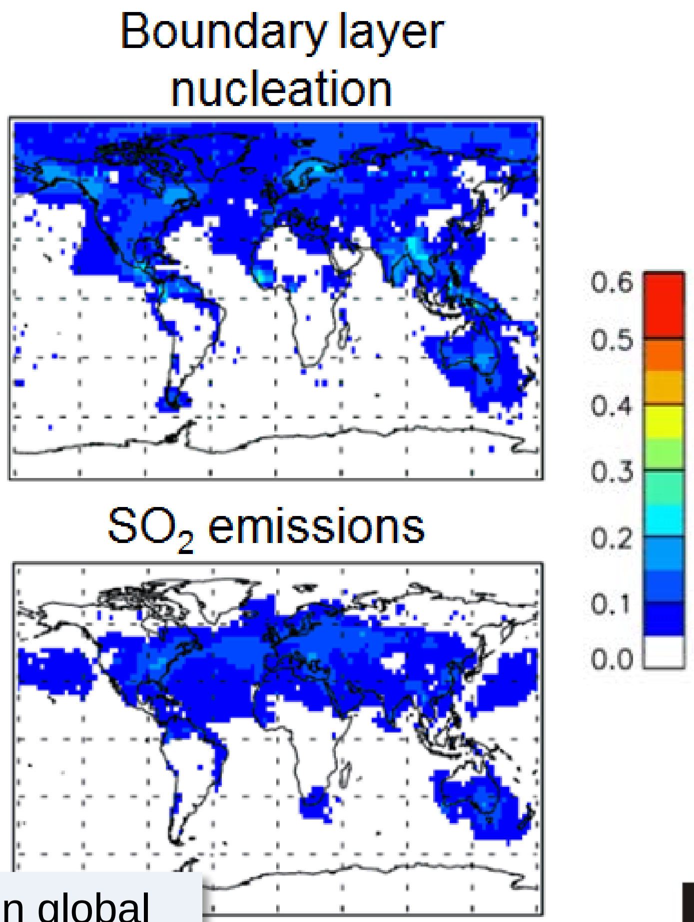
What can we do with a well designed PPE?

1) Very efficiently explore single and multiple process sensitivities and interactions





Lee, L.A. et al., The magnitude and causes of uncertainty in global model simulations of cloud condensation nuclei, ACP 2013.

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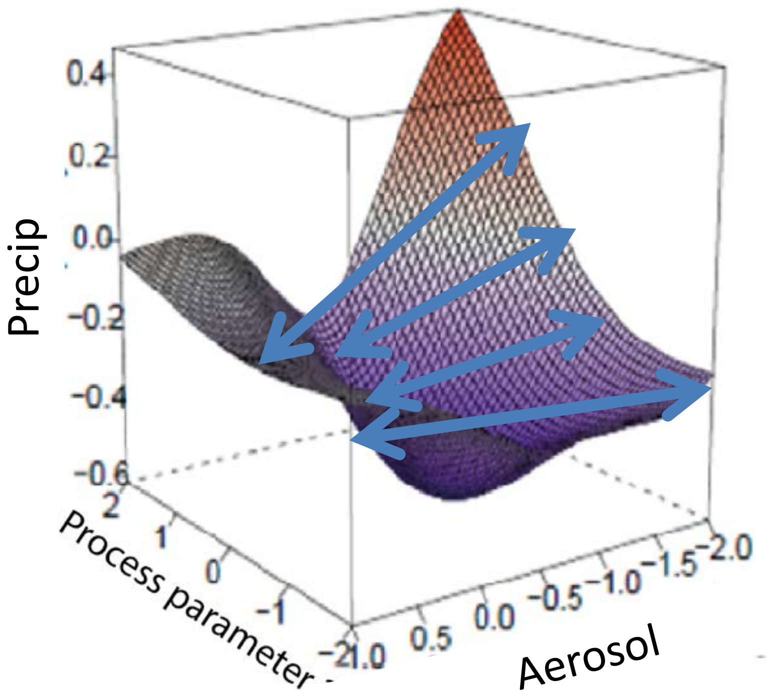
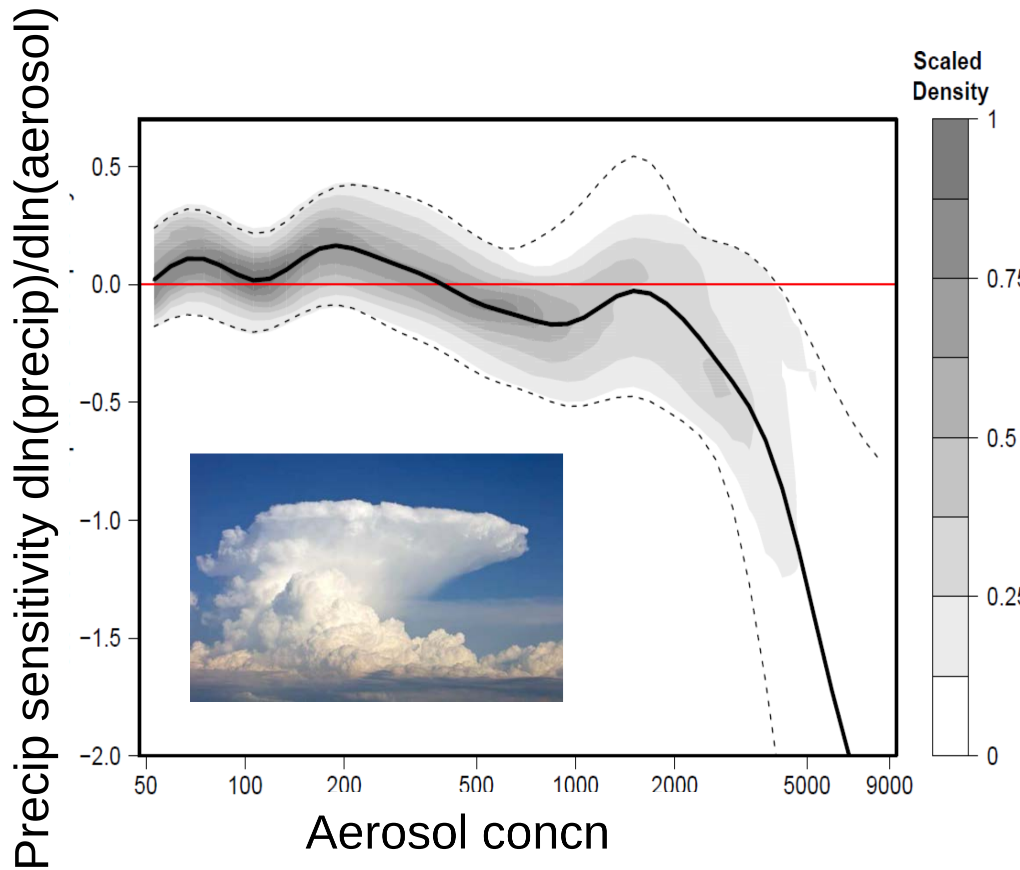
What can we do with a well designed PPE?

2) Quantify uncertainty in model responses





Johnson, J. et al., Evaluating uncertainty in convective cloud microphysics using statistical emulation, JAMES, 2013.

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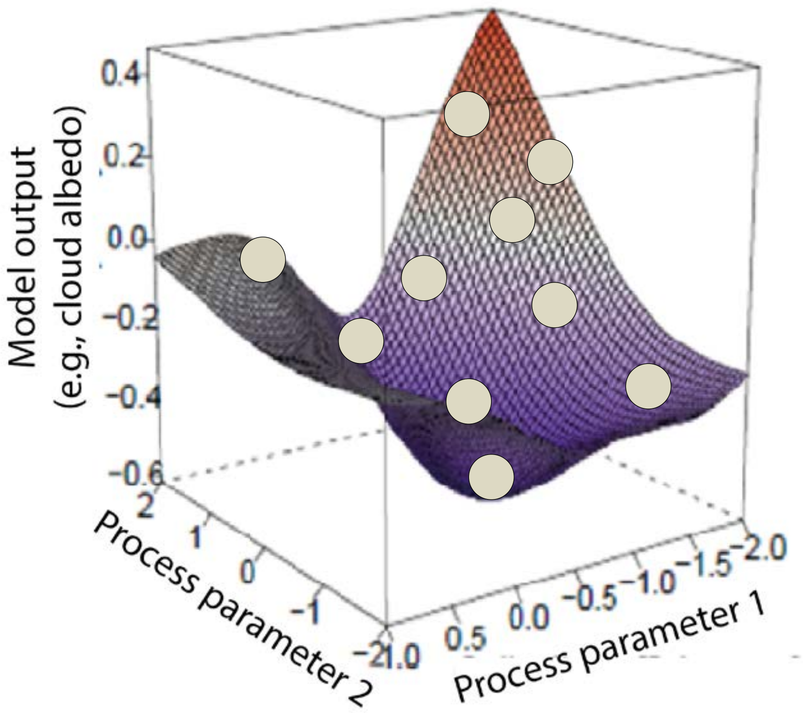
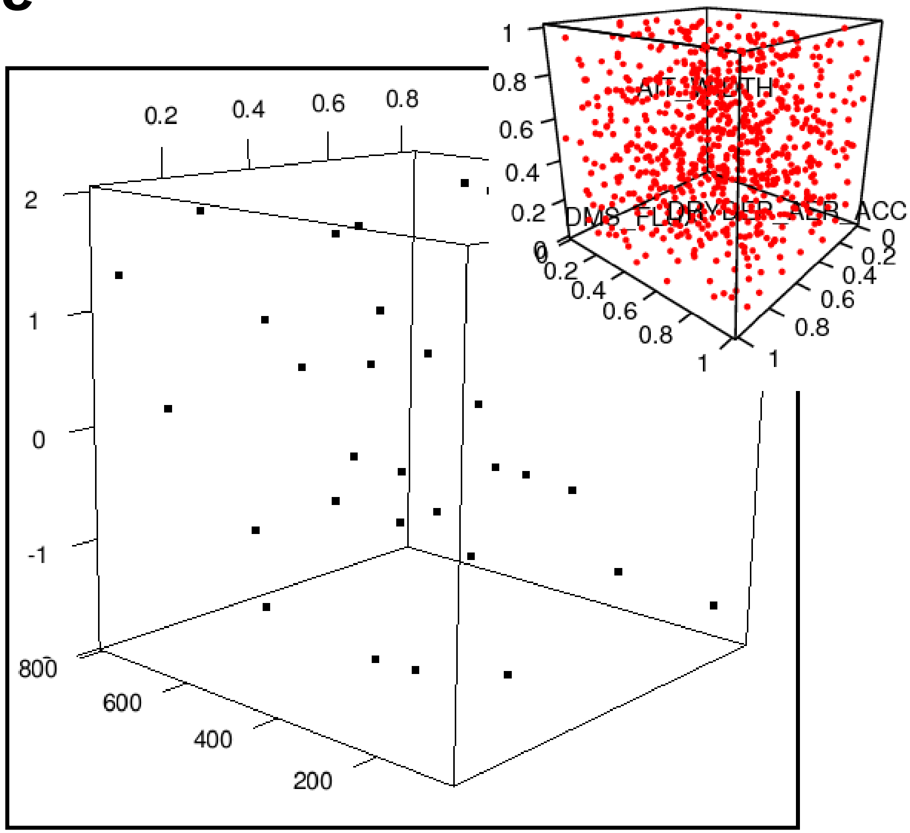
What can we do with a well designed PPE?

