Could slab model emulation be a useful tool in ocean uncertainty quantification?

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1. Existing Problems for ocean UQ

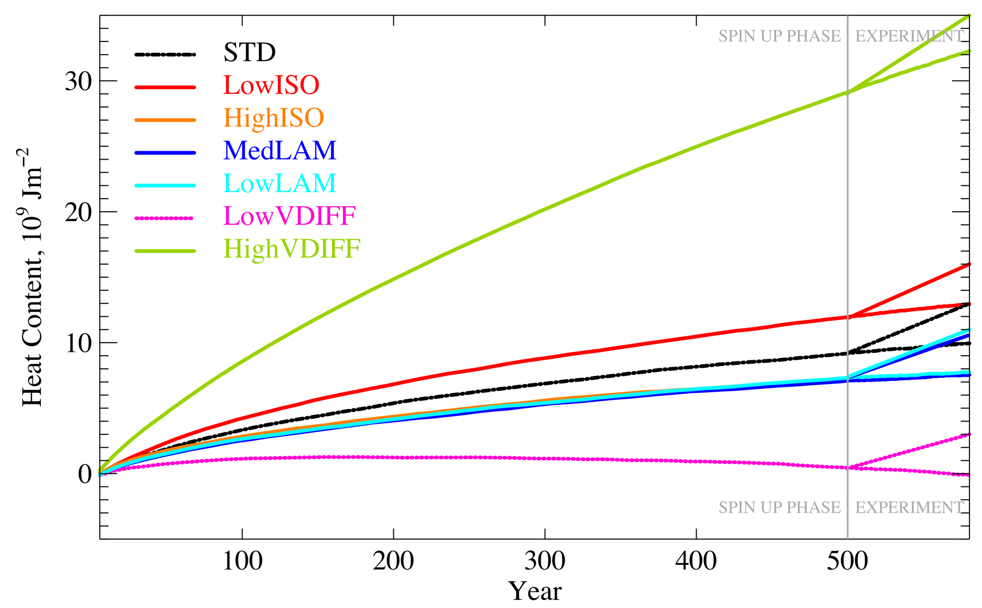
Early investigations into ocean model uncertainty in climate projections found it has important regional impacts (Brierley et al., 2010), if not global ones (Collins et al., 2007). They also exposed two technological challenges.

Structural Uncertainty

The conventional method of quantifying model uncertainty involves perturbing the value of physical parameters within a single climate model. Other model choices may also contain uncertainty, yet are unfeasible to perturb. An example might be whether the model uses depth or density as its vertical coordinate. Multi-model ensembles are one approach to estimate this "structural" uncertainty. Comparison of perturbed physics to multi-model ensembles implies ocean model uncertainty has little global impact or that it has a significant structural component (Collins et al., 2007).

Length of Spin-up

The ocean dominates the longer time scale responses in the climate system - in effect providing a source of memory. This also means it takes a long time to respond to any parameter perturbations. Substantial resources are expended to reach a new "spun up" steady-state before a climate change experiment can be performed. Shorter spin ups risk interactions between the climate response to the radiative forcing and the parameter perturbation.



The changes in ocean heat content (from observed initial conditions) in a perturbed ocean physics ensemble through a 500 year spin up followed by a 1% CO_2 experiment (Collins et al., 2007)

