Improved climate simulations through a stochastic parameterization of ocean eddies

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Motivation

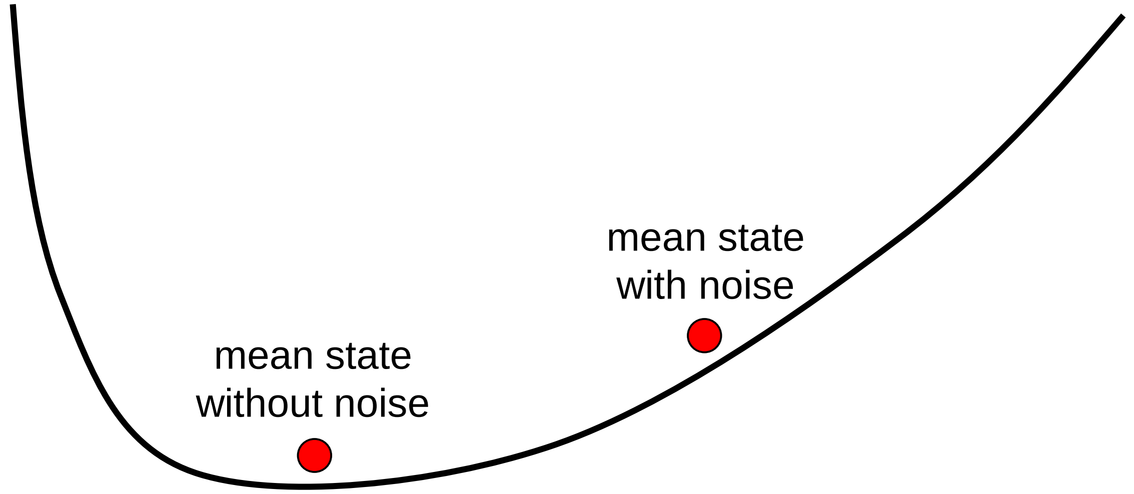
- Deterministic parameterizations of sub-grid processes (e.g. Gent and McWilliams 1990) assume that the impact of the sub-grid scales on the resolved scales is uniquely determined by the resolved scales (e.g. Williams 2005). This is clearly just a first-order approximation

- 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)