3) Quantify model uncertainty by Monte Carlo sampling from the response surface

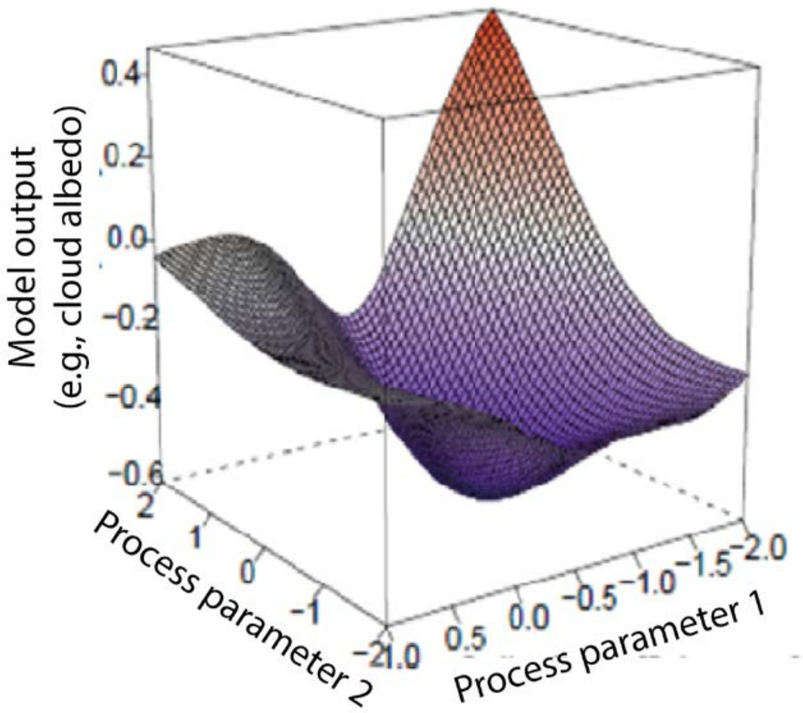




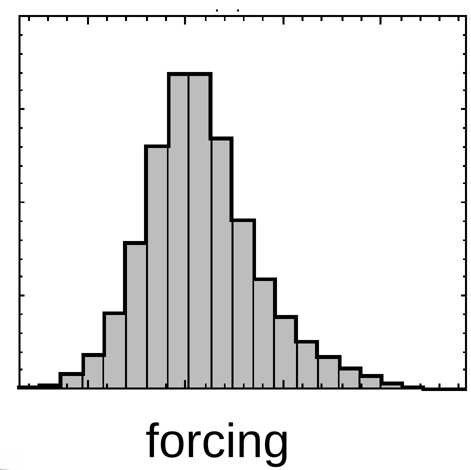
2D **3D**

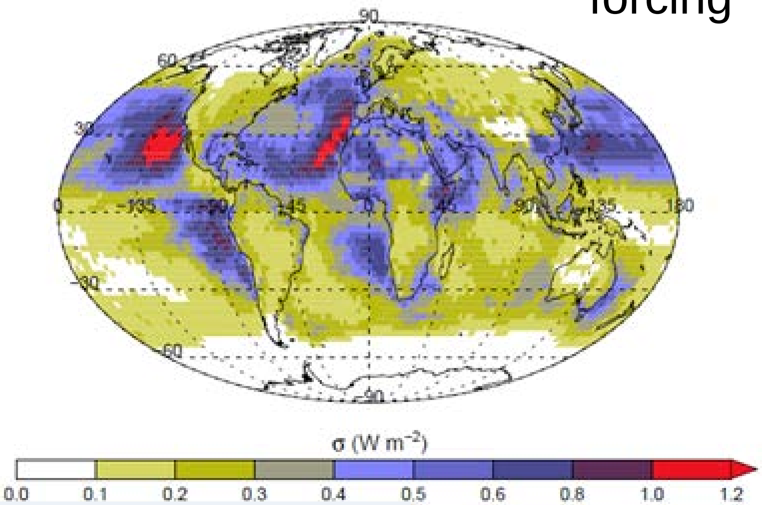
What can we do with a well designed PPE?

3) Quantify model uncertainty by Monte Carlo sampling from the response surface



PDF due to combined effects of 28 parameters in GLOMAP

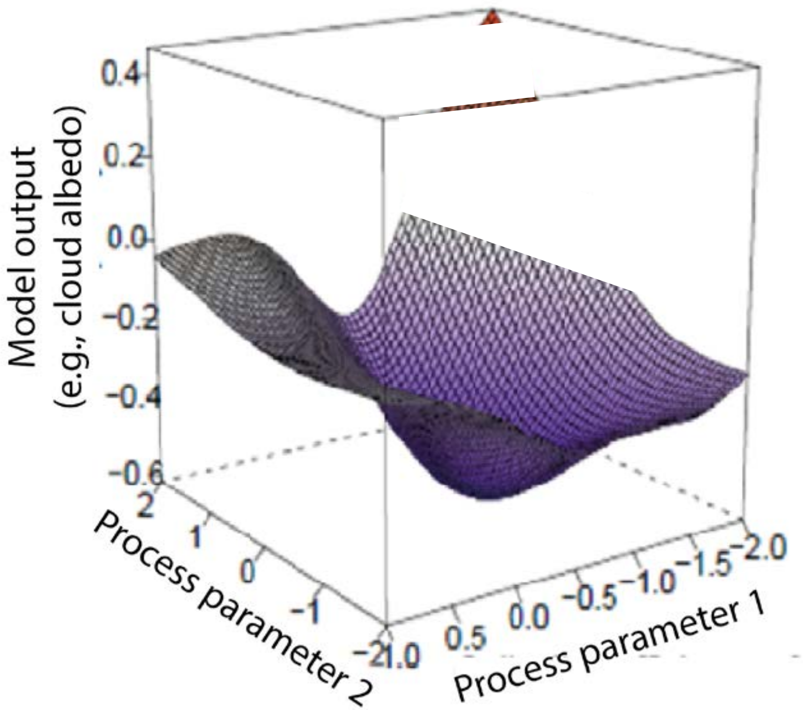




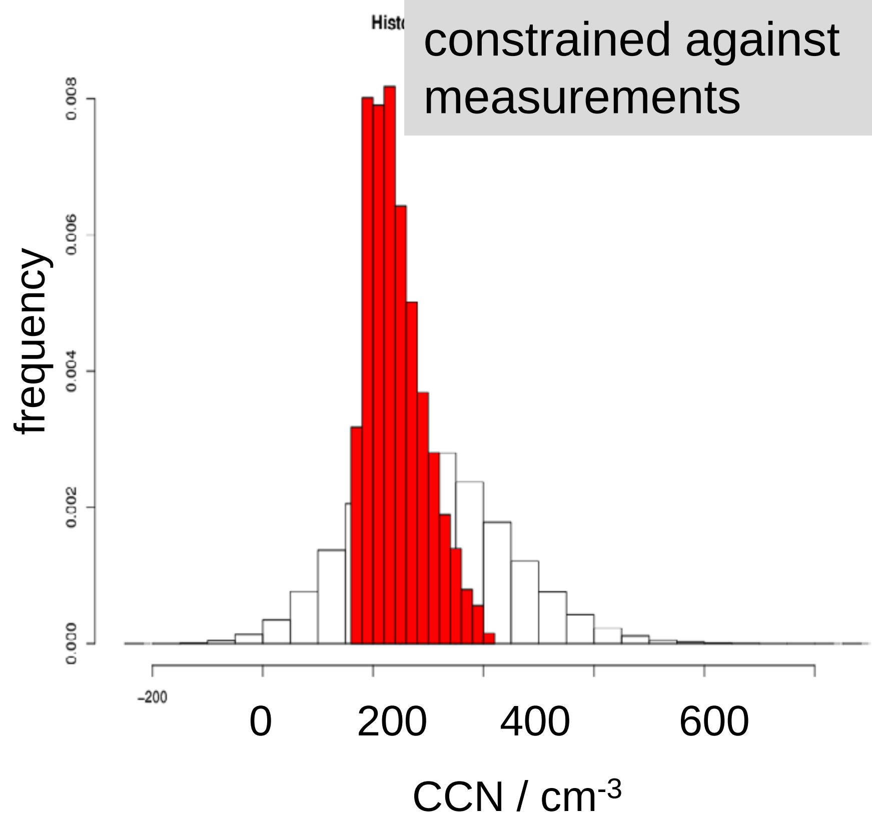
Carslaw, K.S. et al. Large contribution of natural aerosols to uncertainty in indirect forcing, Nature, 2013.

What can we do with a well designed PPE?

4) Constrain the model against measurements



N Atlantic CCN constrained against measurements



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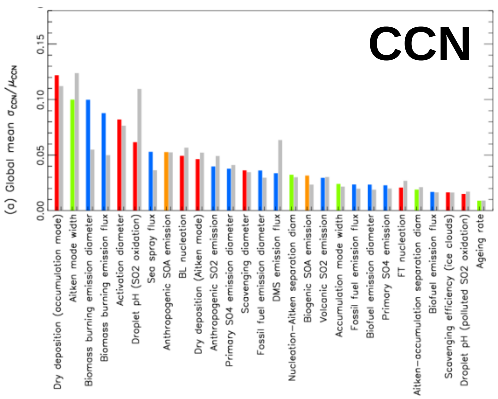
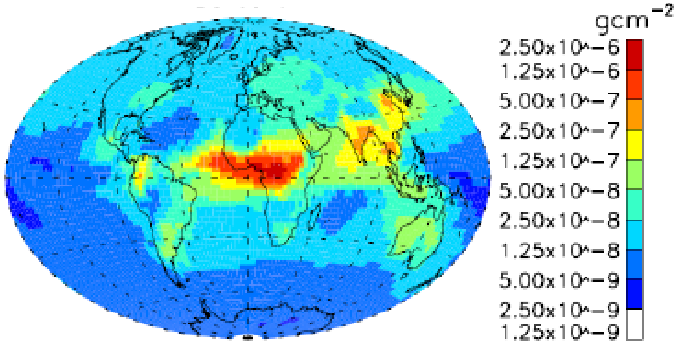
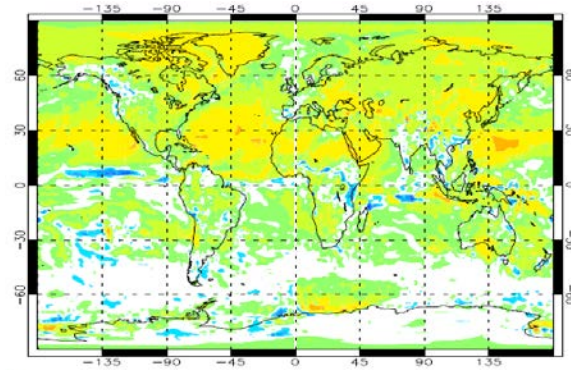
What have we done so far with GLOMAP?



Black carbon

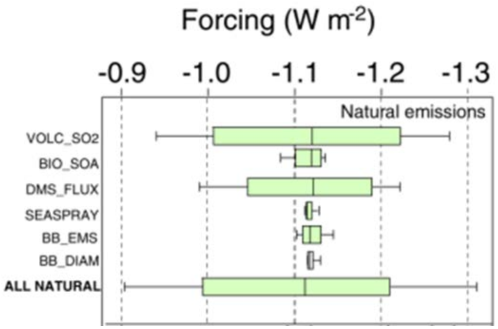


HadGEM-GLOMAP climate model

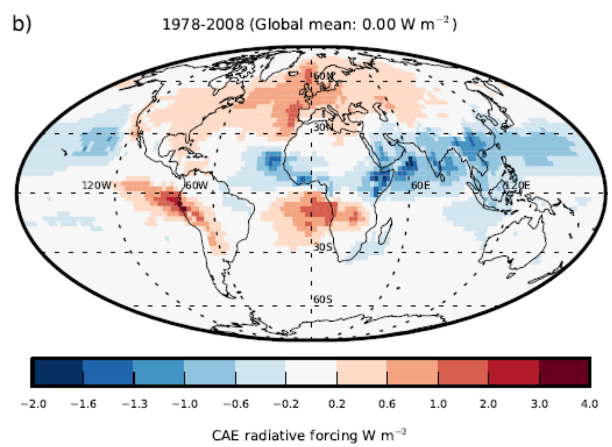


ERF uncertainty
(microphysics, clouds, optical & physics params)

