Model uncertainty estimation in global ocean models: Stochastic parametrizations of ocean mixing

ECMWF Uncertainty Workshop

Stephan Juricke

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T. Palmer, A. Weisheimer, L. Zanna

Overview

1. Introduction: Sub-grid scale variability and model uncertainty

2. Stochastic parametrization approach

3. Results:

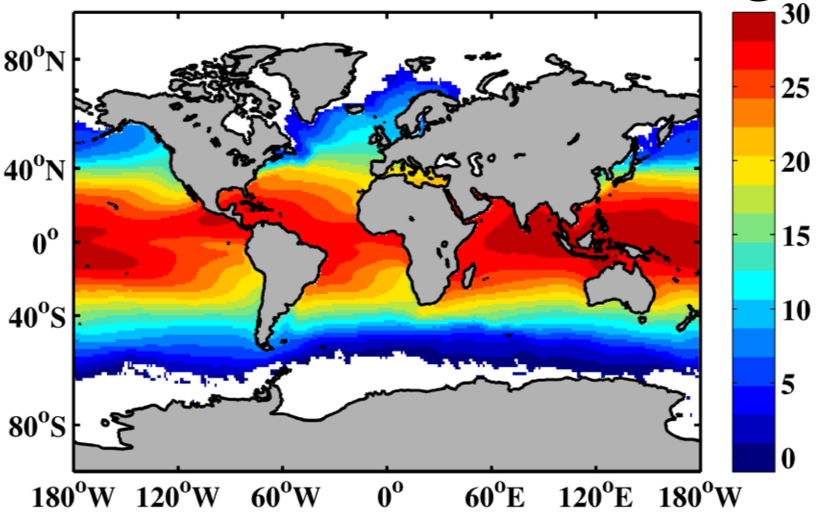
Uncoupled climate simulations

Seasonal forecasts

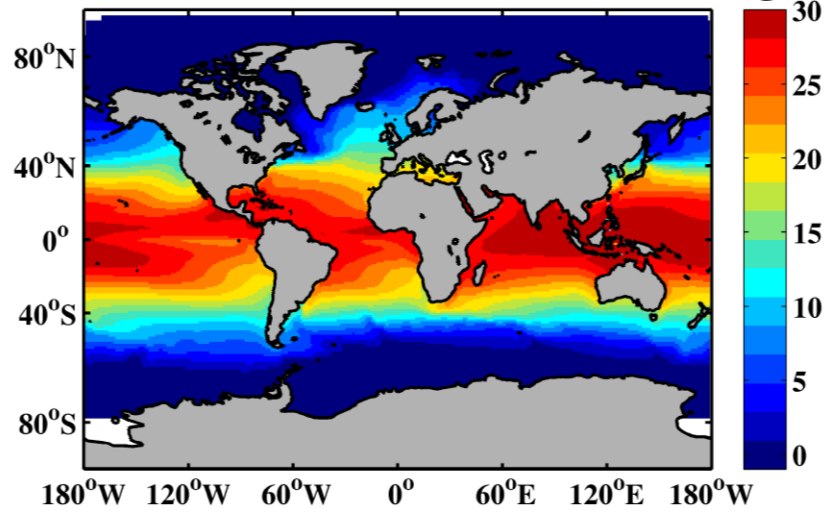
4. Conclusions & Outlook

Introduction

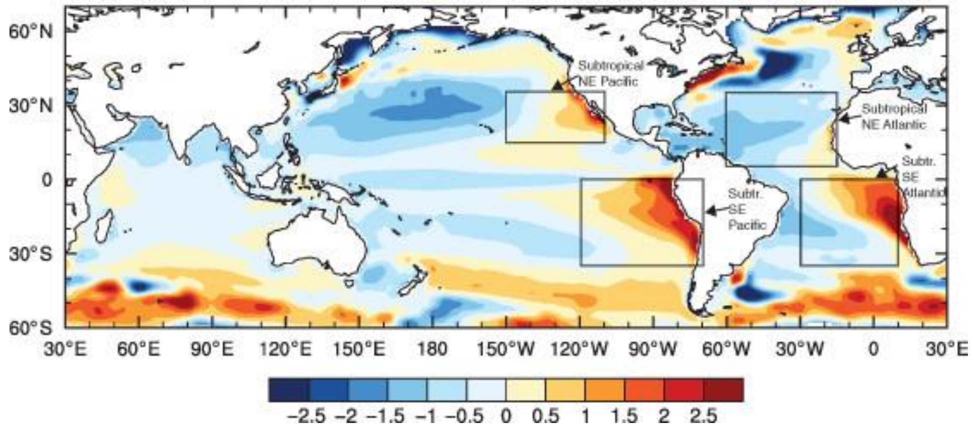