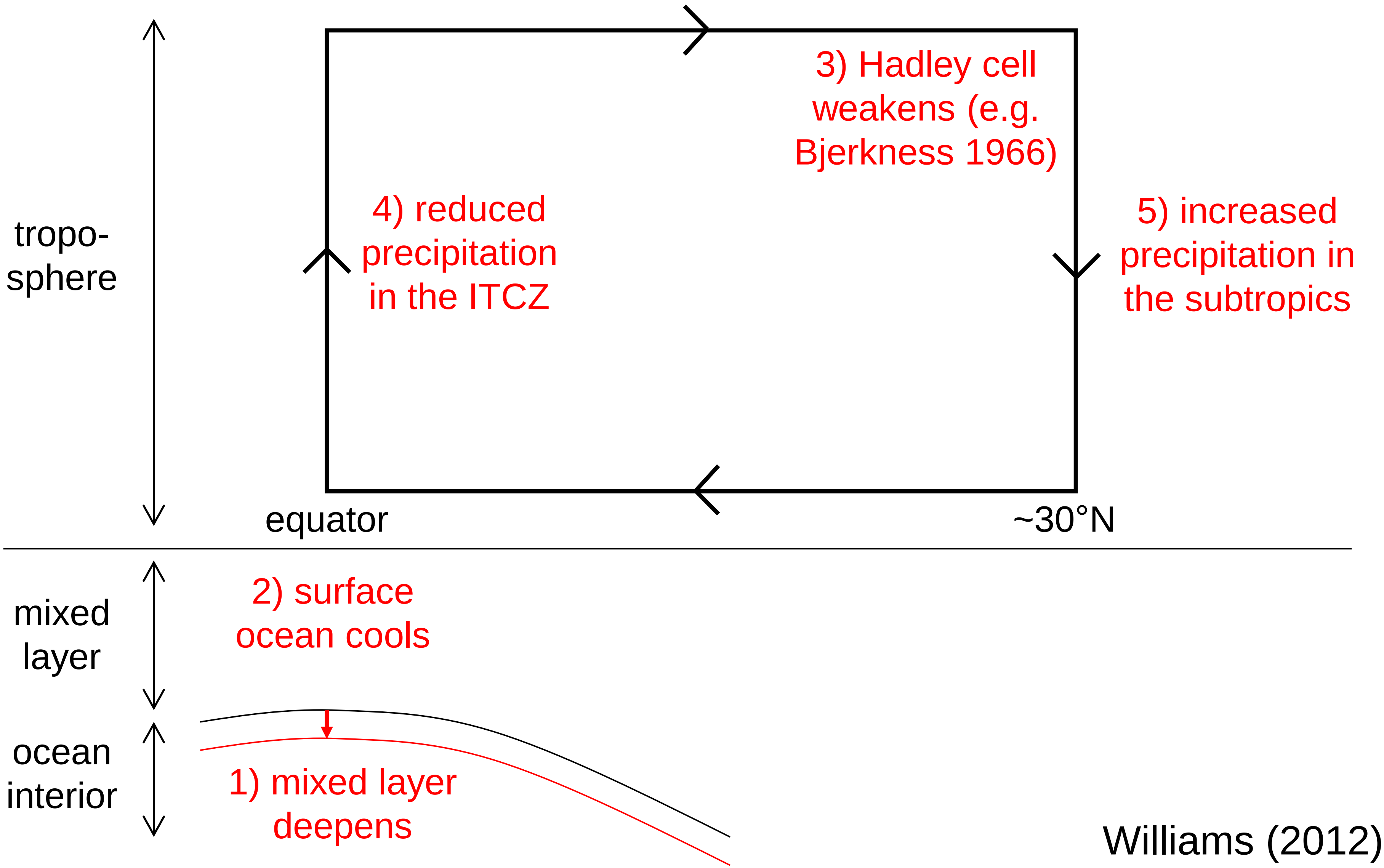
Motivation

- 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



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:

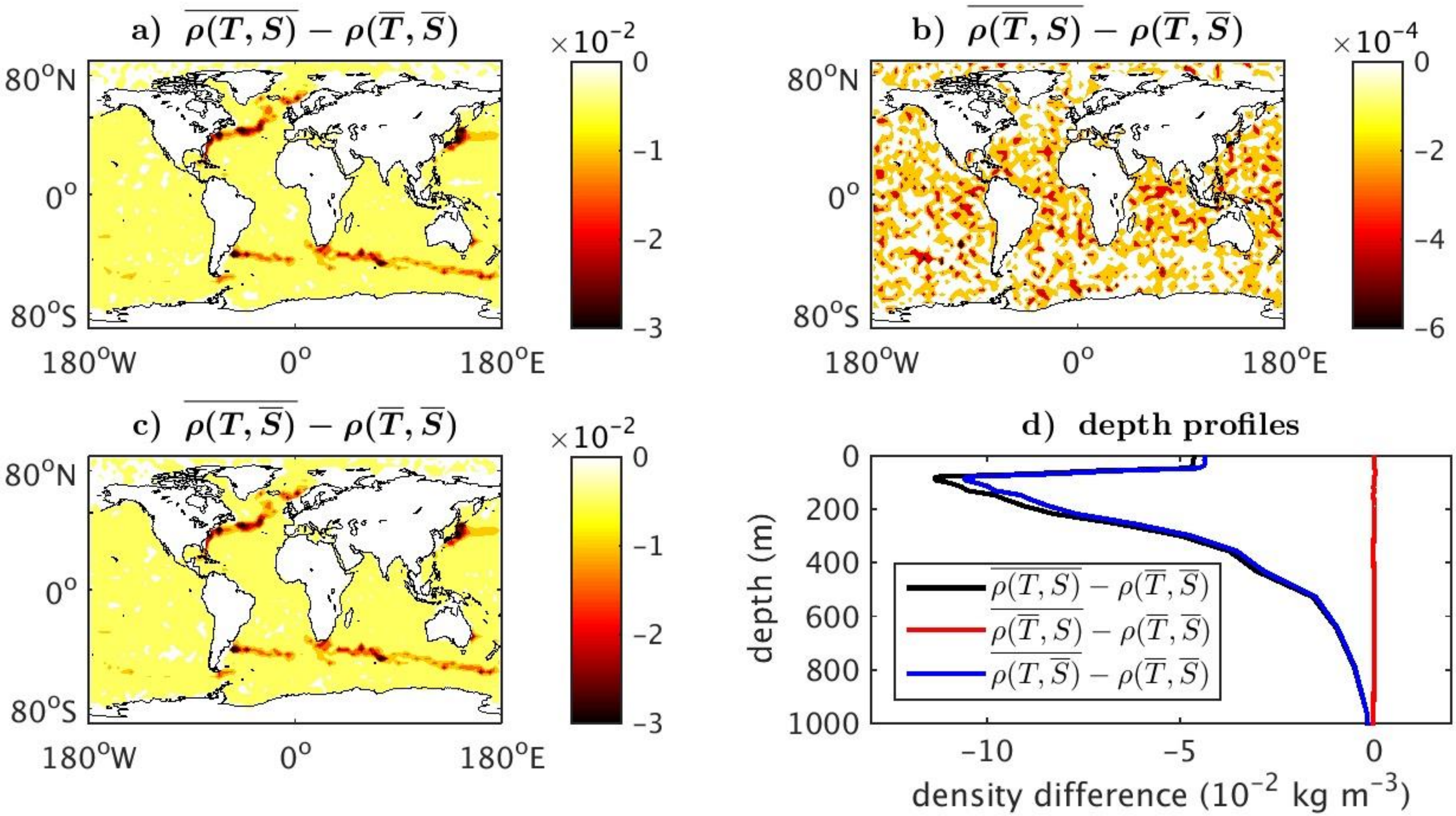
FAMOUS

- 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

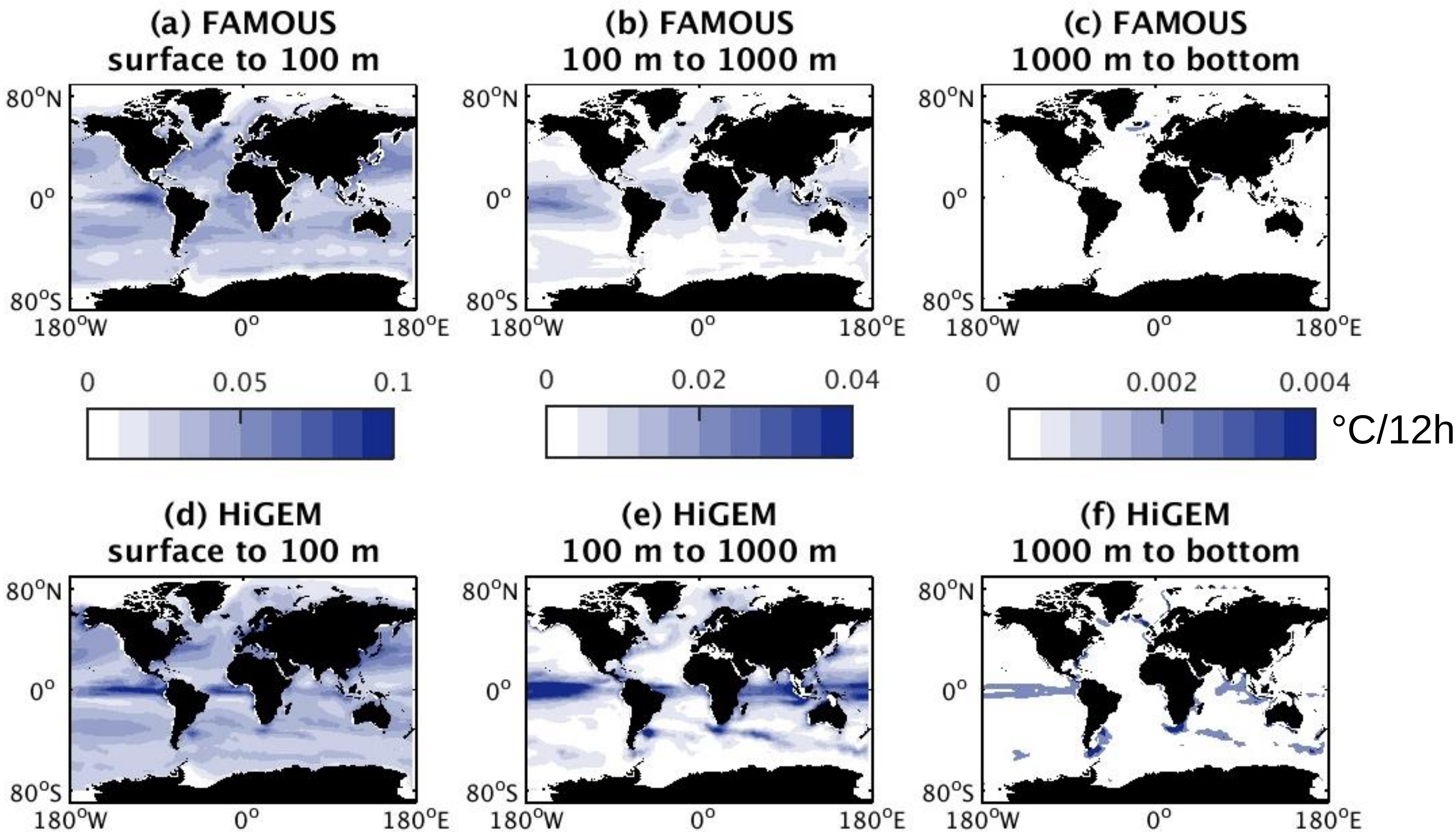
Diagnosing subgrid variability in HiGEM



→ stochastically perturb temperature field only

Brankart (2013), Williams et al. (2016)