First indirect effect 1750-2000



First indirect effect Recent decades and regional

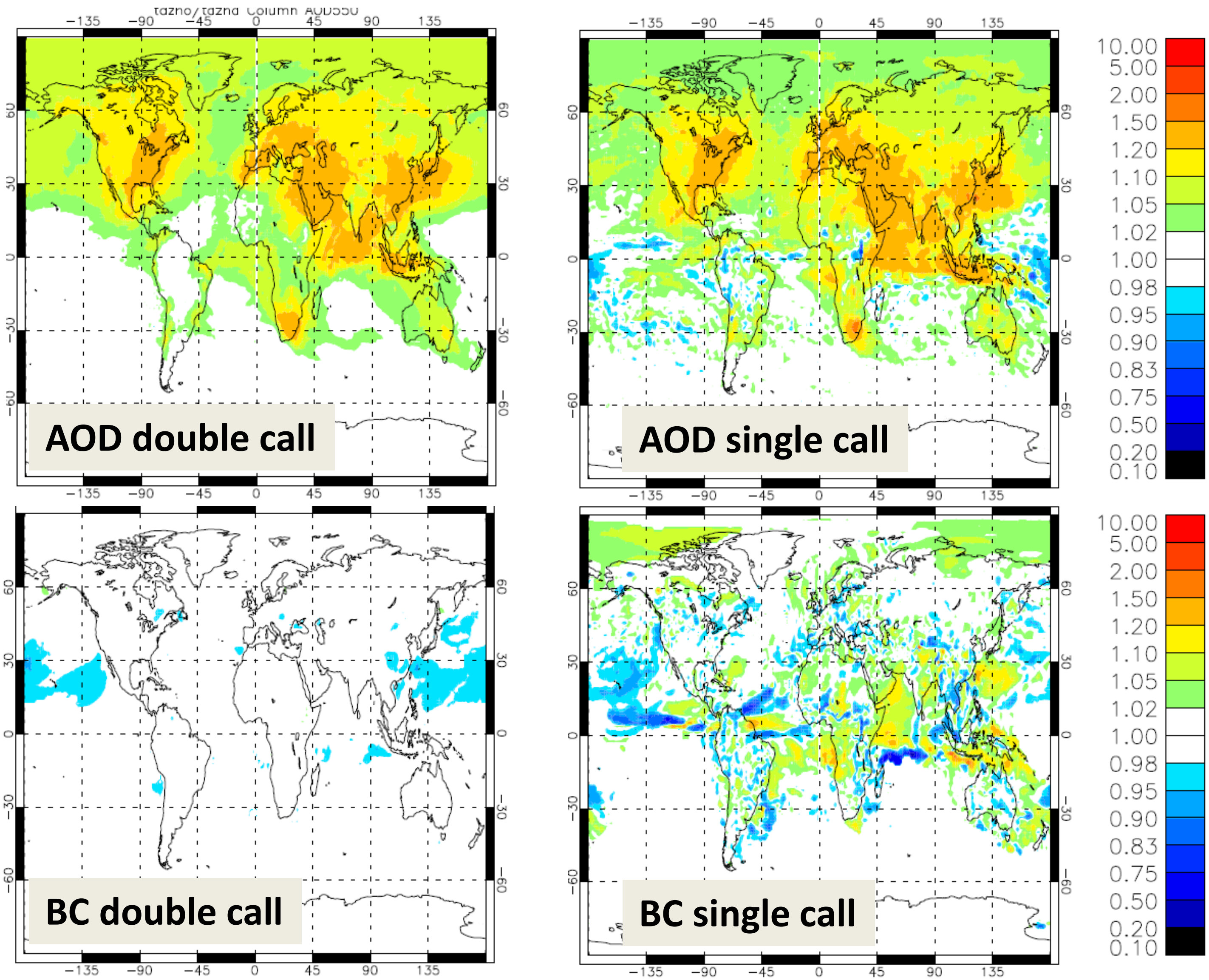


What’s the cost?

- From our experience, you need ~10 simulations per perturbed parameter
- Linear scaling: so 100 runs for 10 parameters
- Our studies have perturbed 28 and 31 parameters
- Climate model will perturb 27 parameters related to emissions, microphysics and optics, clouds, model physics
- But this delivers HUGE information

Nudged single versus double call (1 month)

Fractional changes when SO_2 emissions perturbed



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What is our “uncertainty reduction methodology”?

Improve processes

Model

2^{nd} model

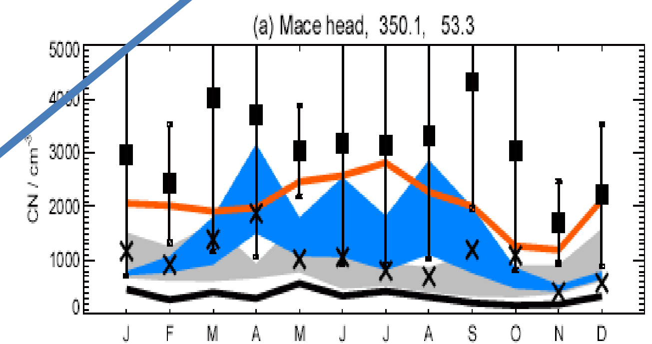
3^{rd} model

Lots of state variables (CCN, AOD, BC, etc)

Not forcing

Measured state variables

Model skill



An improved model that is closer to observations is not necessarily a less uncertain model

You can’t demonstrate a reduction in uncertainty until you have calculated it

Knutti and Sedlacek, **Robustness and uncertainties in the new CMIP5 climate model projections.** Nature Climate Change (2012)

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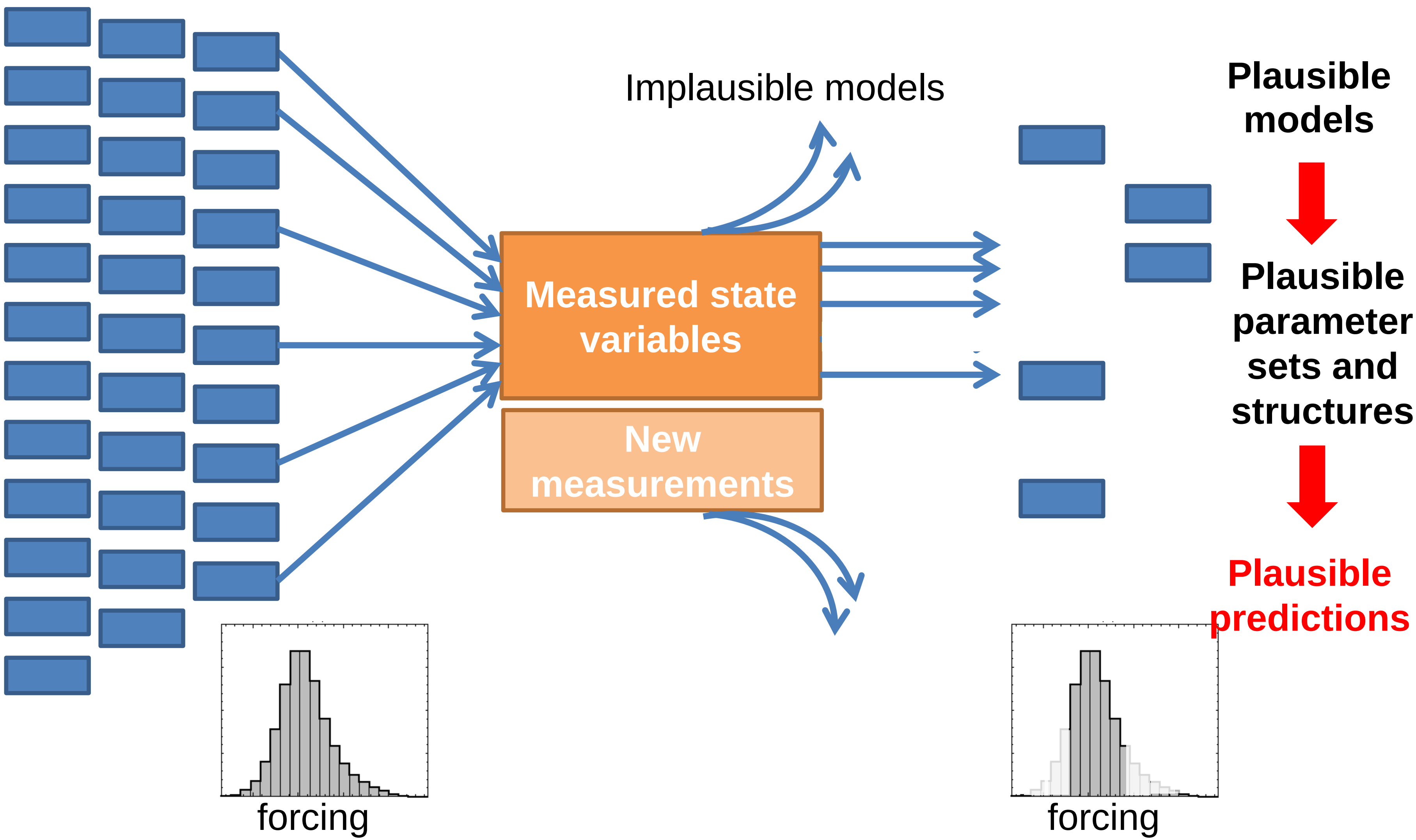
The best we can do

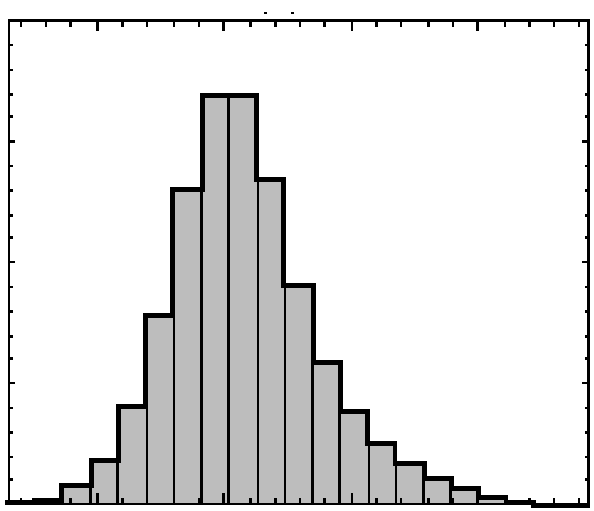
**This is an enormous problem!
There will be many combinations of plausible models**

Many models covering all conceivable structural and parametric uncertainties



A definition of forcing uncertainty

- The range of predictions of a model accounting for all possible uncertain model quantities (parameters) and structures, after rejecting models that are implausible compared to measurements



Steps towards exploring the full model uncertainty space

Restricted to:

- A nudged global aerosol model (GLOMAP)
- Uncertain parameter values
- Aerosol processes and emissions

- 28 parameters related to **aerosol microphysical processes, removal rates and emissions**

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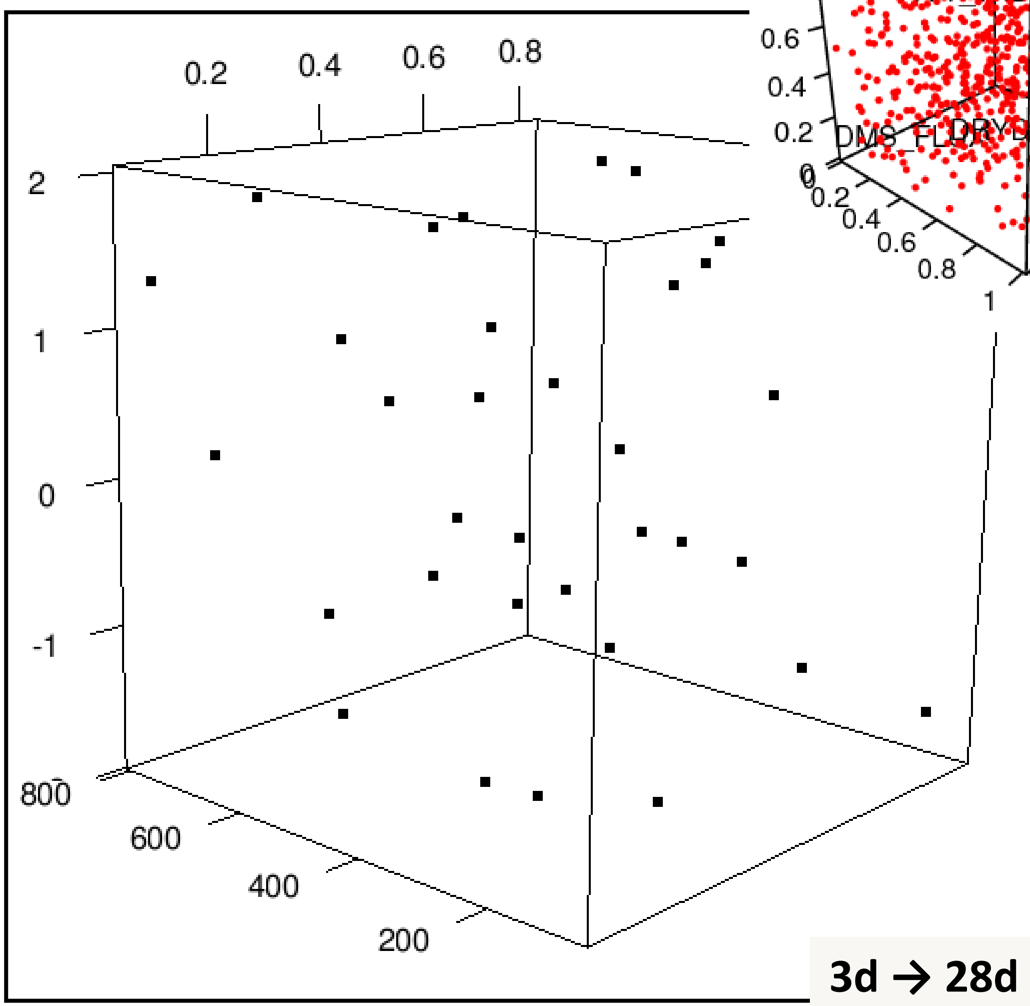
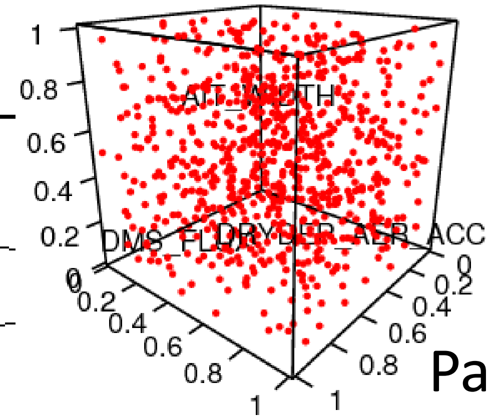
Multi-dimensional parameter sampling