HadISST mean SST, 1960-2004 °C



REF model mean SST °C



Annual mean SST error in CIMP5 ensemble

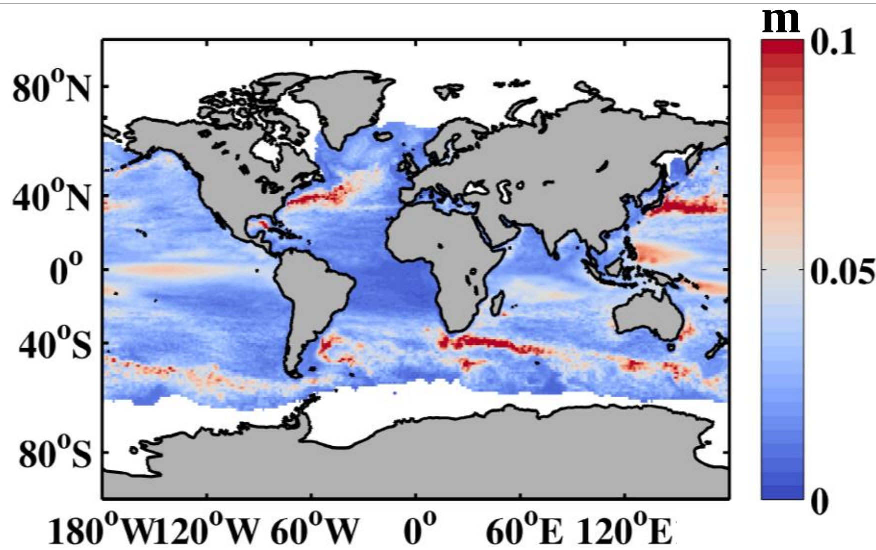


°C

Richter, 2015

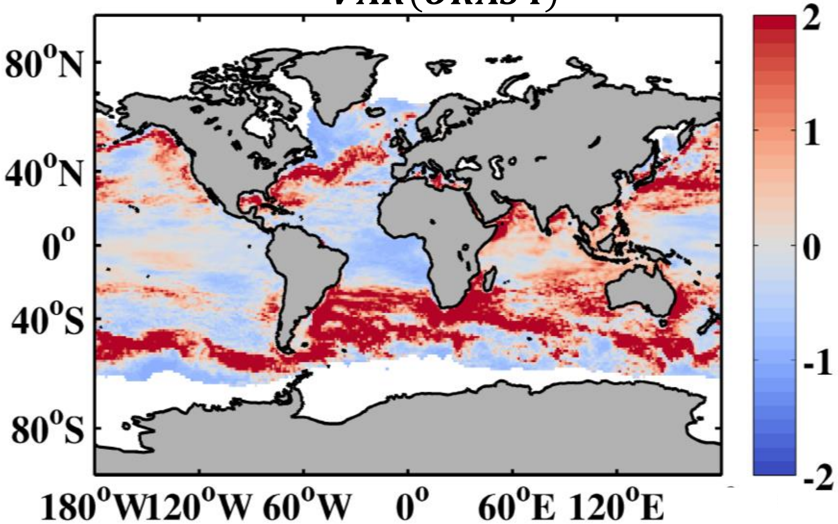
Introduction

AVISO standard deviation of annual mean SSH, 1993-2013

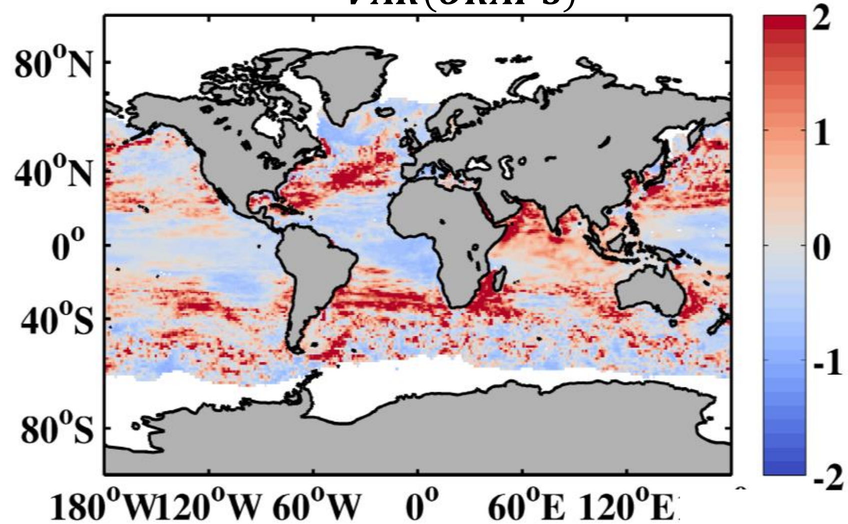


Relative difference in variance of annual mean SSH

$$\frac{VAR(AVISO) - VAR(ORAS4)}{VAR(ORAS4)}$$



$$\frac{VAR(AVISO) - VAR(ORAP5)}{VAR(ORAP5)}$$



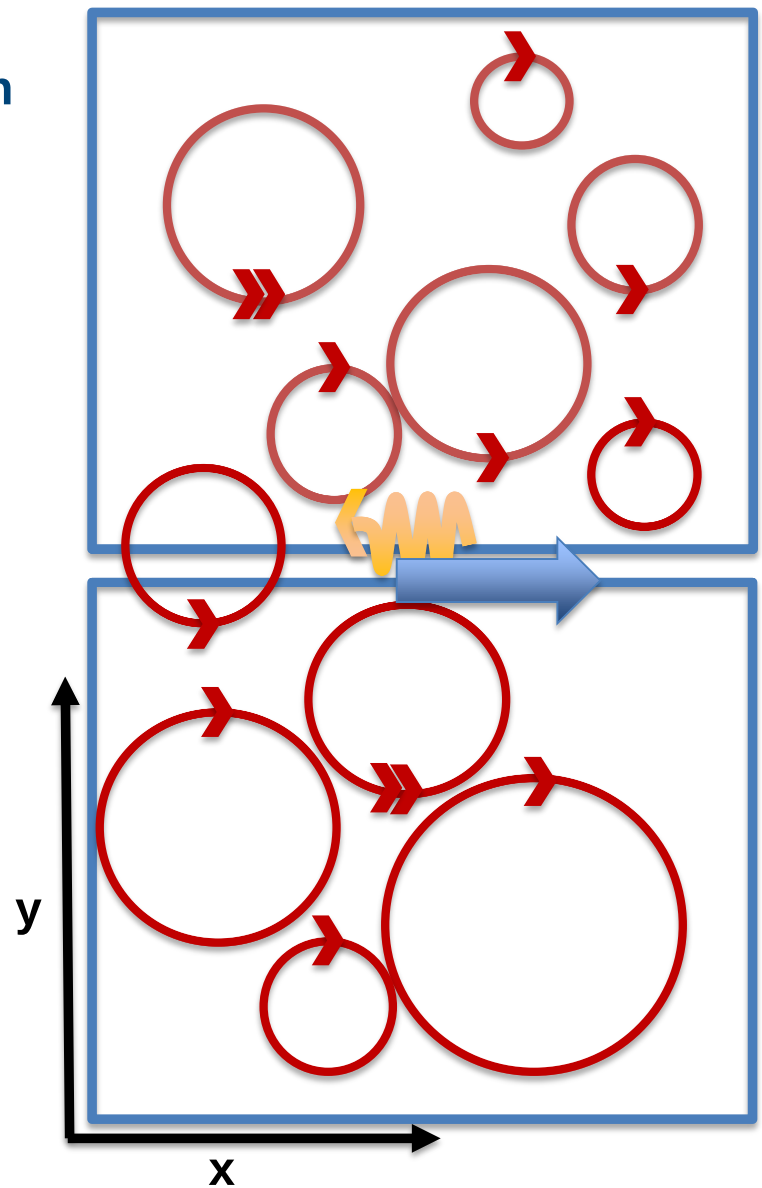
Introduction

Resolved advection