Variability of temperature tendencies



→ stochastically perturb temperature tendency

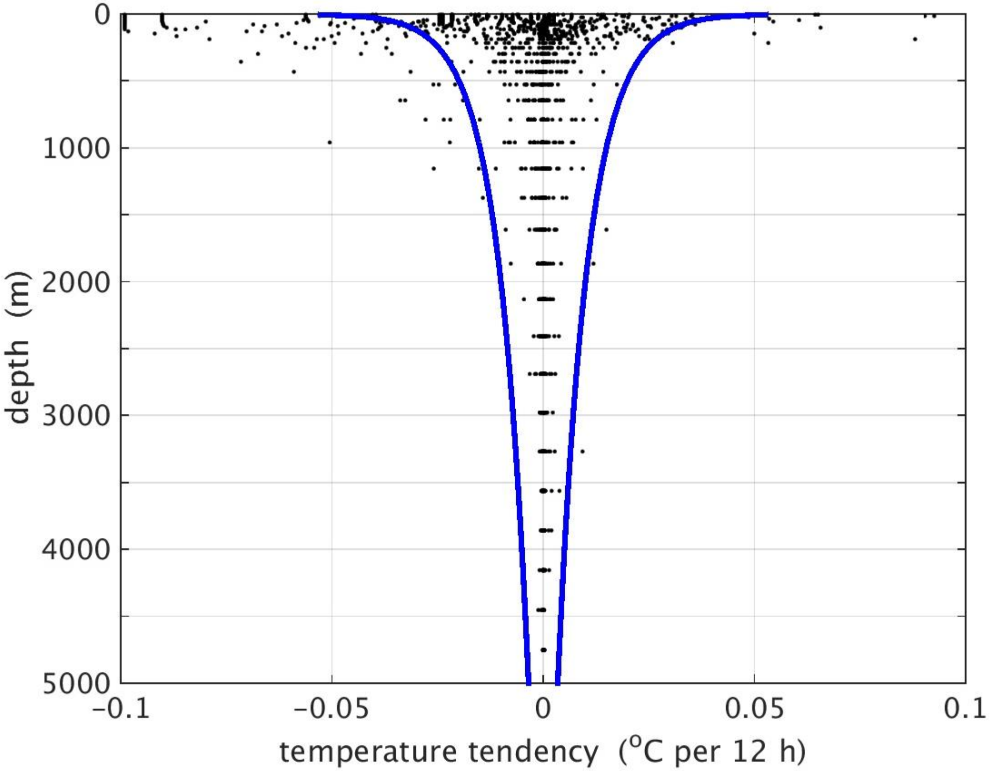
Williams et al. (2016)

Noise amplitude and distribution

- A HiGEM control integration is used to diagnose the noise properties
- Horizontally uncorrelated, vertically coherent, temporally correlated (red) Gaussian noise η is added to the temperature tendency dT/dt at each ocean grid point and time step:

$$T_{n+1} = T_{n-1} + 2\Delta t\,(dT/dt_n + \eta)$$

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



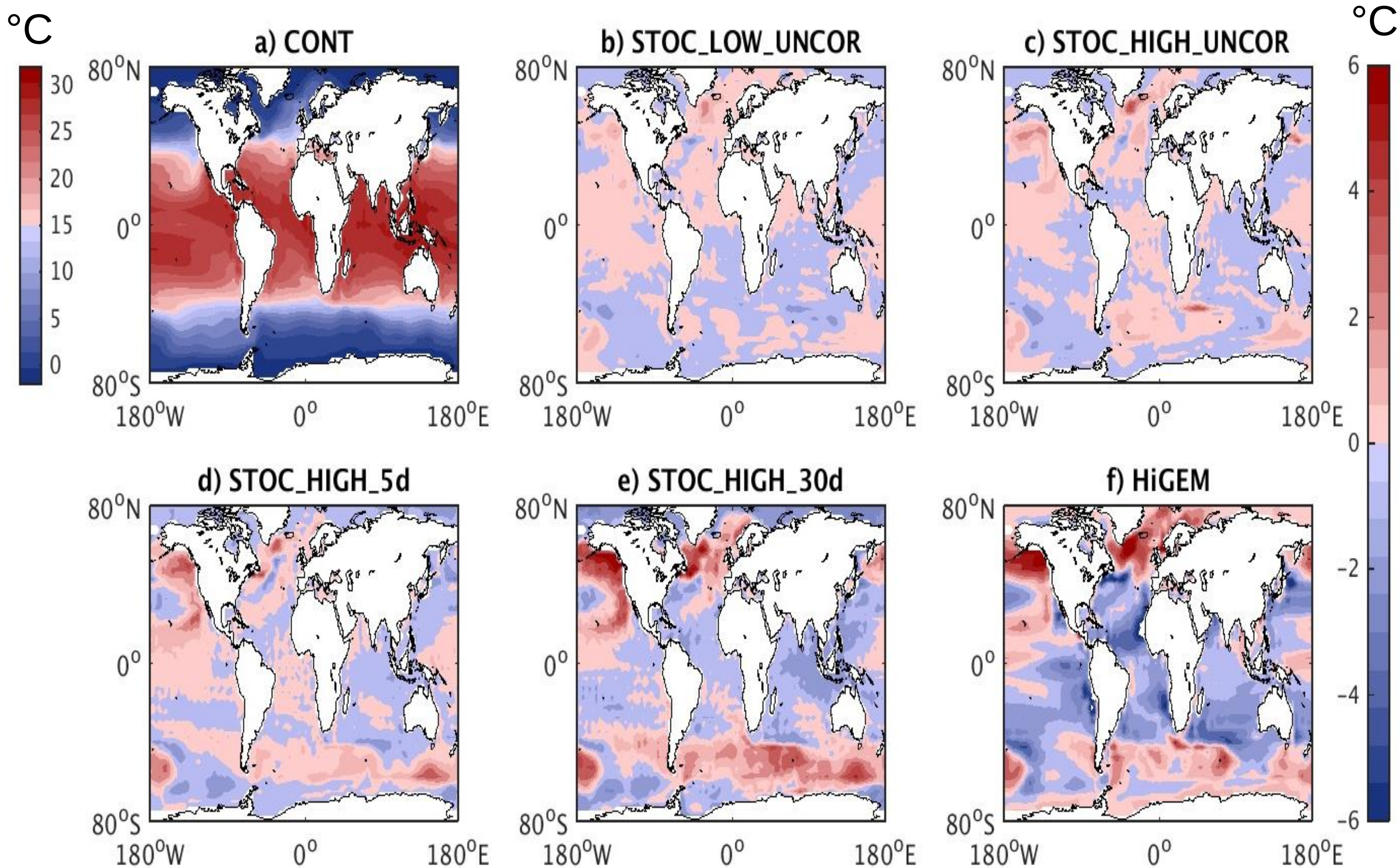
Williams et al. (2016)

FAMOUS simulations

Experiment name	Noise amplitude at surface (°C per 12 h)	Decorrelation time (days)	Number of ensemble members
CONT	0	–	1
STOC_LOW_UNCOR	0.05	0	1
STOC_HIGH_UNCOR	0.1	0	3
STOC_HIGH_5d	0.1	5	1
STOC_HIGH_30d	0.1	30	1

Williams et al. (2016)