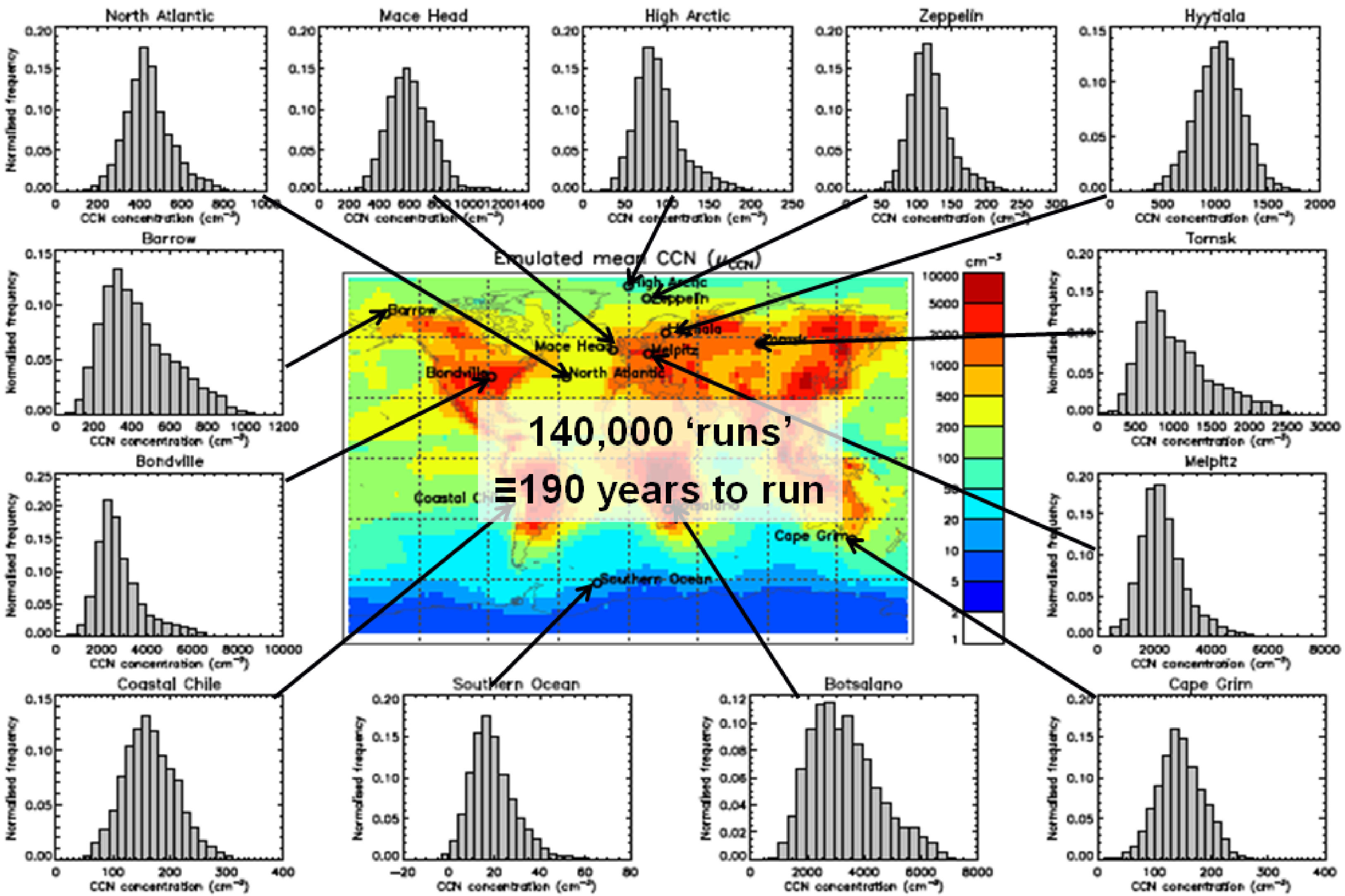
3d → 28d

Parameter perturbations cover 28-dimensional uncertainty space of a global model

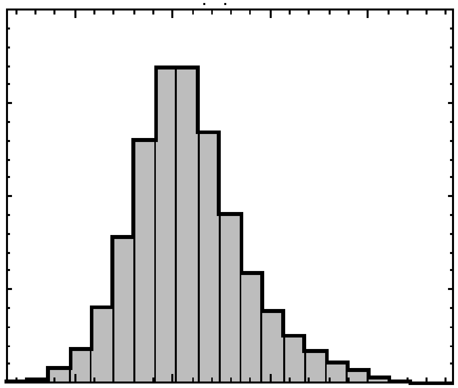
168 model runs needed for 28 parameter dimensions

Pdfs of CCN in every grid box

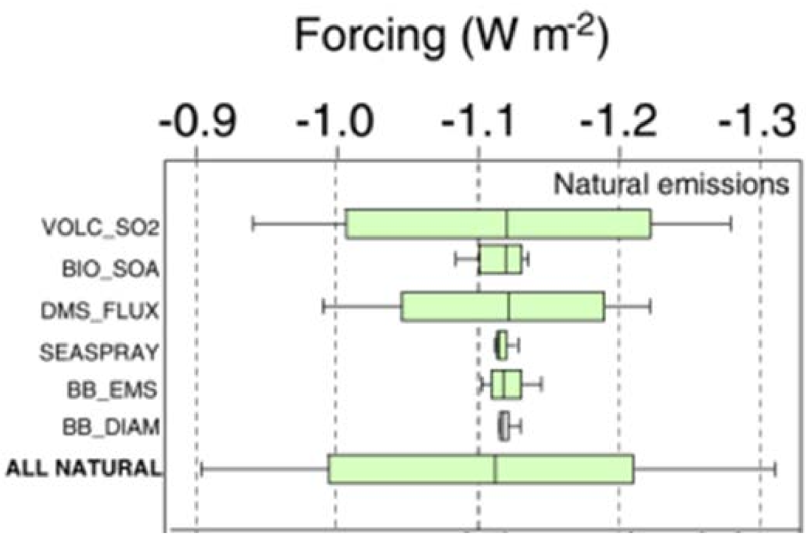
This is not CCN variability, it's parametric uncertainty in the monthly mean CCN state



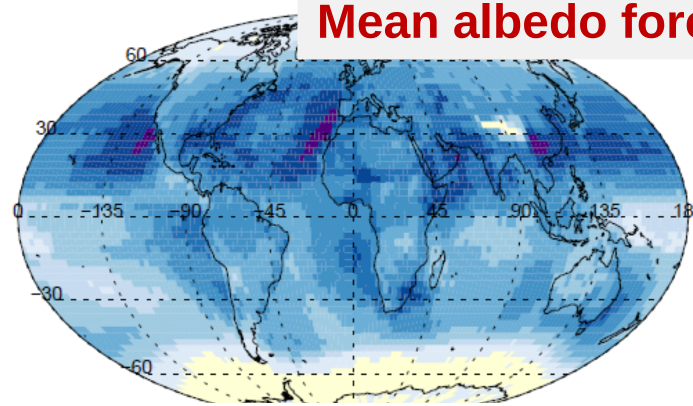
Albedo forcing and (prior) uncertainty



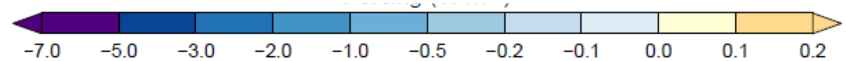
forcing



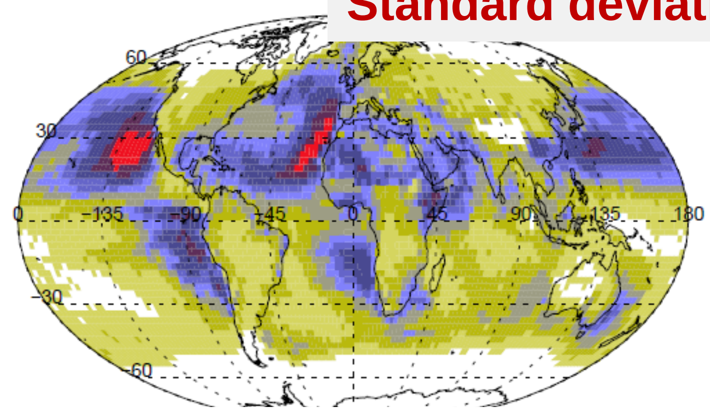
Mean albedo forcing



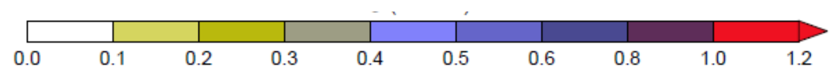
Mean = **-1.1 Wm^{-2}**



Standard deviation

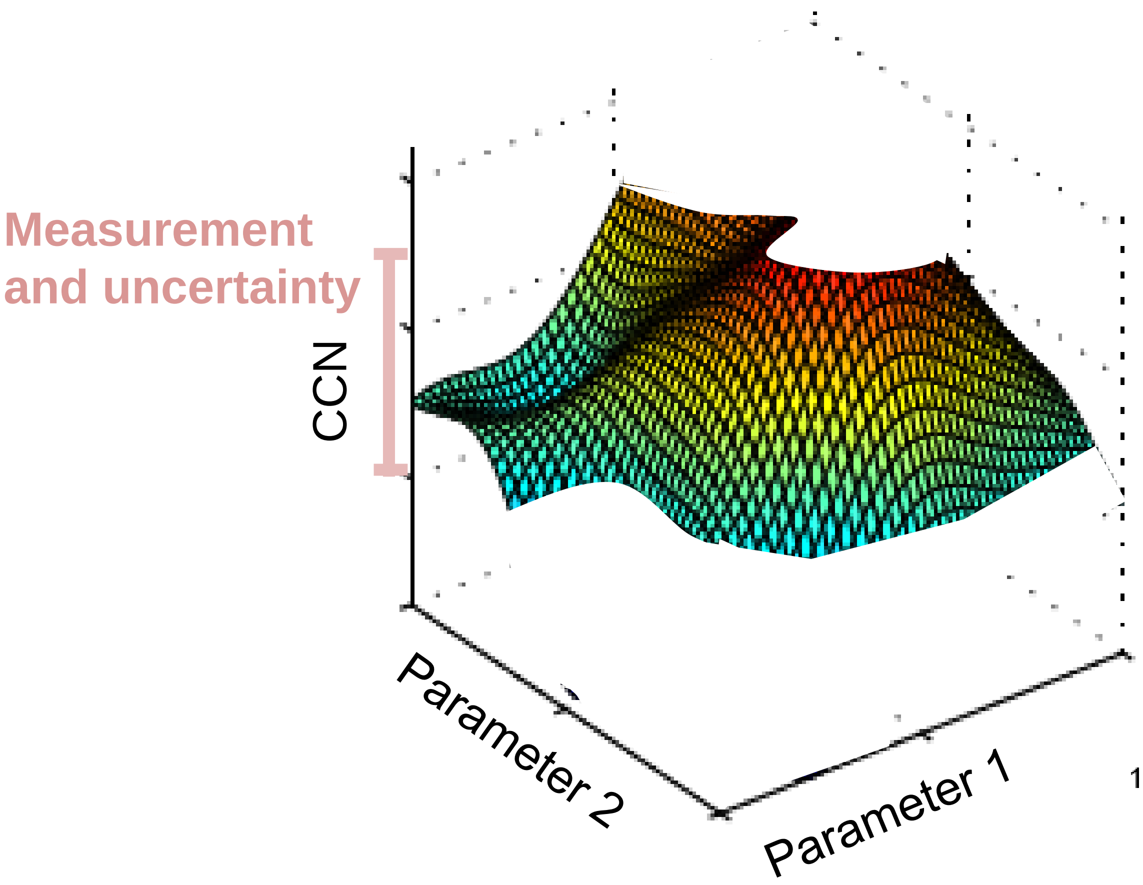


95% CI = **-0.7 to -1.6 Wm^{-2}**

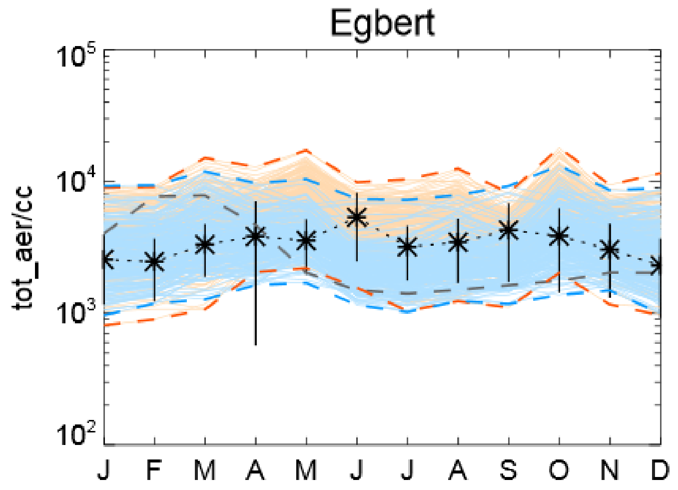


Carslaw et al. Large contribution of natural aerosols to uncertainty in indirect forcing, Nature (2013)