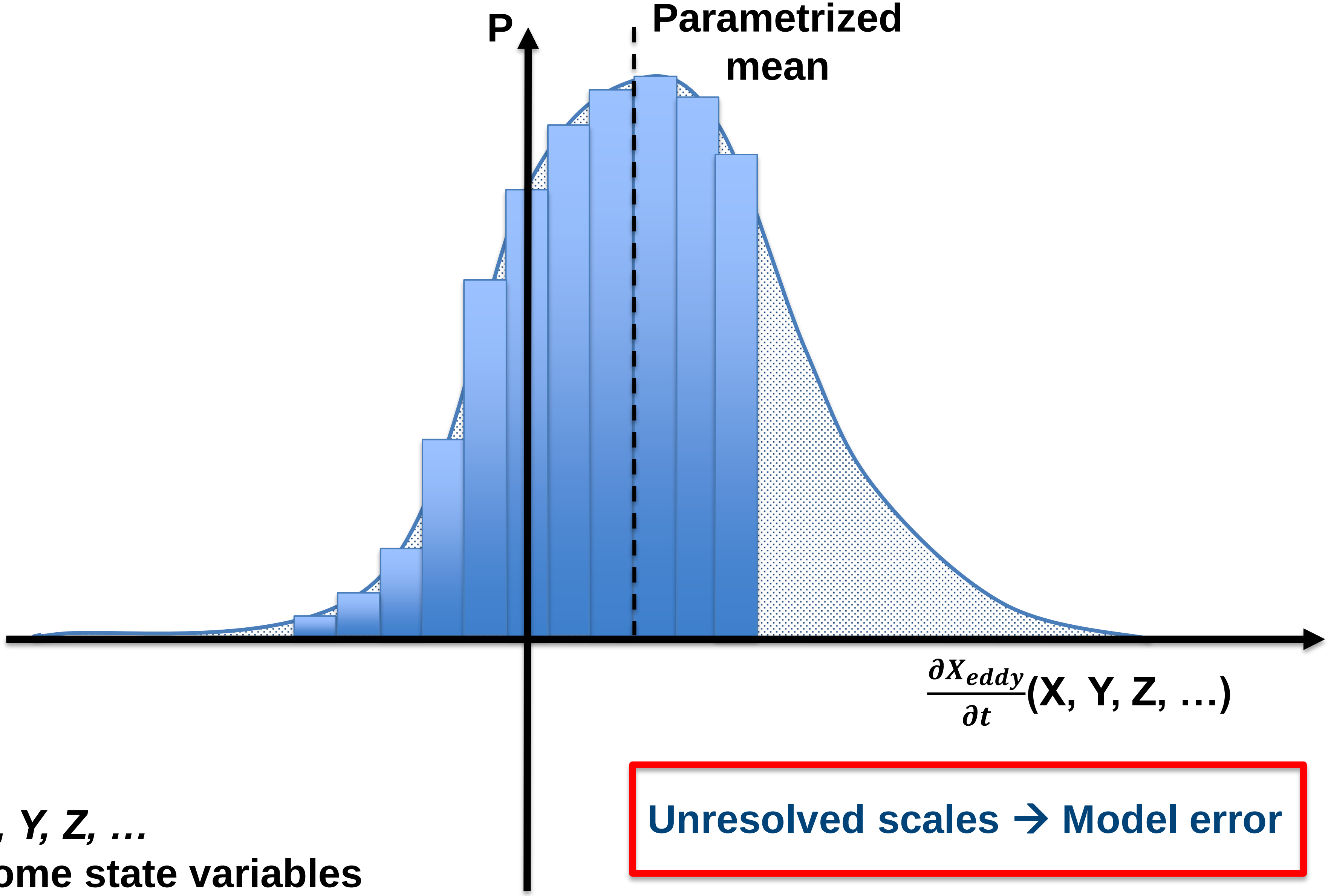
Unresolved, parametrized mixing

Unresolved process (e.g. eddy, convection)

Model grid box



Introduction



X, Y, Z, …
some state variables

Unresolved scales → Model error

Stochastic parametrization

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Aim is to:

1. Represent uncertainty in unresolved scales
2. (Re-) Introduce sub-grid scale variability

General approach:

Perturbations to crucial and imperfectly constrained parameters and/or tendencies in established parametrizations

For example:

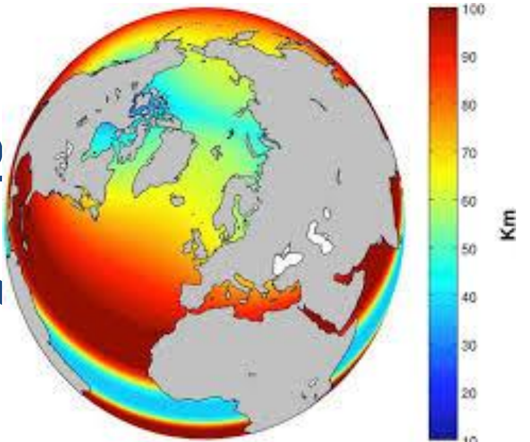
$$\boldsymbol{P(i,j) = \big(1 + x(i,j)\big) \cdot P_{ref}}$$

Perturbation to parameter P at timestep i and grid point j by random number $x(i,j)$ to simulate uncertainty and sub-grid scale variations not captured by deterministic parametrizations

Stochastic parametrization

Model configuration:

- **1° Resolution ORCA1L46 grid**
- **DFS atmospheric forcing for uncoupled simulations**



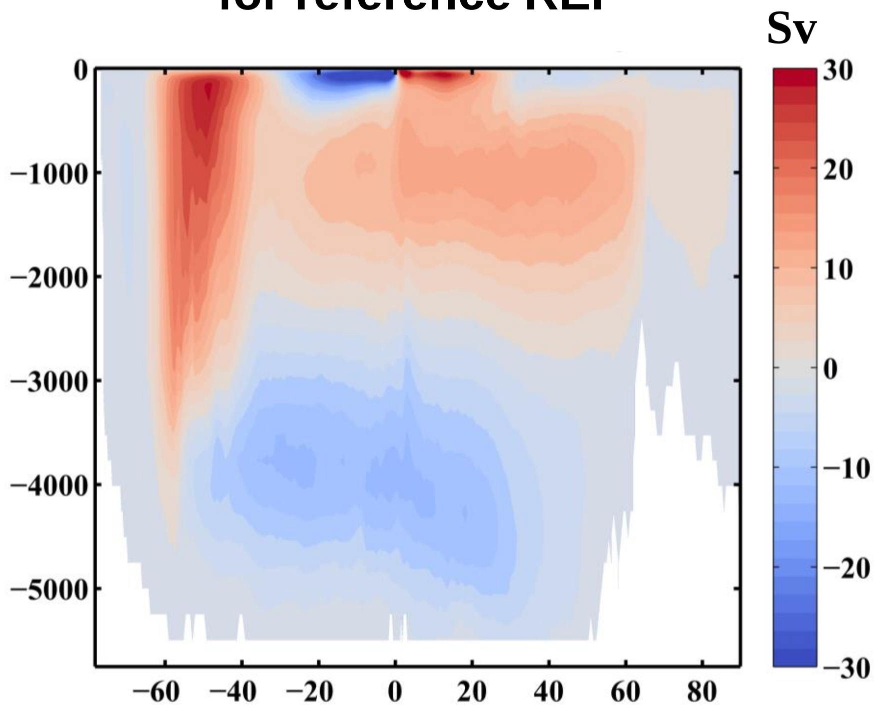
Parametrized aspects of NEMO

- **Horizontal and vertical diffusion through the viscosity a coefficients**
- **Vertical mixing through the vertical viscosity and diffusivity coefficients**
- **Gent-McWilliams parametrization for tracer diffusion; additional term of tracer advection, along isopycnal surfaces of constant potential density**
- **Surface, bottom and boundary parametrizations (not discussed here)**

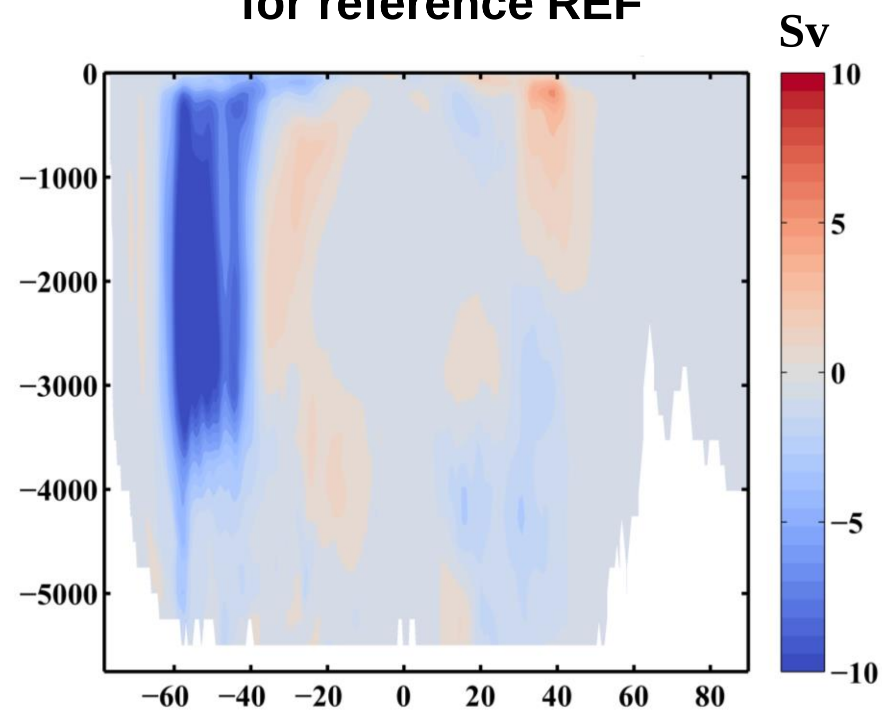
Remark: Numerical stability is ensured by increasing viscosity and diffusivity

Stochastic parametrization

Global climatology of zonally averaged streamfunction ψ_{euler} for reference REF