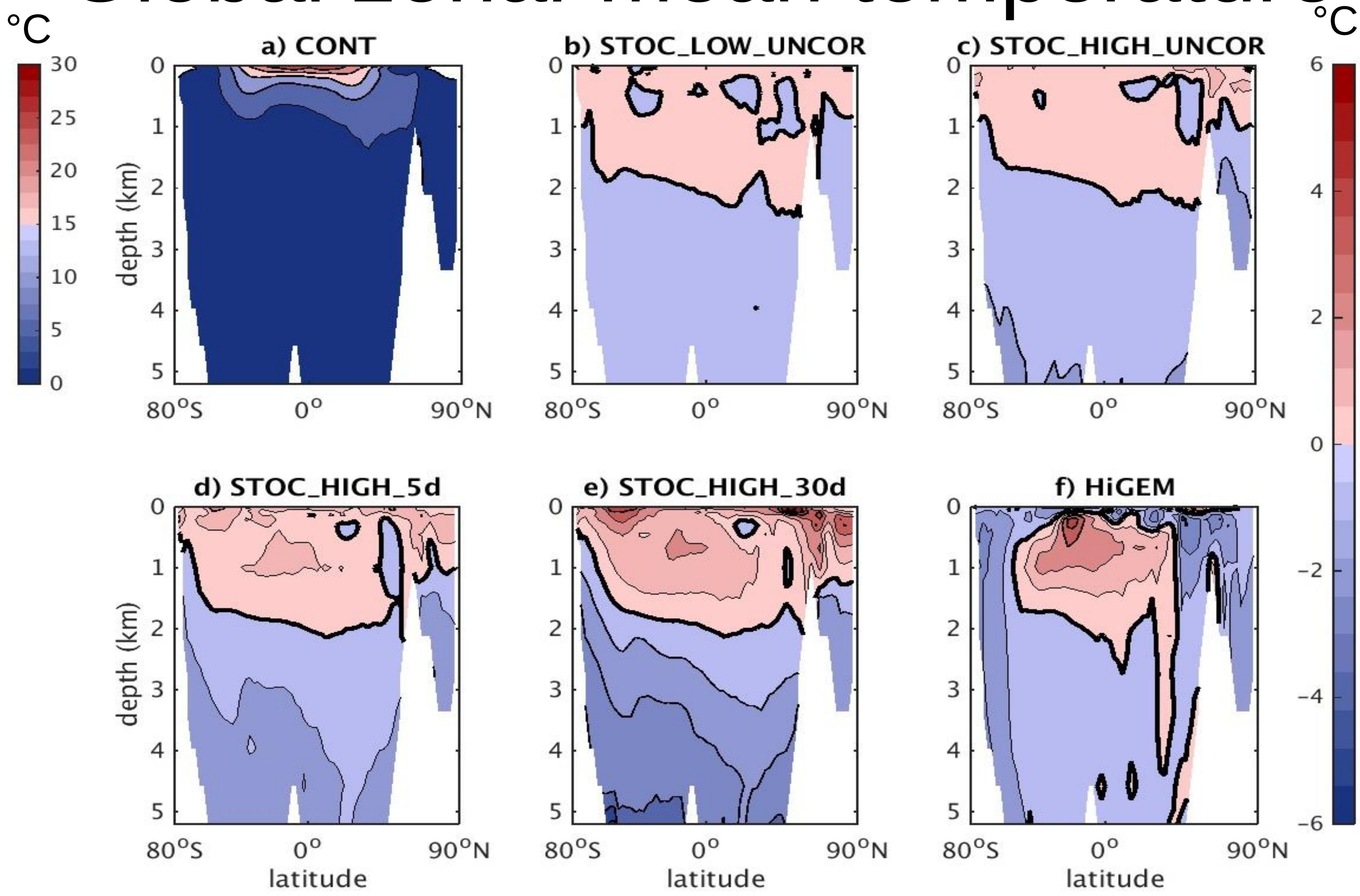
Sea-surface temperature



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

Williams et al. (2016)