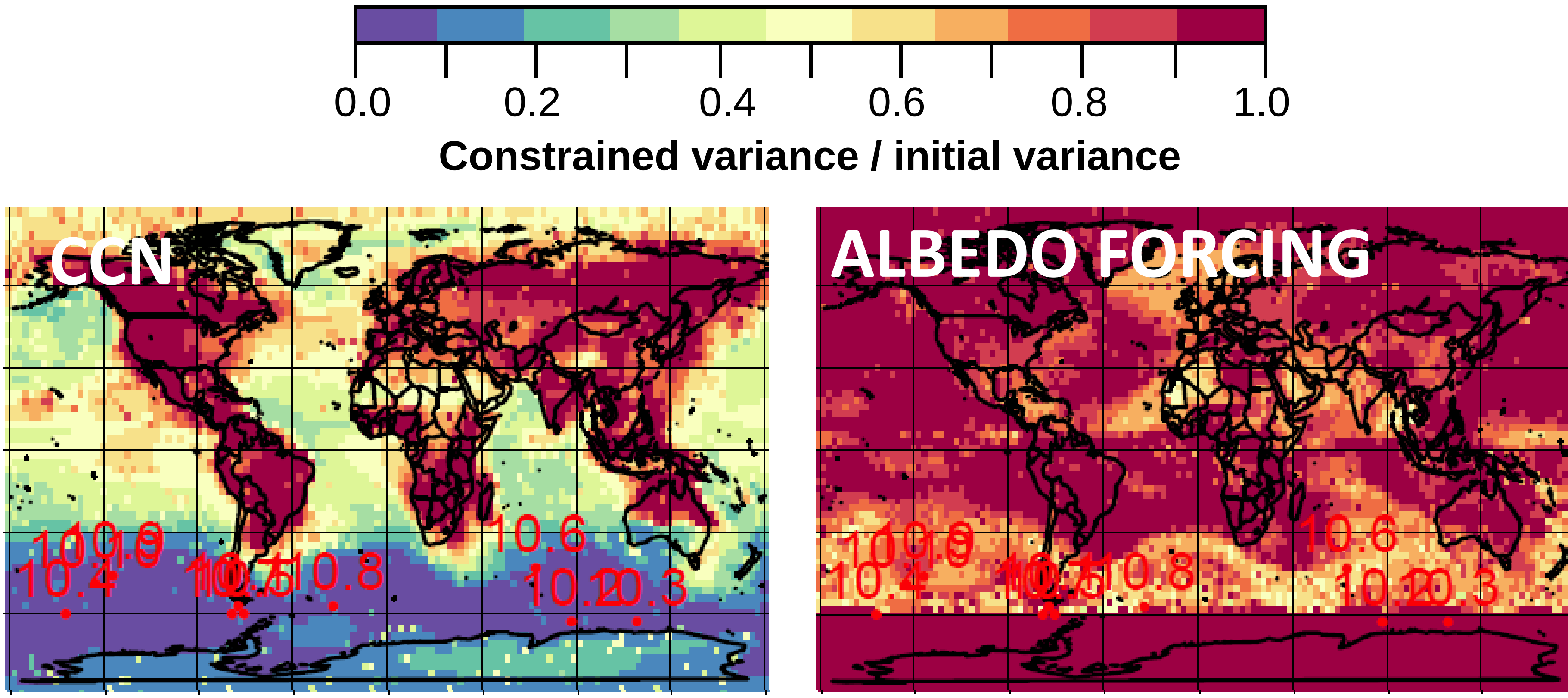
Identifying plausible models



NOTE: measurements define the plausible **parameter space**, not the magnitude of each parameter



Observationally constrained CCN and forcing



Number of CCN measurements (each with ±30% uncertainty): **6**

"Measurements" over S. Ocean drawn from one ensemble member

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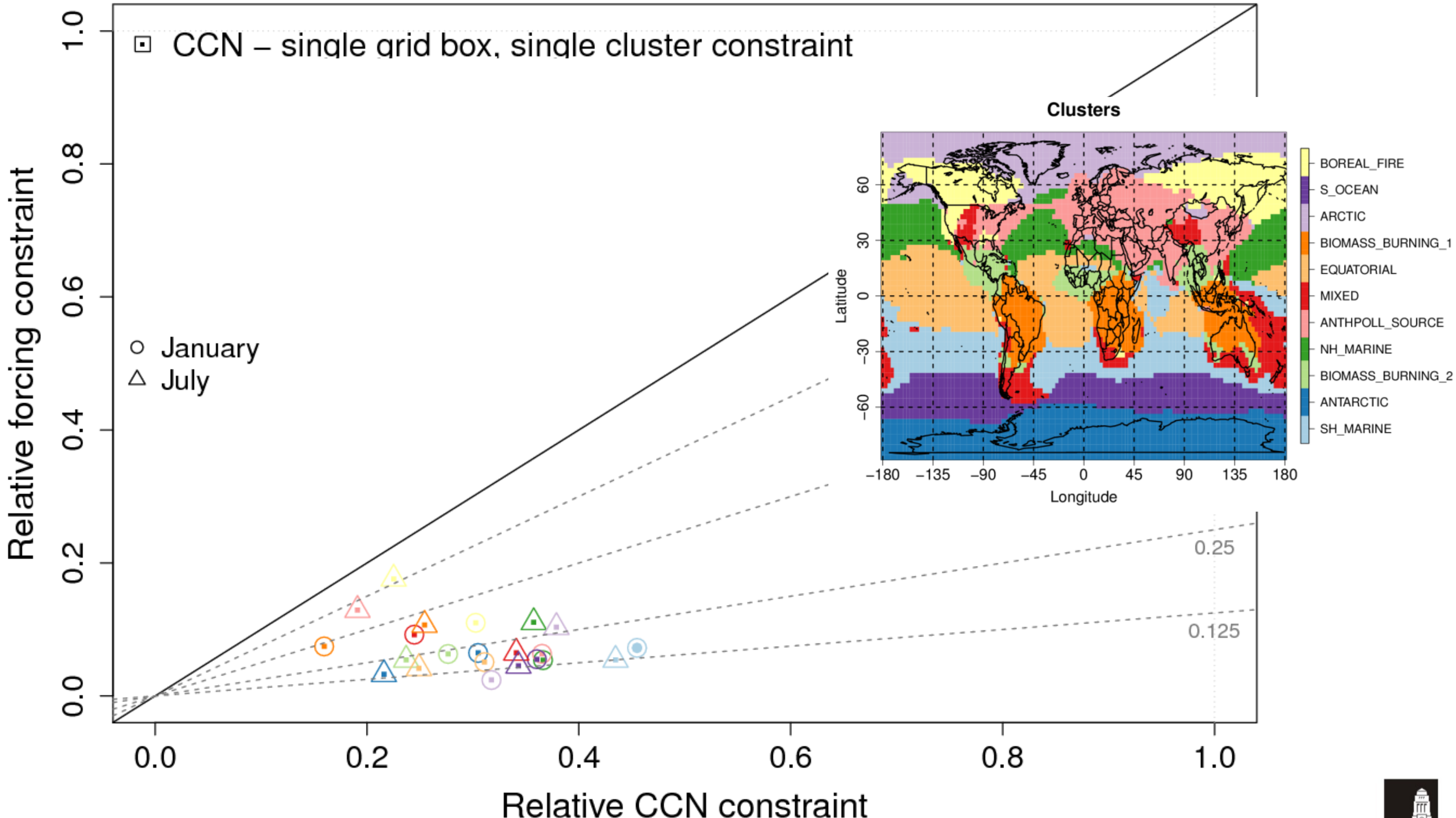
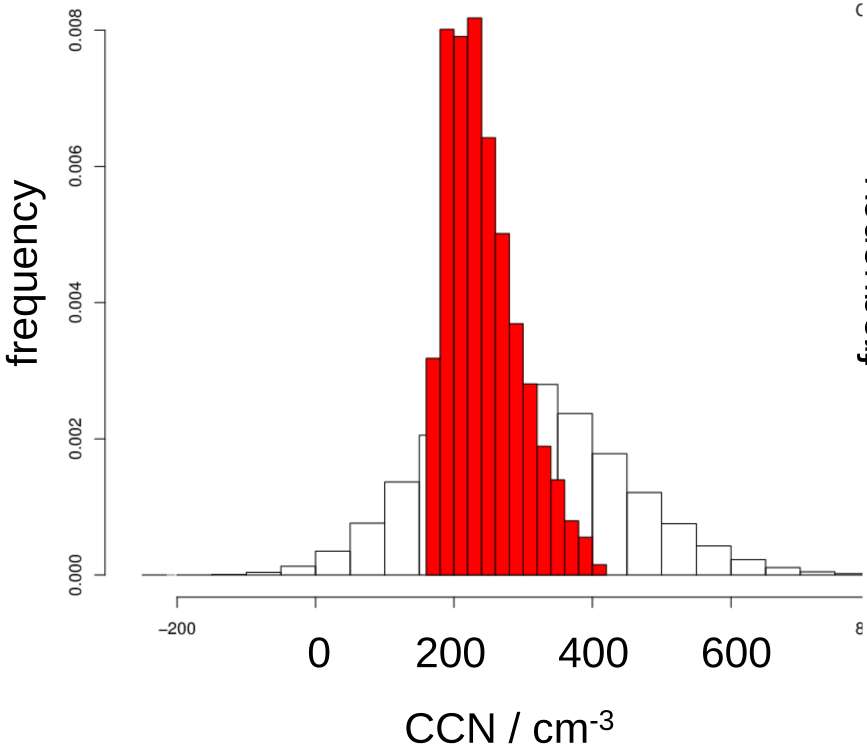
Constrained CCN and forcing



