Model sensitivity and uncertainty analysis
Towards AeroCom MMPPE

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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.
What can we do with a well designed PPE?

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

What can we do with a well designed PPE?

2) **Quantify uncertainty in model responses**

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

What can we do with a well designed PPE?

4) Constrain the model against measurements

N Atlantic CCN constrained against measurements
What have we done so far with GLOMAP?

First indirect effect
1750-2000

Black carbon

HadGEM-GLOMAP climate model

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

AOD double call

AOD single call

BC double call

BC single call
What is our “uncertainty reduction methodology”?

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

Not forcing

Model skill

Improve processes

Measured state variables

2nd model

3rd model

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

The best we can do

Many models covering all conceivable structural and parametric uncertainties

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

Measured state variables

Implausible models

Plausible models

Plausible parameter sets and structures

Plausible predictions

New measurements

forcing

forcing
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
Multi-dimensional parameter sampling

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.

140,000 ‘runs’
≈190 years to run
Albedo forcing and (prior) uncertainty

Identifying plausible models

NOTE: measurements define the plausible parameter space, not the magnitude of each parameter
Observationally constrained CCN and forcing

Constrained variance / initial variance

CCN

ALBEDO FORCING

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

6

“Measurements” over S. Ocean drawn from one ensemble member
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

- CCN – single grid box, single cluster constraint
- CCN – multiple grid box, single cluster constraint
- CCN – multiple cluster constraint
- CN – multiple cluster constraint
- Multiple variable, multiple cluster constraint

Relative forcing constraint vs. Relative CCN constraint

- January
- July
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

What about multi-model ensembles?

Each model has chosen a single (presumably plausible) location in multi-dimensional uncertainty space.
Extension to cloud-scale processes

Uncertainty in precipitation susceptibility

Accumulated Precipitation Susceptibility

Aerosol Concentration (cm⁻³)

Journal of Advances in Modeling Earth Systems
RESEARCH ARTICLE
Evaluating uncertainty in convective cloud microphysics using statistical emulation

Key Points:
1. Process-driven uncertainty
What can be done to make better progress?

- Treat uncertainty as the scientific problem to be understood and solved
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., $\frac{d\ln N}{d\ln \tau}$) 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 measurable. 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

- CCN – single grid box, single cluster constraint
- CCN – multiple grid box, single cluster constraint
- CCN – multiple cluster constraint
- CN – multiple cluster constraint

Relative forcing constraint vs. Relative CCN constraint

- January
- July
Constrained CCN and forcing

- CCN – single grid box, single cluster constraint
- CCN – multiple grid box, single cluster constraint

Relative forcing constraint vs. Relative CCN constraint for January and July.
What is the situation now?

- Not a good constraint on model state variables
- Not a good constraint on model responses
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…