Global climatology of zonally averaged streamfunction ψ_{eddy} for reference REF



Stochastic parametrization

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Stochastic peturbations to:

1. **Gent-McWilliams coefficient**
2. **Enhanced vertical diffusivity in case of unstable stratification**
3. **Shear and buoyancy tendencies in the prognostic equation of turbulent kinetic energy used to parametrize vertical viscosity and diffusivity**

Example equation for temperature: $\frac{\partial T}{\partial t} = -\nabla\left(T\left(\vec{U} + \vec{U}_{eddy}\right)\right) + D_T + F_T$

with 3D velocity $\vec{U}$, parametrized eddy velocity $\vec{U}_{eddy}$, parametrized temperature tendencies D_T and forcing F_T

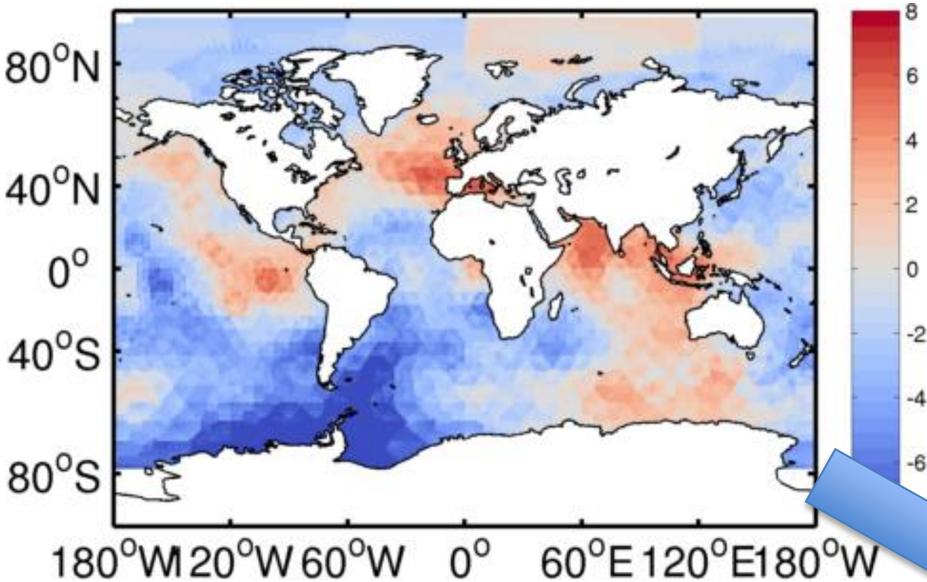
Gent-McWilliams eddy induced velocity (*u* component): $\mathbf{u_g} = -\frac{\partial}{\partial z}(A\,S)$

with A eddy induced velocity coefficient, S slope of isoneutral surfaces (with regard to geopotential surfaces) → formulation is non-divergent

$$\Rightarrow \mathbf{u_g} = -\frac{\partial}{\partial z}\left(\left(1 + r_{GM}\right) * A\,S\right)$$

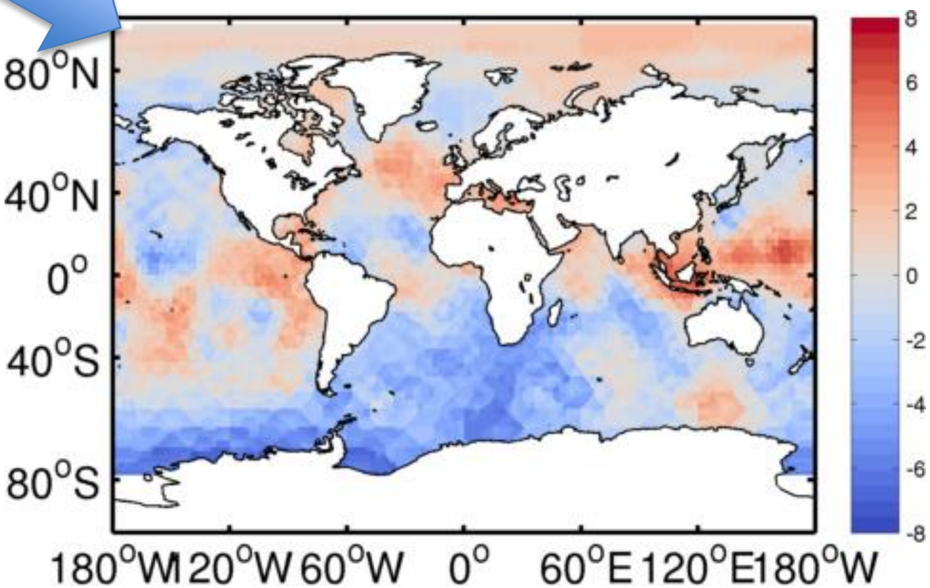
with random number r_{GM}

Stochastic parametrization



Day 1

Stochastic pattern with temporal and spatial correlation, before transformation into bounded range