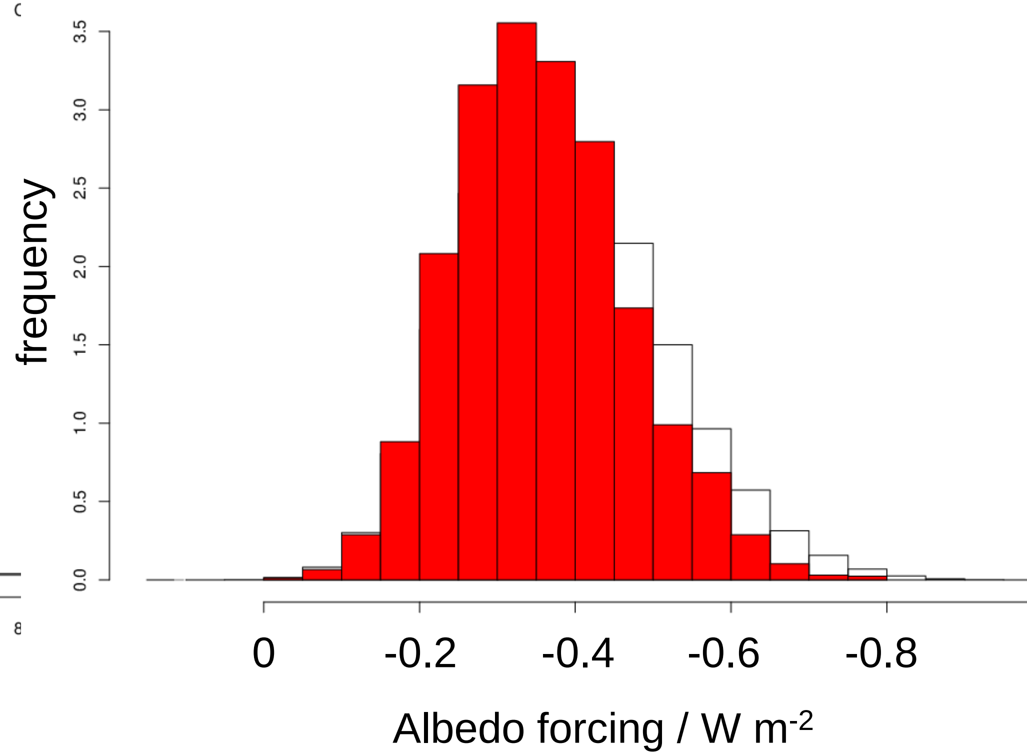
Prior and constrained distributions

Constrained using a CCN “measurement” with ±40% uncertainty

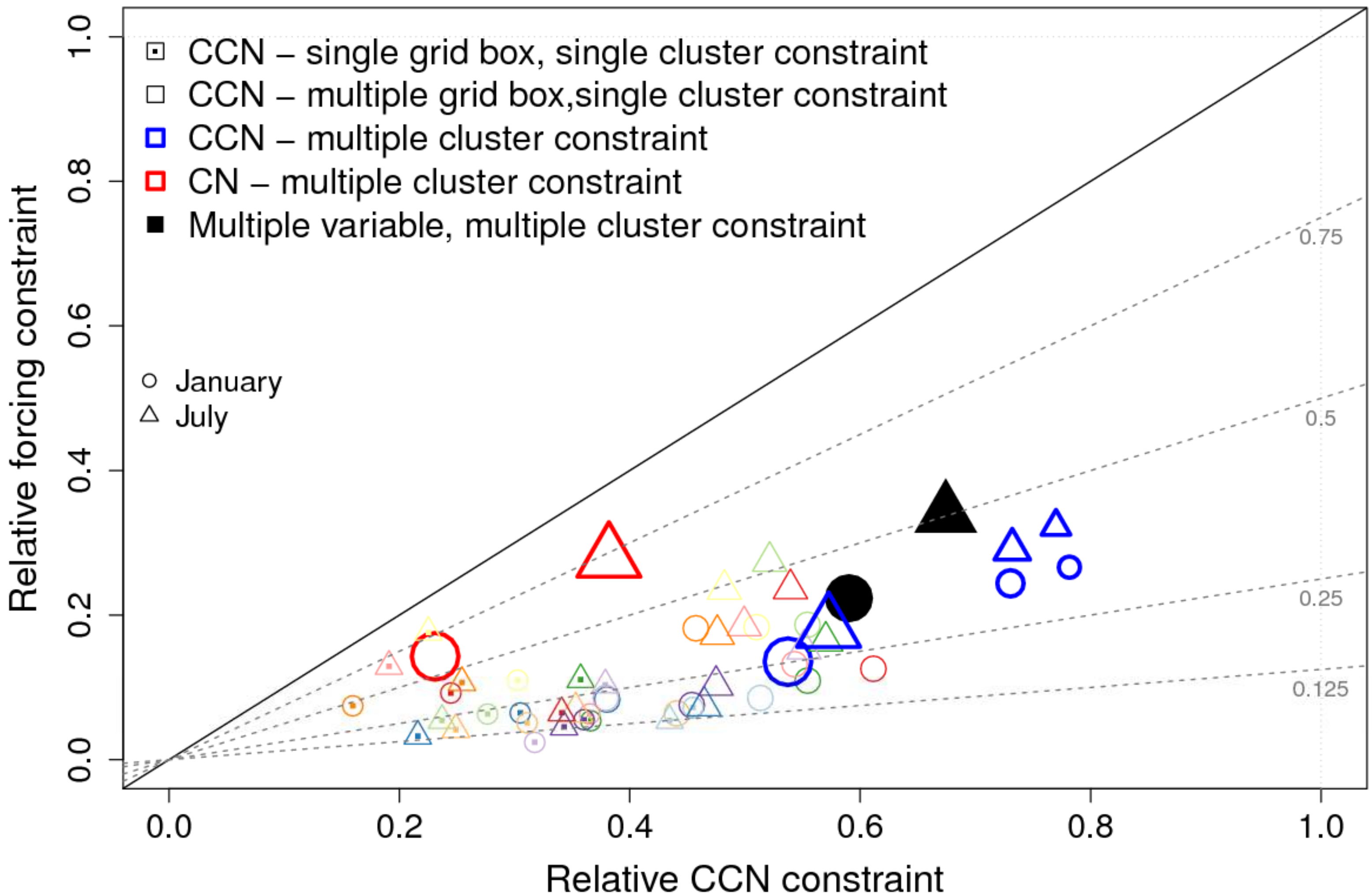
N Atlantic CCN



N Atlantic albedo forcing



Constrained CCN and forcing



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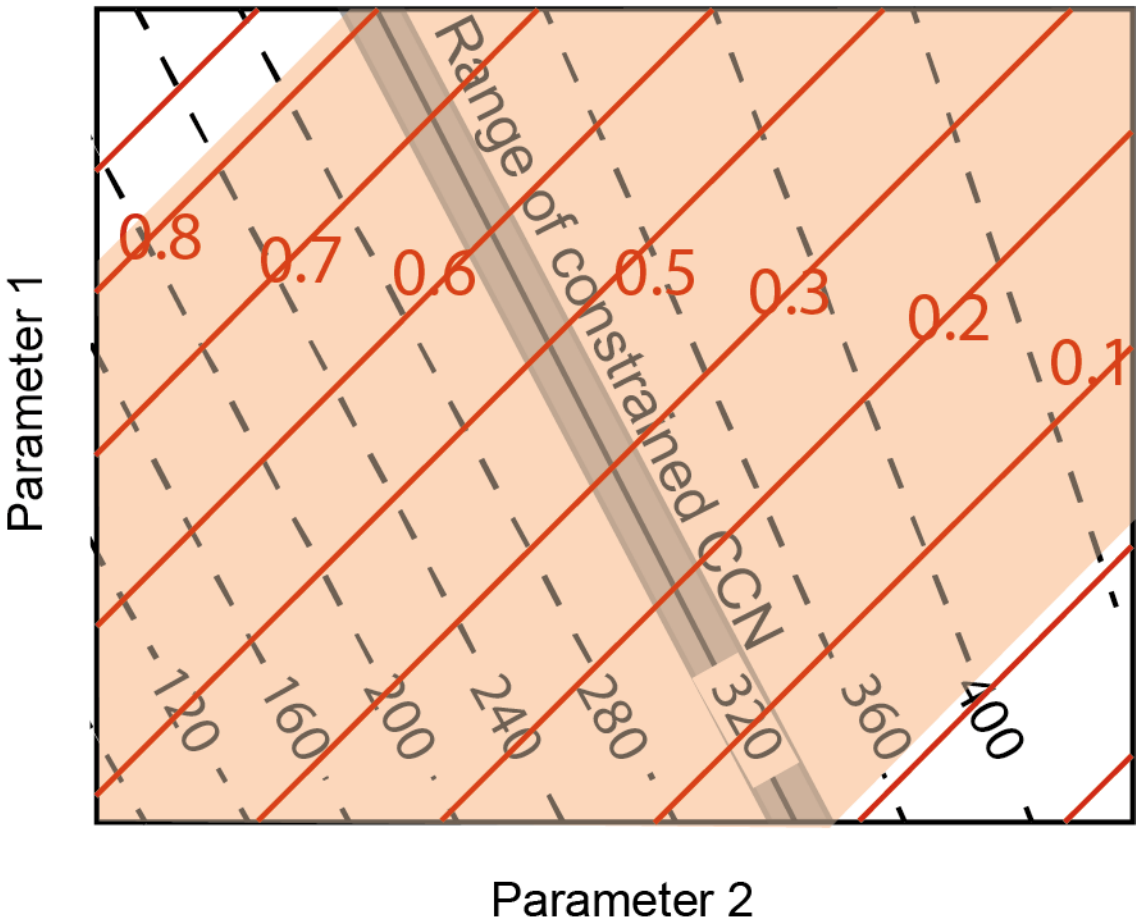
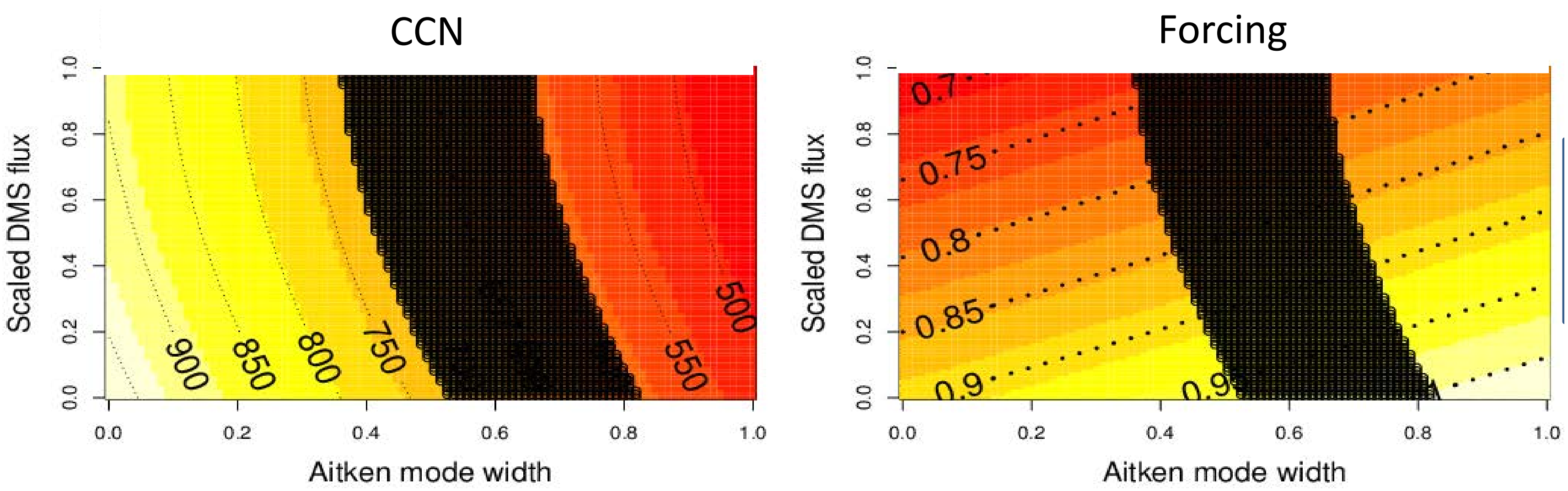
Multi-dimensional uncertainty constraint

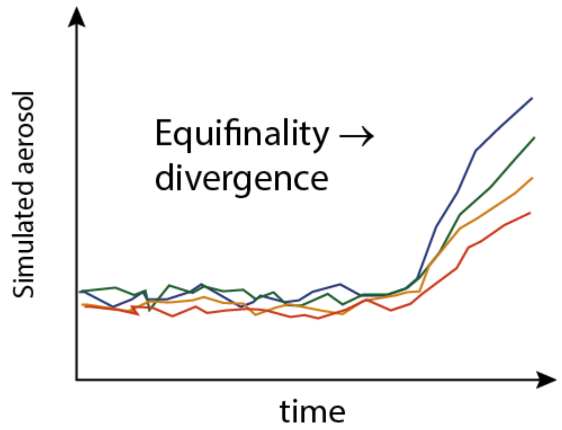


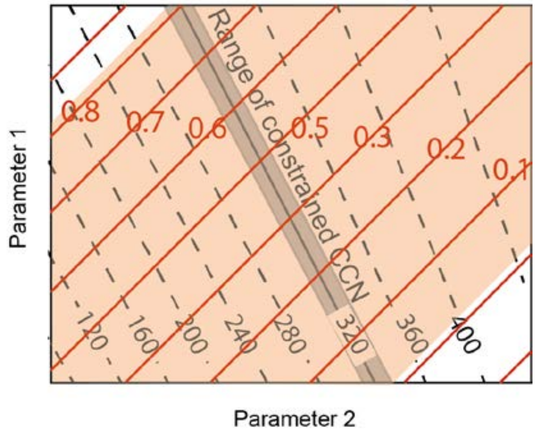
Multi-dimensional uncertainty constraint