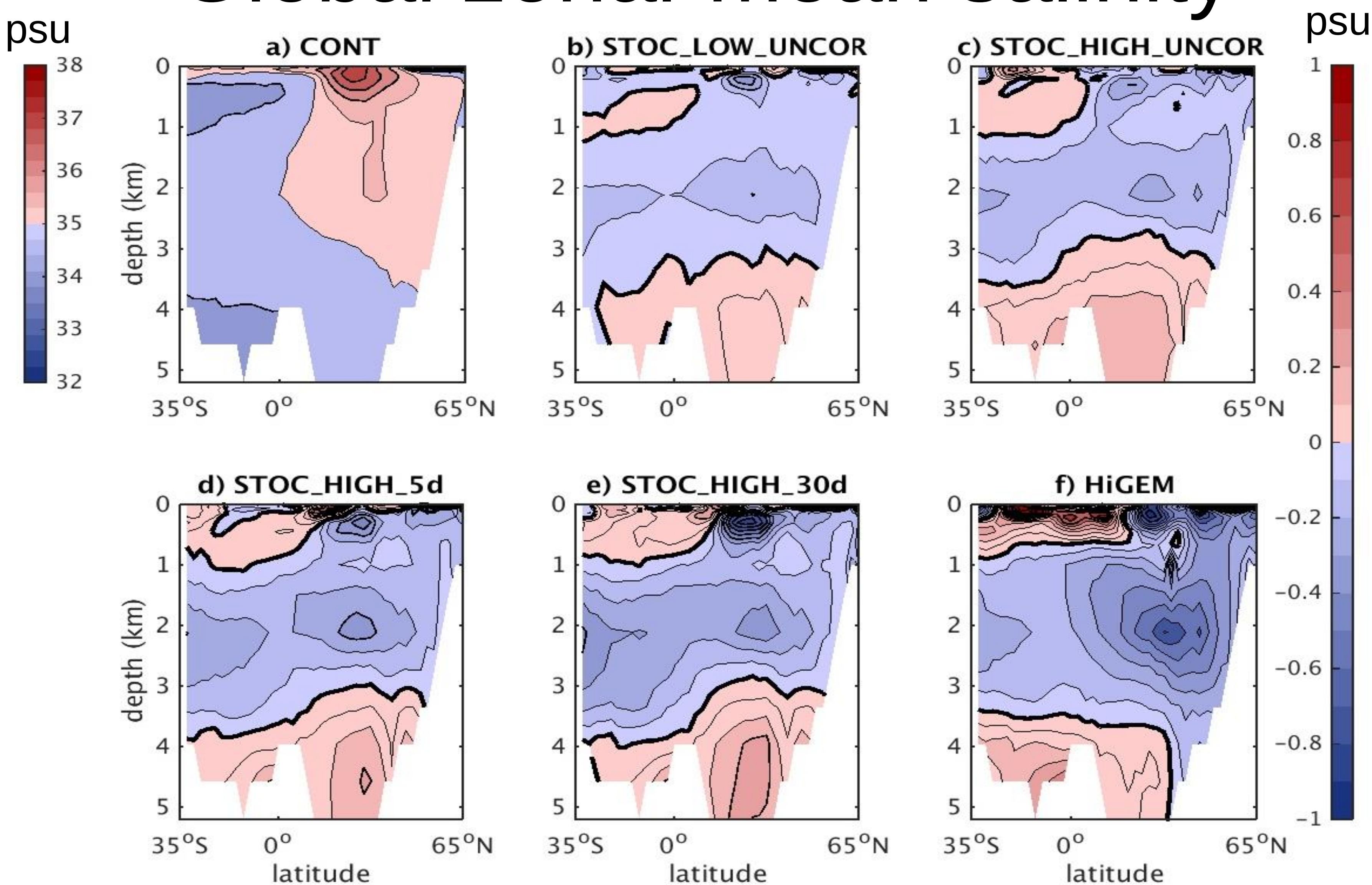
Global zonal-mean temperature



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

Williams et al. (2016)