Day 2

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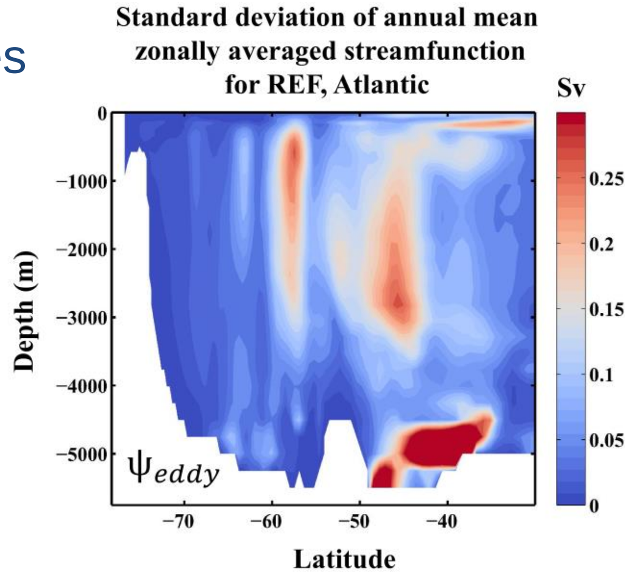
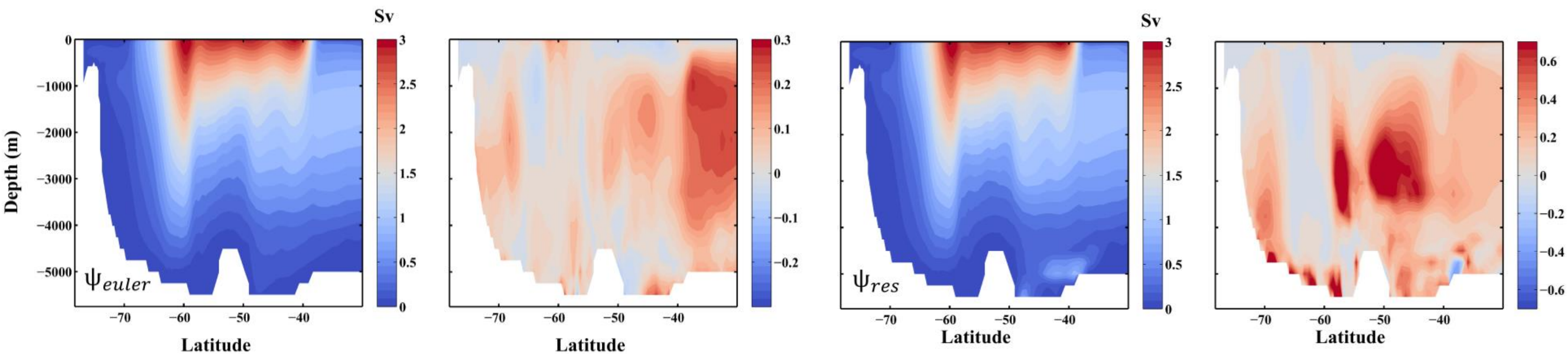
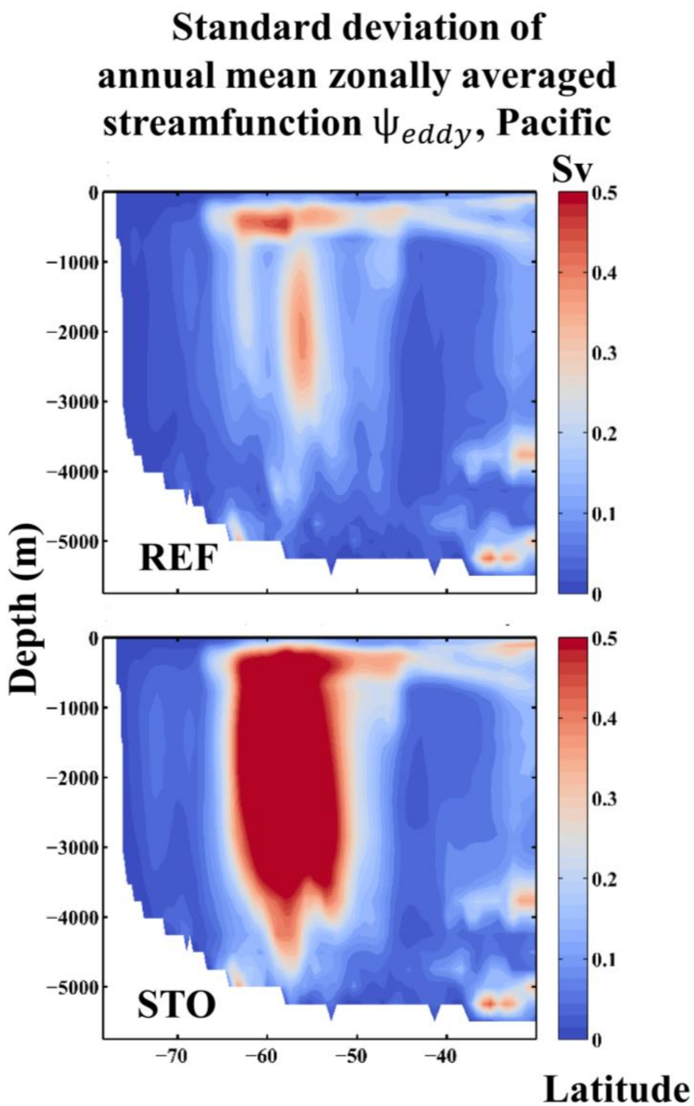
Results: Uncoupled