A slice through the 28-dimensional emulator in one grid box



Equifinality





- In a model with many compensating uncertainties, there are many ways to achieve equally plausible agreement with state variable measurements – **Equifinality**

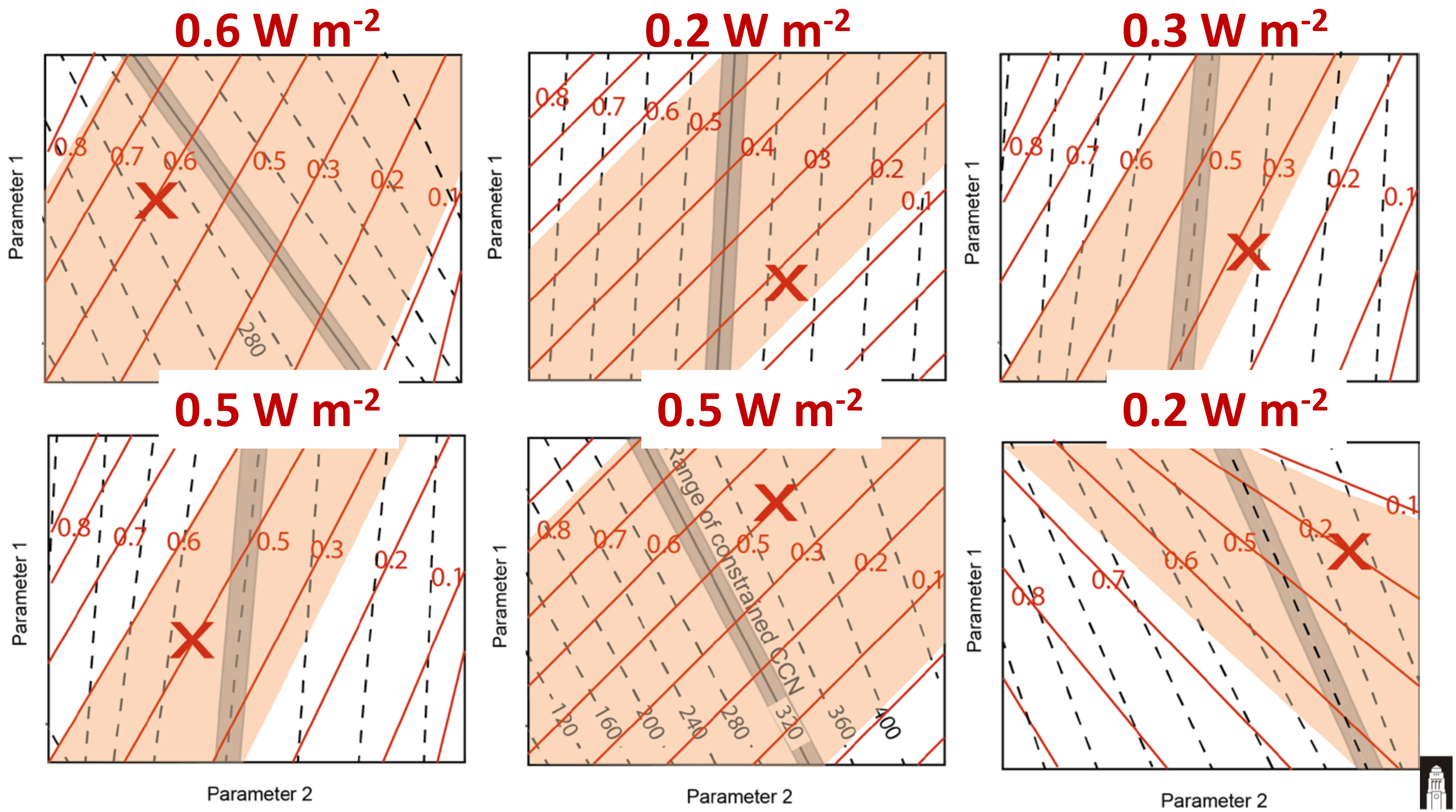
- Different parts of parameter space can evolve differently

- Forcing is a response to changes in emissions, so **a well constrained model state does not imply a well constrained forcing**

Keith Beven, *A manifesto for the equifinality thesis*, J. Hydrol. (2006).

What about multi-model ensembles?

Each model has chosen a single (presumably plausible) location in multi-dimensional uncertainty space



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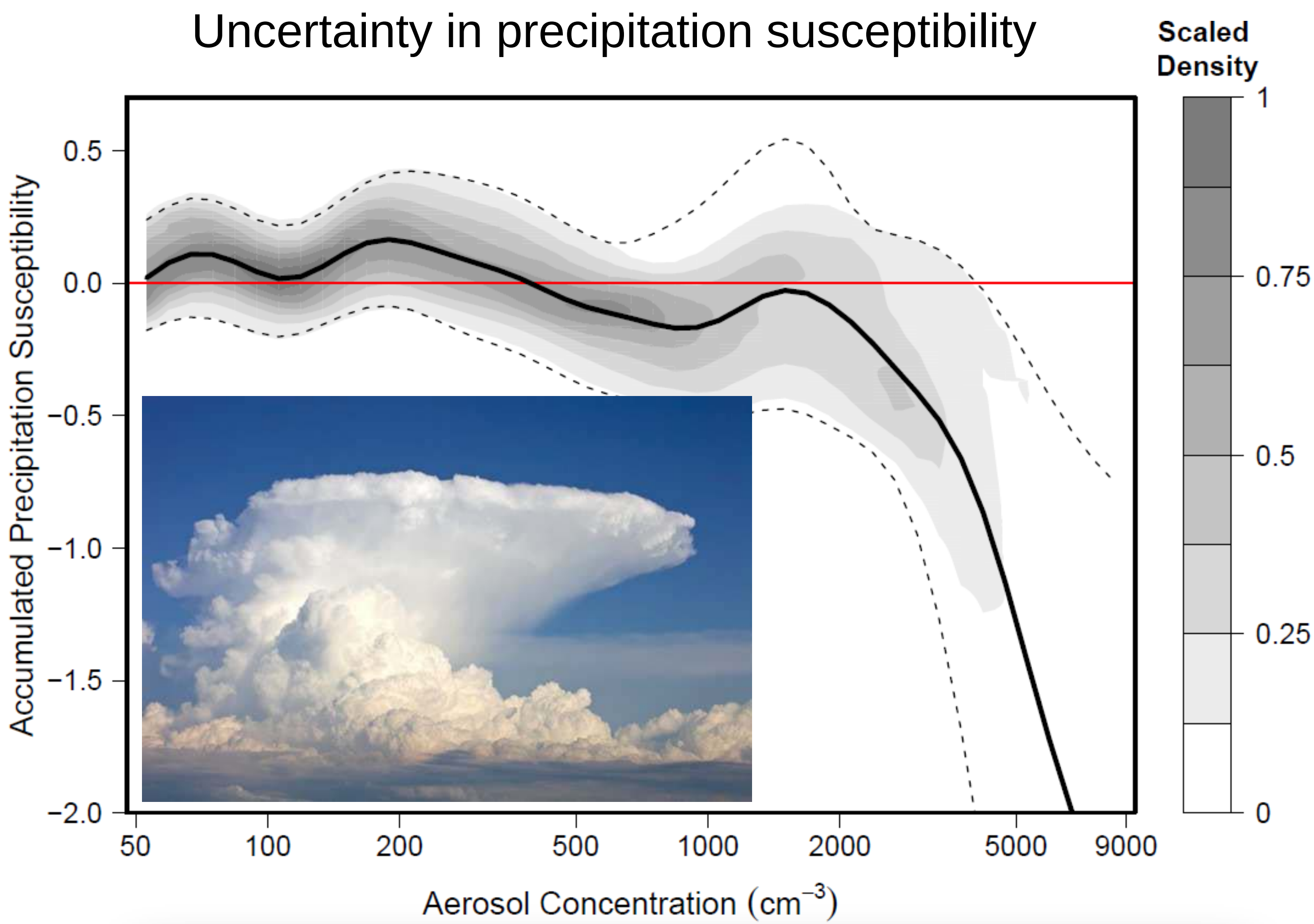
Extension to cloud-scale processes



AGU PUBLICATIONS

Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

10.1002/2014MS000383

Evaluating uncertainty in convective cloud microphysics using statistical emulation

J. S. Johnson[1], Z. Cui[1], L. A. Lee[1], J. P. Gosling[2], A. M. Blyth[1,3], and K. S. Carslaw[1]

Key Points:

- Processes driving uncertainty in

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What can be done to make better progress?

- **Treat uncertainty as the scientific problem to be understood and solved**

Uncertainty modeller Process modellers

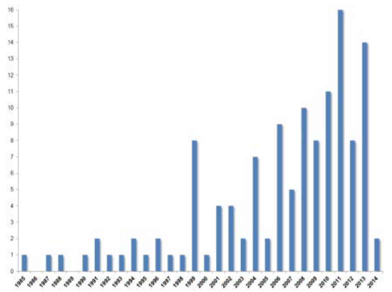
http://www.adrants.com/images/

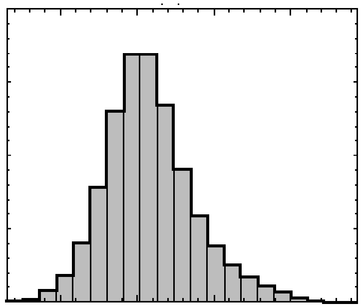
What can be done to make better progress?

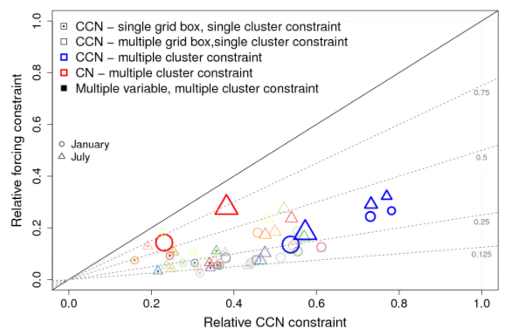
- **Treat uncertainty as the scientific problem to be understood and solved**
- Understand how state variable measurements constrain uncertainty
  - E.g., AOD, COD etc are likely to suffer from equifinality
- Understand how response measurements (e.g., $\mathrm{dln}N_d/\mathrm{dln}\tau$) constrain uncertainty
- Determine how well our current observing systems constrain uncertainty, not just how well a particular model agrees with the measurements
- Work towards a small number of plausible models for which we understand the uncertainties

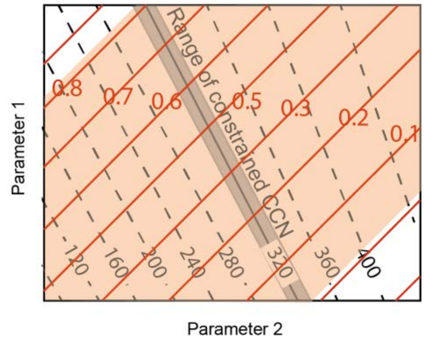
Summary

- Knowledge uncertainty reduction doesn’t match model uncertainty reduction. This is partly due to a lack of uncertainty reduction methodology
- Emulators enable the full uncertainty distribution of a model to be quantified
- Forcing is not directly measureable. Observational constraint of observable state variables doesn’t constrain forcing as much as expected
- With many uncertainties, there are many equally plausible (equifinal) models within the uncertainty of the measurements. Equifinal models diverge.