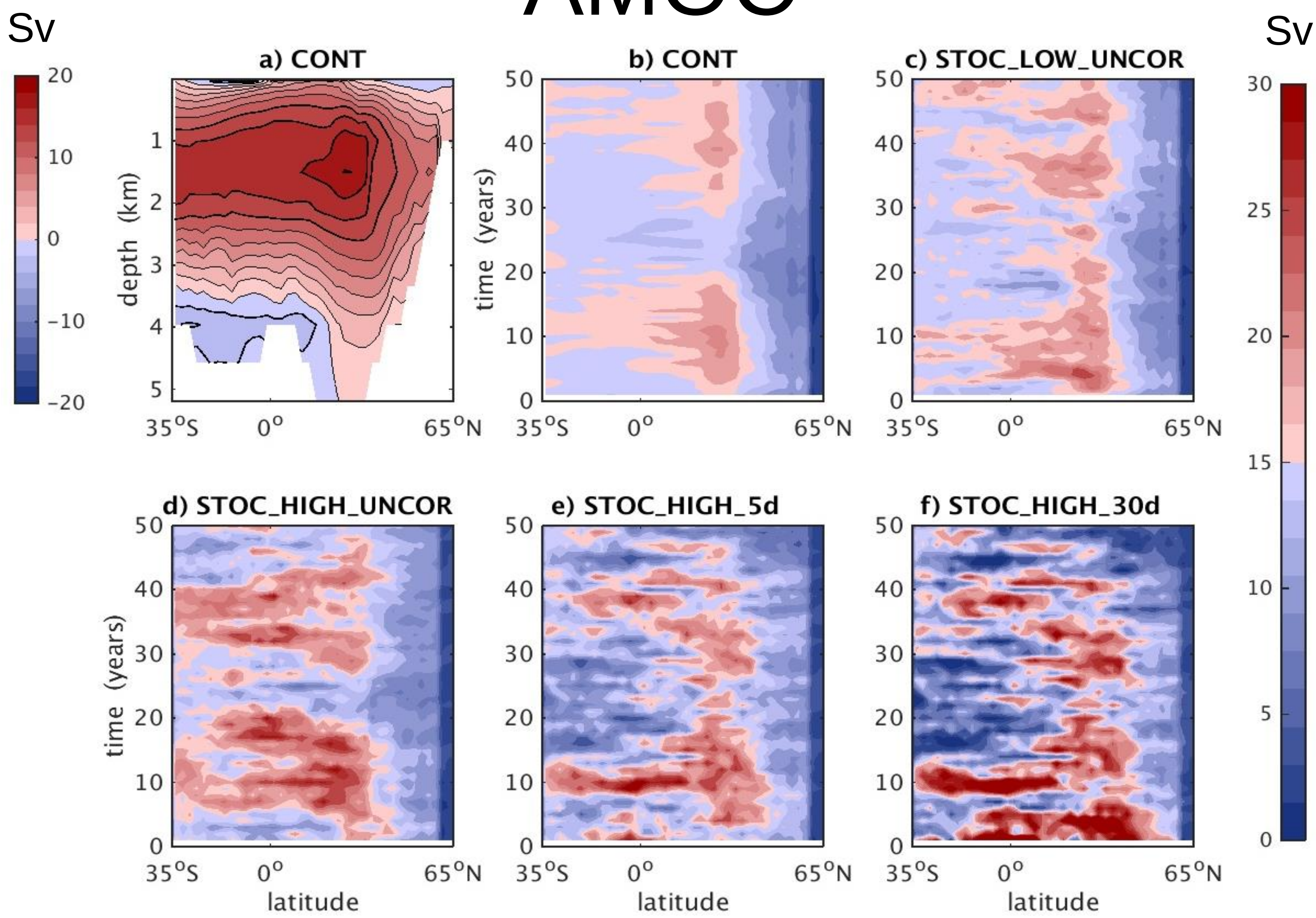
Global zonal-mean salinity



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

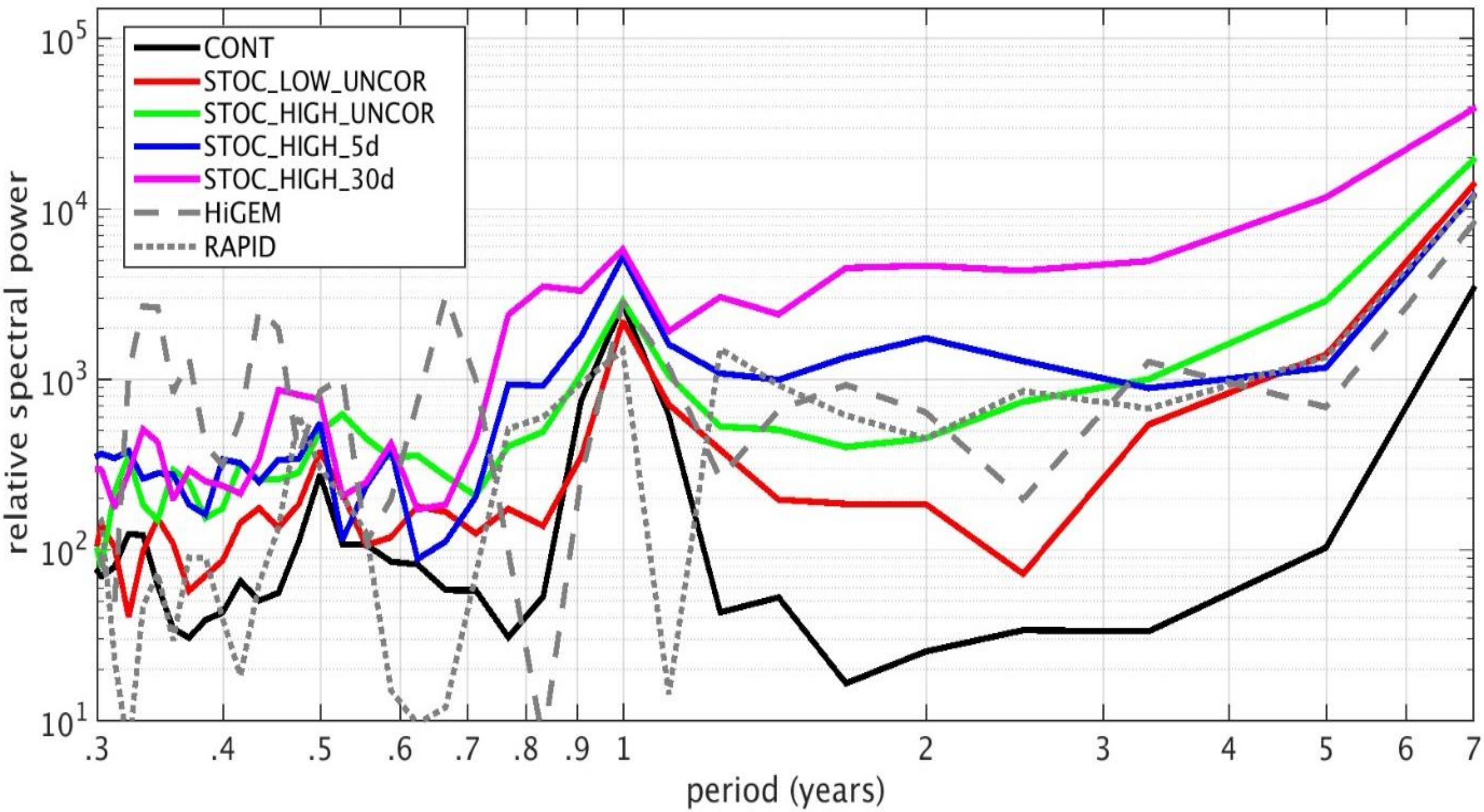
Williams et al. (2016)

AMOC



Williams et al. (2016)

AMOC variability



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!

Journal of Climate paper: doi 10.1175/JCLI-D-15-0746.1