105 years, repeated cycles (1990-2004, 2x 1960-2004), with 30 years of spin-up

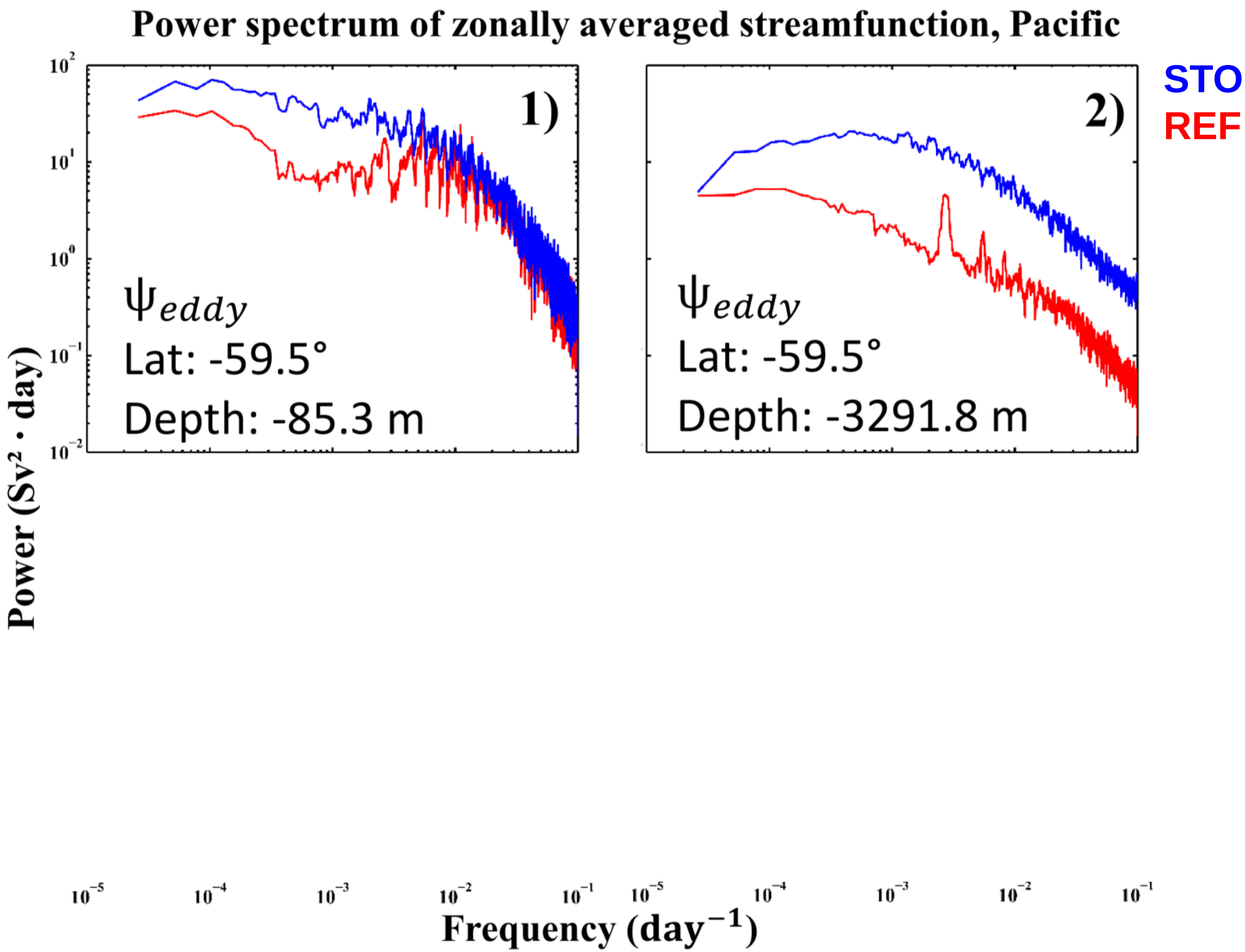




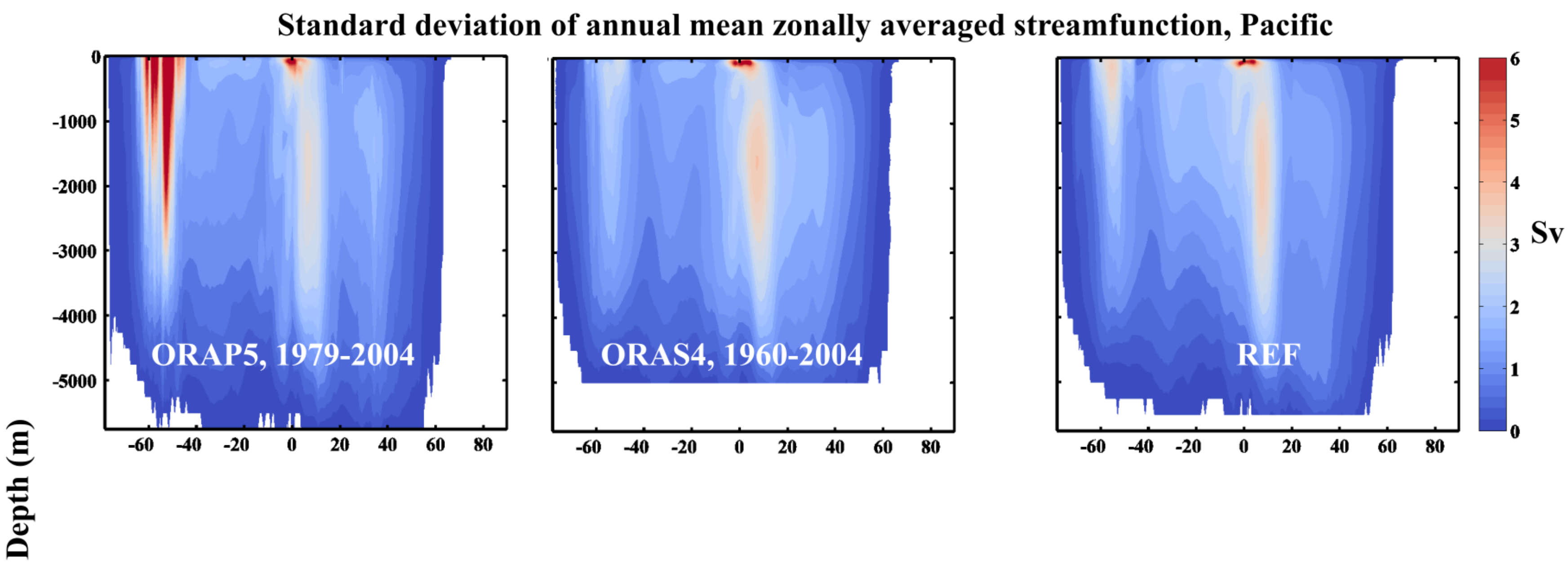
Results: Uncoupled



Results: Uncoupled

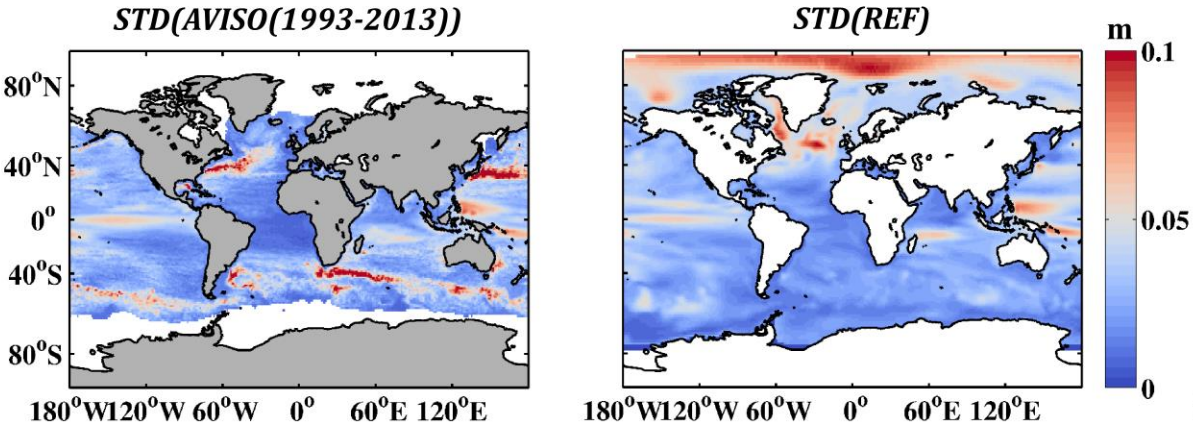


Results: Uncoupled



Results: Uncoupled

Standard deviation and relative difference in variance of annual mean SSH

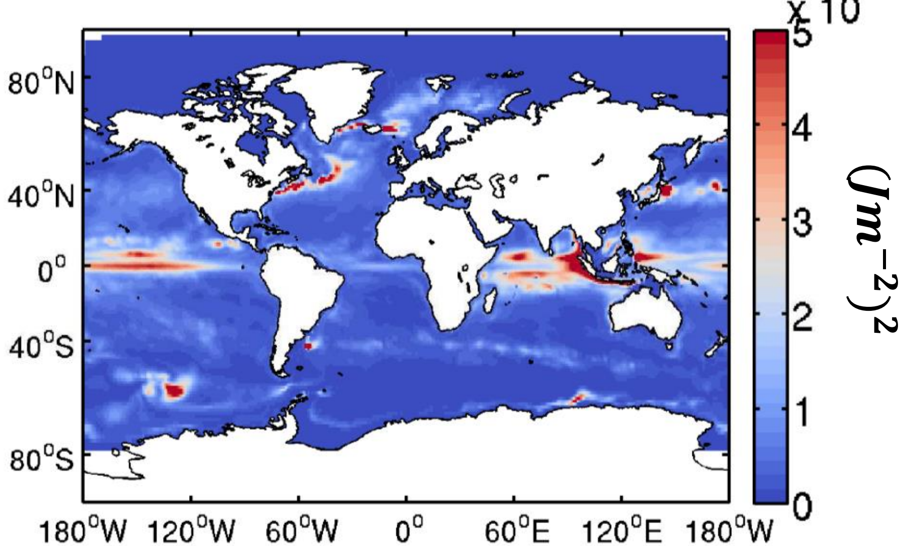