2. Existing Methods

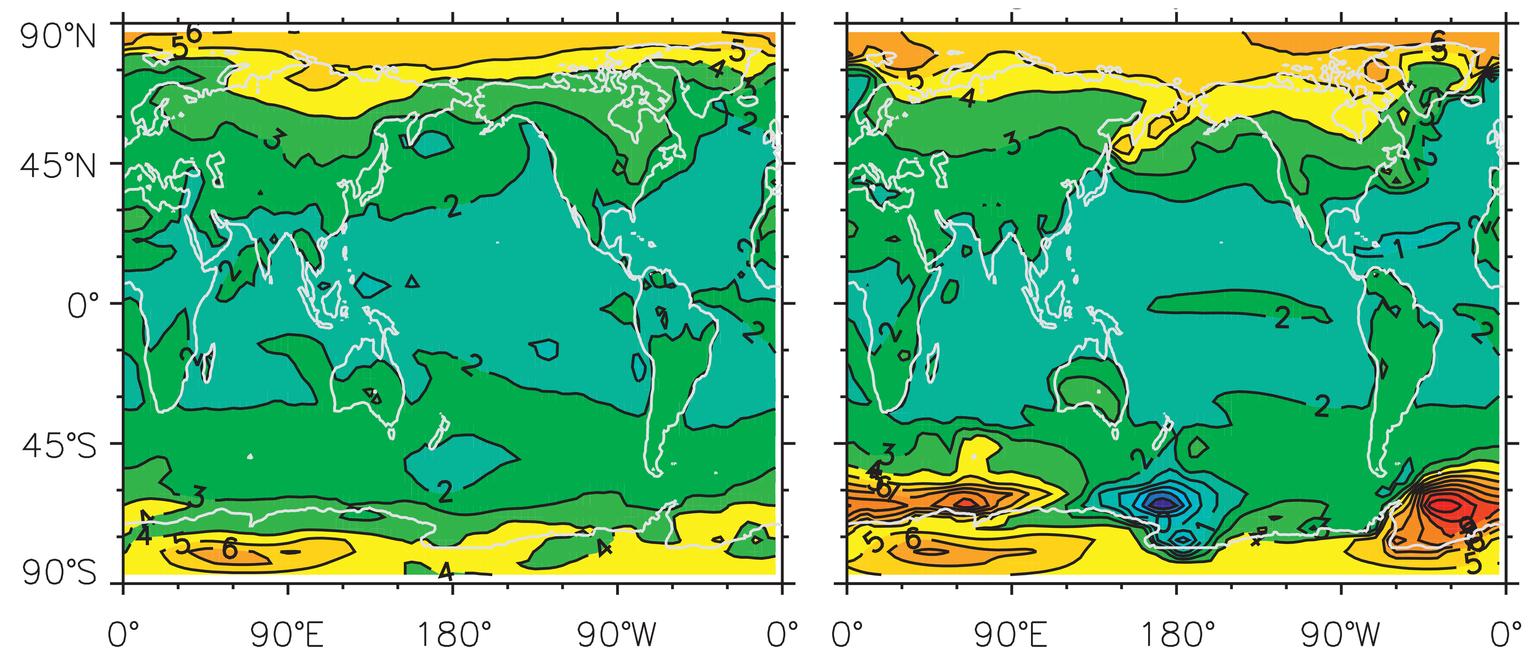
A variety of approaches have been attempted to tackle these two problems.

- Performing ocean & atmosphere UQ alone - neglecting coupled feedbacks.
- Using flux adjustments – partly to allow shorter spin up times.
- Coupler interfaces to allow switching of ocean components (Guilyardi et al., 2006).
- Fitting a simple model to GCM behaviour (Frame et al., 2005; Forest et al., 2006).
- Accelerating the deep ocean or asynchronous coupling (effectively both run the ocean interior at a faster rate than the atmosphere).

3. What is a "slab" model

Running a mixed-layer-only ocean underneath an atmosphere is referred to as a slab model. The mixed layer component captures the thermodynamic responses, but has no dynamics incorporated into it. The amount of heat transported by the ocean interior must be prescribed and is invariant. This removes timescales longer than about a month. So a slab model requires no long spin up, but also does not simulate any interannual climate variability.

Slab models can quickly estimate the equilibrium response of the climate system to an imposed radiative forcing or parameter perturbation. Prior to the IPCC's AR5, they were required to calculate a model's climate sensitivity. The error in a slab model's estimate of the equilibrium response occurs in the Southern Ocean, North Atlantic and eastern tropical Pacific (Danabasoglu & Gent, 2009). This used the low resolution CCSM3 coupled model, which has a cold bias (so more sea ice) versus the observationally-constrained slab model.



Steady-state annual mean surface air temperature changes in response to a doubling of CO_2 (in °C) as calculated by a slab model (left) and in the fully coupled version run for 3000 years (right). The global mean of this field is the equilibrium climate sensitivity (Danabasoglu & Gent, 2009)