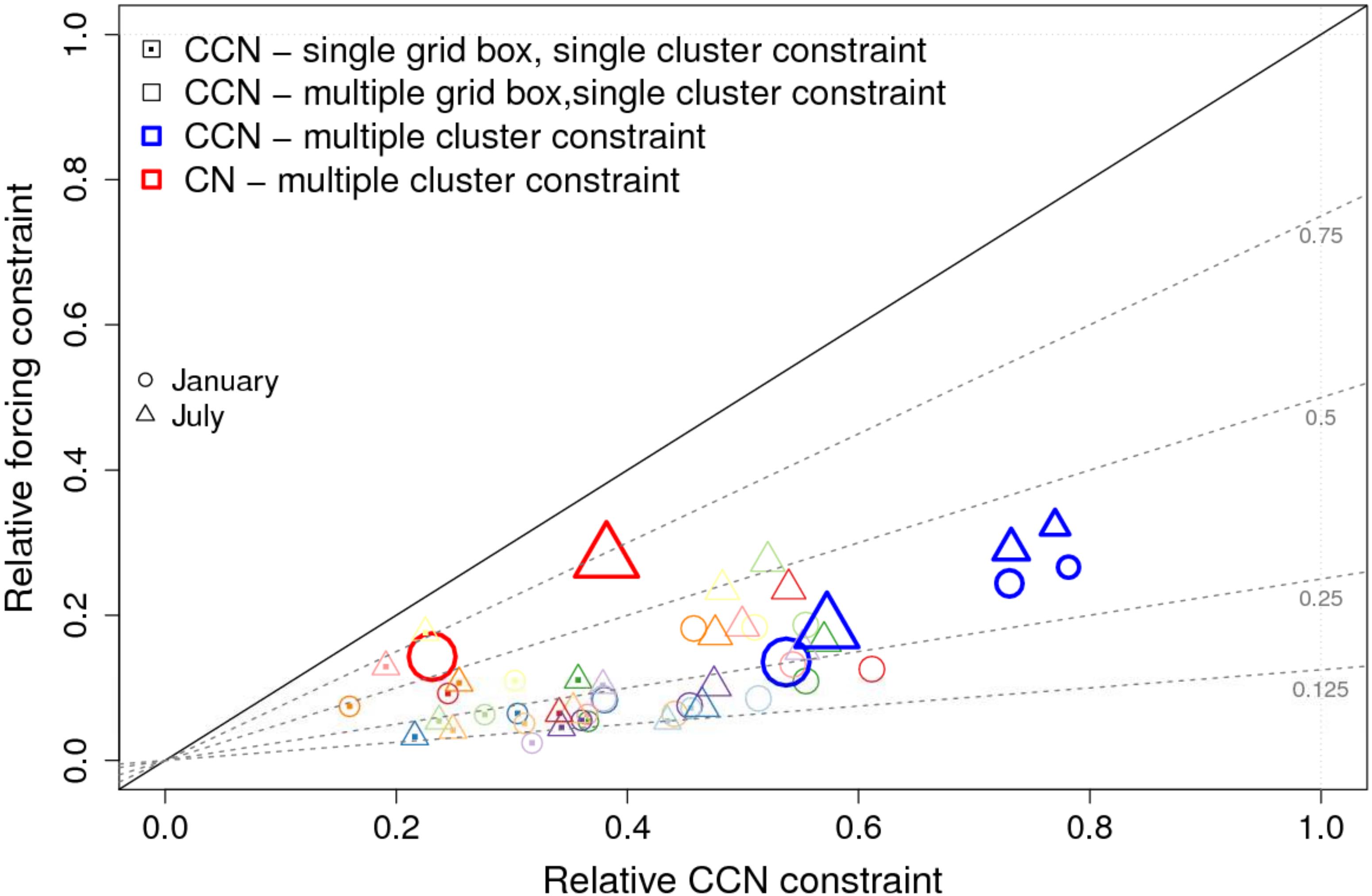








Constrained CCN and forcing



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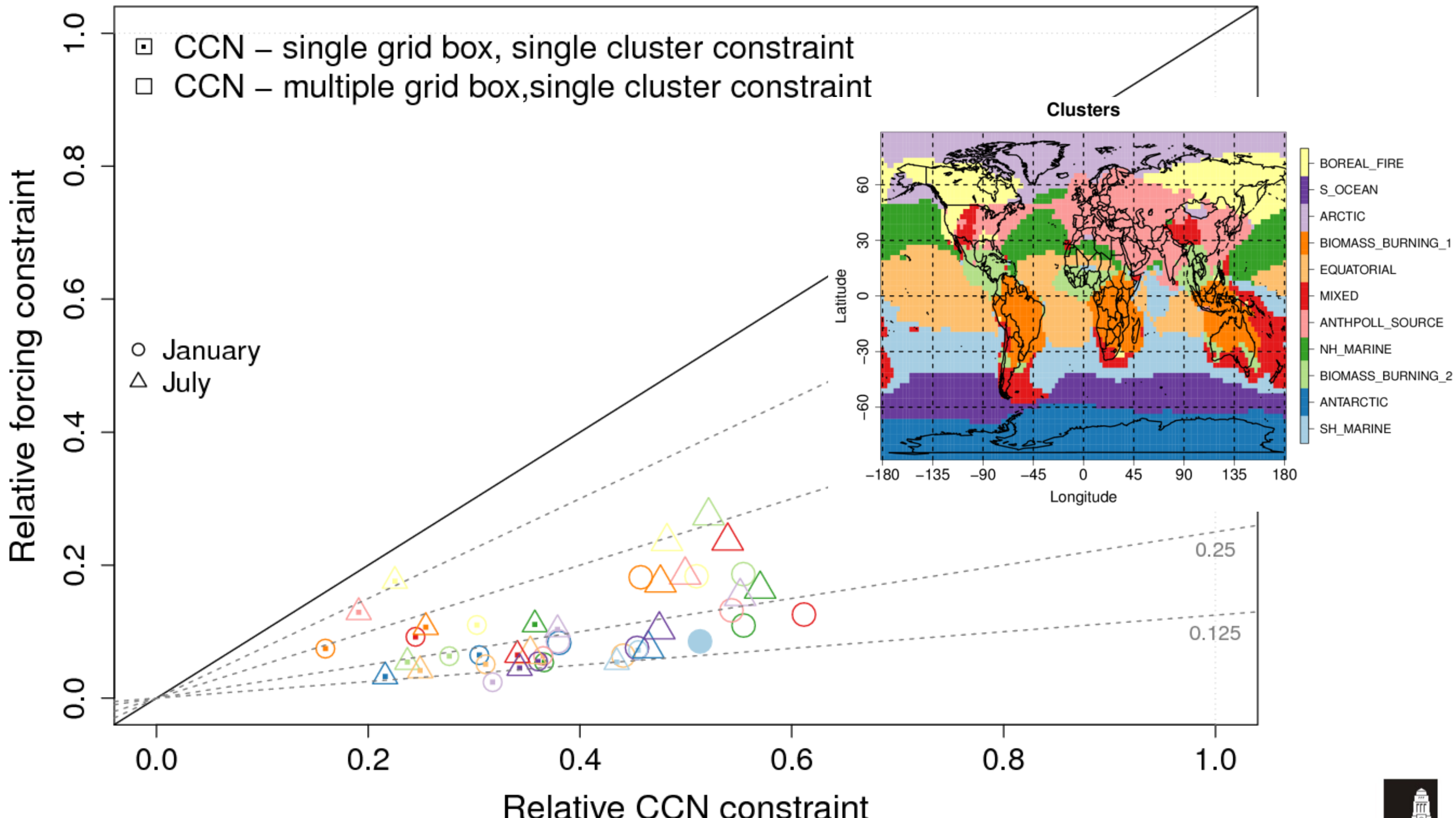
Constrained CCN and forcing



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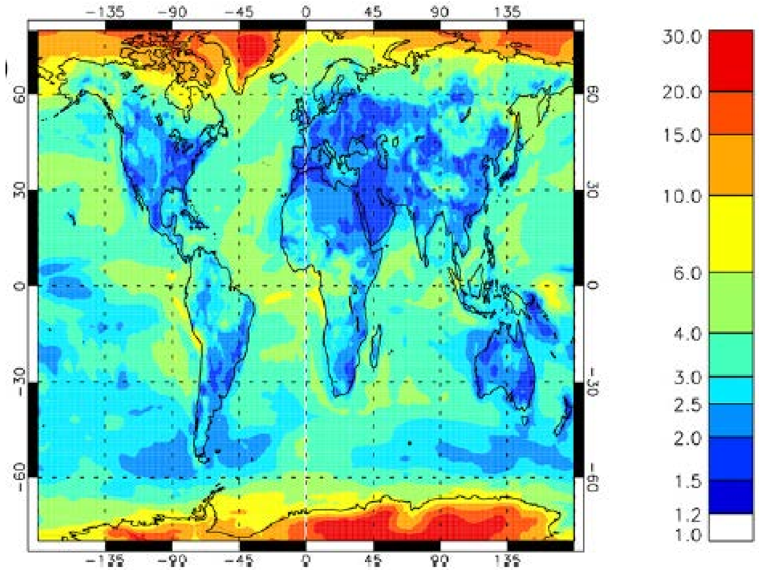
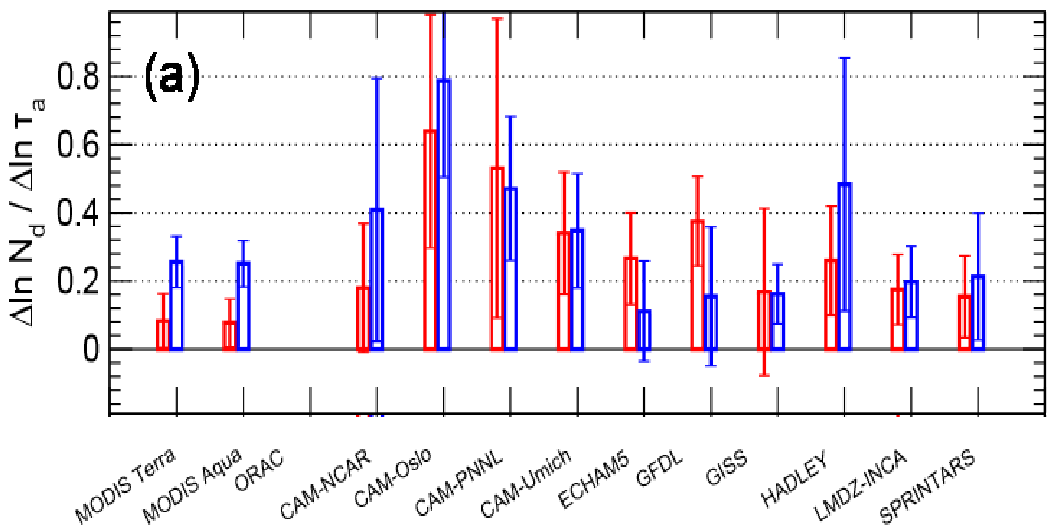
What is the situation now?



- Not a good constraint on model state variables



- Not a good constraint on model responses

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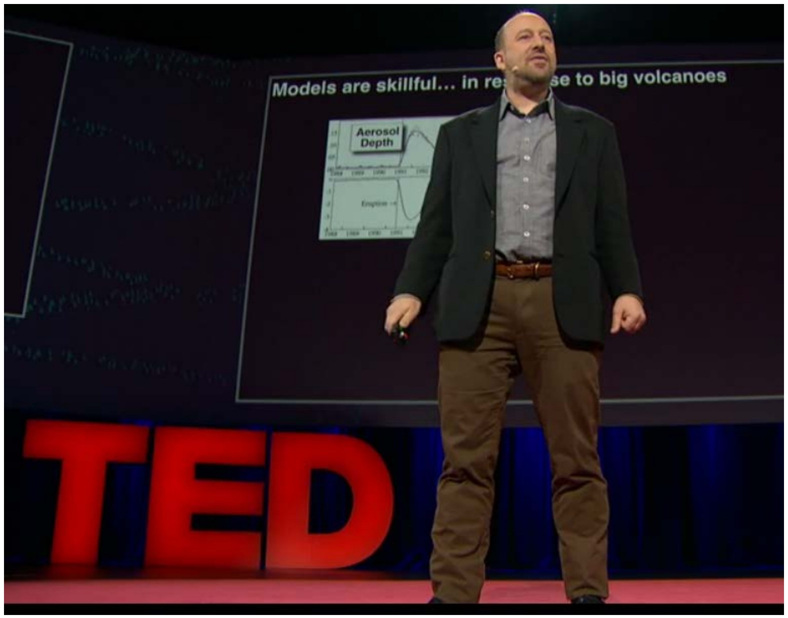
Model skilfulness



Gavin Schmidt

The Emergent Patterns of Climate Change (March 2014)

"Models are skilful if they tell you more information than you had otherwise."

(i) Ozone hole effect on SLP
(ii) T response to Pinatubo
(iii) Solar cycle effects on ozone
(iv) 20th century T trends
(v) Etc…