Improved climate simulations through a stochastic parameterization of ocean eddies

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Motivation

- **Deterministic parameterizations** of sub-grid processes (e.g. Gent and McWilliams 1990) assume that the impact of the sub-grid scales on the resolved scales is uniquely determined by the resolved scales (e.g. Williams 2005). This is clearly just a first-order approximation.

- **Stochastic parameterizations** use random numbers to capture sub-grid variability; they are routinely used in numerical weather prediction (e.g. Buizza et al. 1999, 2005) but not (yet!) in oceanography and climate science.

- Promising stochastic parameterizations of ocean eddies are being developed (e.g. Cooper and Zanna 2015).
Motivation

- One of the main possible benefits is a reduction in ocean model errors via noise-induced rectification:

  - For example, stochastically perturbed air–sea fluxes in a coupled GCM produce significant changes to the mean mixed-layer depth, SST, and Hadley cell (Williams 2012)…
Motivation

1) Mixed layer deepens
2) Surface ocean cools
3) Hadley cell weakens (e.g. Bjerkness 1966)
4) Reduced precipitation in the ITCZ
5) Increased precipitation in the subtropics

Williams (2012)
Methodology

We use simulations from a **high-resolution, eddy-permitting model** to calculate the eddy statistics needed to inject realistic stochastic noise into a **low-resolution, non-eddy-permitting version** of the same model:

### FAMOUS

- Essentially a **low-resolution version** of HadCM3 (Smith et al., 2008)
- **Ocean model**
  - 2.5° in latitude and 3.75° in longitude
  - 20 levels that increase in vertical resolution toward the surface
  - Time step is 12 hours
- **Gent and McWilliams (1990) scheme** is switched **on**

### HiGEM

- Essentially a **high-resolution version** of HadCM3 (Shaffrey et al., 2009)
- **Ocean model**
  - 1/3° in latitude and 1/3° in longitude
  - 40 levels that increase in vertical resolution toward the surface
  - Time step is 20 minutes
- **Gent and McWilliams (1990) scheme** is switched **off**
Diagnosing subgrid variability in HiGEM

→ stochastically perturb temperature field only

Brankart (2013), Williams et al. (2016)
Variability of temperature tendencies

(a) FAMOUS surface to 100 m
(b) FAMOUS 100 m to 1000 m
(c) FAMOUS 1000 m to bottom

(d) HiGEM surface to 100 m
(e) HiGEM 100 m to 1000 m
(f) HiGEM 1000 m to bottom

→ stochastically perturb temperature tendency

Williams et al. (2016)
A HiGEM control integration is used to diagnose the noise properties

Horizontally uncorrelated, vertically coherent, temporally correlated (red) Gaussian noise $\eta$ is added to the temperature tendency $dT/dt$ at each ocean grid point and time step:

$$T_{n+1} = T_{n-1} + 2\Delta t \left( \frac{dT}{dt}n + \eta \right)$$

The amplitude and its depth profile are determined empirically from a fitted logarithmic envelope function (blue curve)

Noise amplitude and distribution

Williams et al. (2016)
## FAMOUS simulations

<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Noise amplitude at surface (°C per 12 h)</th>
<th>Decorrelation time (days)</th>
<th>Number of ensemble members</th>
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Williams et al. (2016)
Sea-surface temperature

(b)-(f) are anomalies w.r.t. (a)

Williams et al. (2016)
Global zonal-mean temperature

(b)-(f) are anomalies w.r.t. (a)
Global zonal-mean salinity

(b)-(f) are anomalies w.r.t. (a)

Williams et al. (2016)
Summary

• The ocean contains sub-grid variability that is too fast or short to be explicitly resolved in GCMs

• Stochastic parameterizations in the ocean can yield reductions in climate model error that are comparable to those obtained by refining the resolution, but without the increased computational cost

• Is it time for the IPCC/CMIP climate simulations to embrace the benefits of stochastic noise? Yes!

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