4. Tropical ocean heat convergence

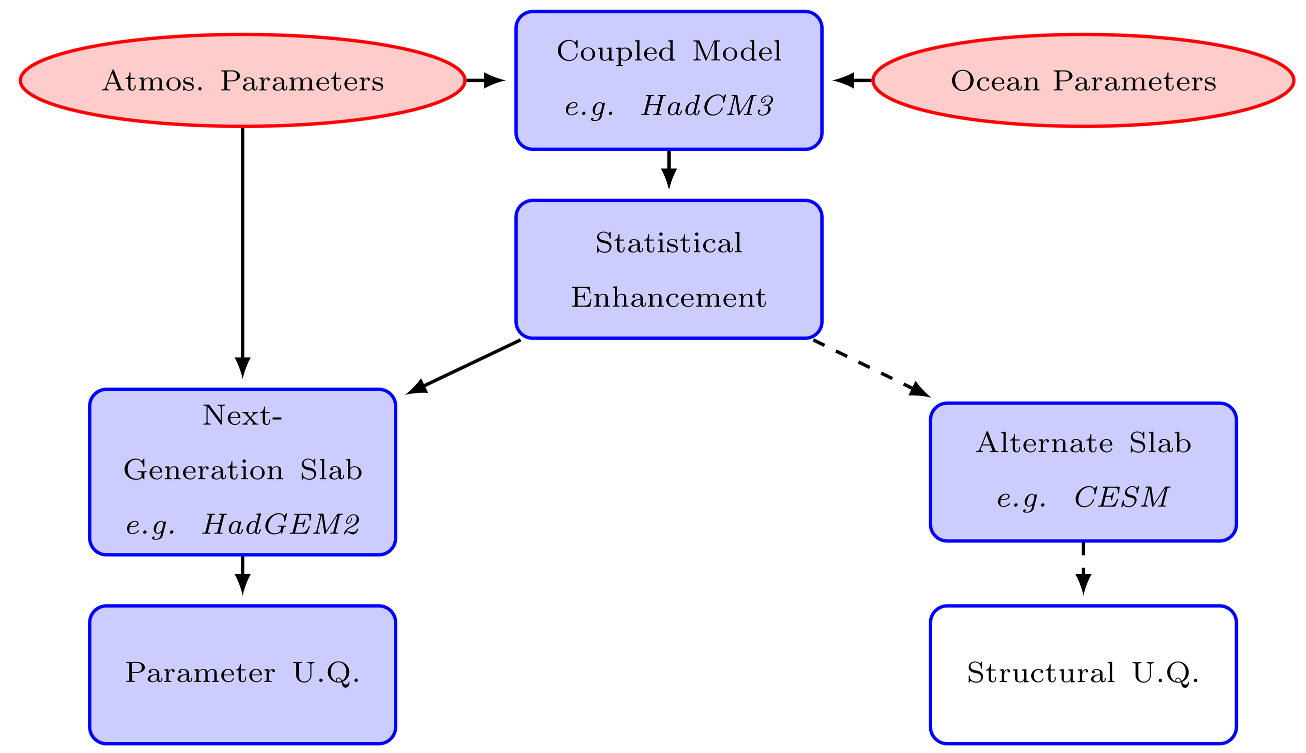
The eastern tropical Pacific errors and the lack of ENSO variability (the dominant mode of global climate variability) both arise from the lack of feedbacks involving the ocean interior in the region. These two issues could be alleviated by incorporating monthly responses of the local ocean interior - without increasing the length of the model's spin up.

We propose to use a statistical emulator to capture the dependence of the anomalous local ocean heat convergences on the atmospheric conditions and prior ocean state. One effective method to do this may be using fitted empirical orthogonal functions (Cook, 2007) to devise a lightweight prediction system. Such an enhancement would have minimal computational expense.

5. Potential Advantages

One feature of climate models' development is their continuously increasing sophistication to utilise ever-growing computer resources. There is no practical method to incorporate a quantification of the uncertainty of an outdated model to its current generation. Any system that could provide a method for porting uncertainty through generations would also be able to port it between different climate models - allowing structural uncertainty to be addressed.

If a lightweight slab enhancement can be created, then the impact of atmosphere model uncertainty on ENSO projections can be readily addressed using conventional UQ methodologies. More importantly, multiple variants of it could be tuned to replicate the range of behaviour seen in an ocean perturbed physics ensemble. It would therefore be able to encapsulate the ocean model uncertainty sampled by an ensemble and allow that to be inserted underneath an atmosphere model.



Outline of the potential of an enhanced slab model to assist with porting uncertainty up a model hierarchy and to address structural model uncertainties.

6. Limitations

This proposed approach only tackles the tropical Pacific on interannual timescales. It could potentially be developed to encompass North Atlantic decadal variability - but with an accompanying increase in the length of any model spin up. The differences in the Southern Ocean relate to a cold bias in the coupled model's control and can be corrected for (Bailey et al., 2009).

Its main limitations, though, afflicts all equilibrium studies. How relevant are they to a future in which the radiative forcing is changing so rapidly that an equilibrium is never reached? How relevant are they for a climate system involving tipping-points and dependent on the trajectory followed to reach that equilibrium?

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