Results: Seasonal

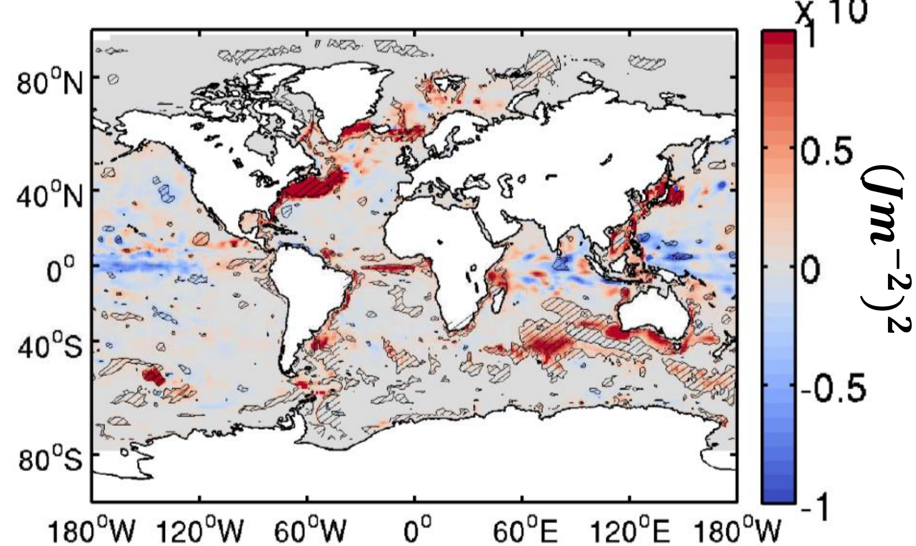
Andrejczuk et al., 2016

300 m heat content
Month 3

Control ensemble variance



SPPT variance – Control variance



Deterministic and stochastic (ocean SPPT) ensembles
3 months forecasts
10 years, 10 ensemble members, ECMWF System 4, NEMO ORCA1L42

Results: Seasonal

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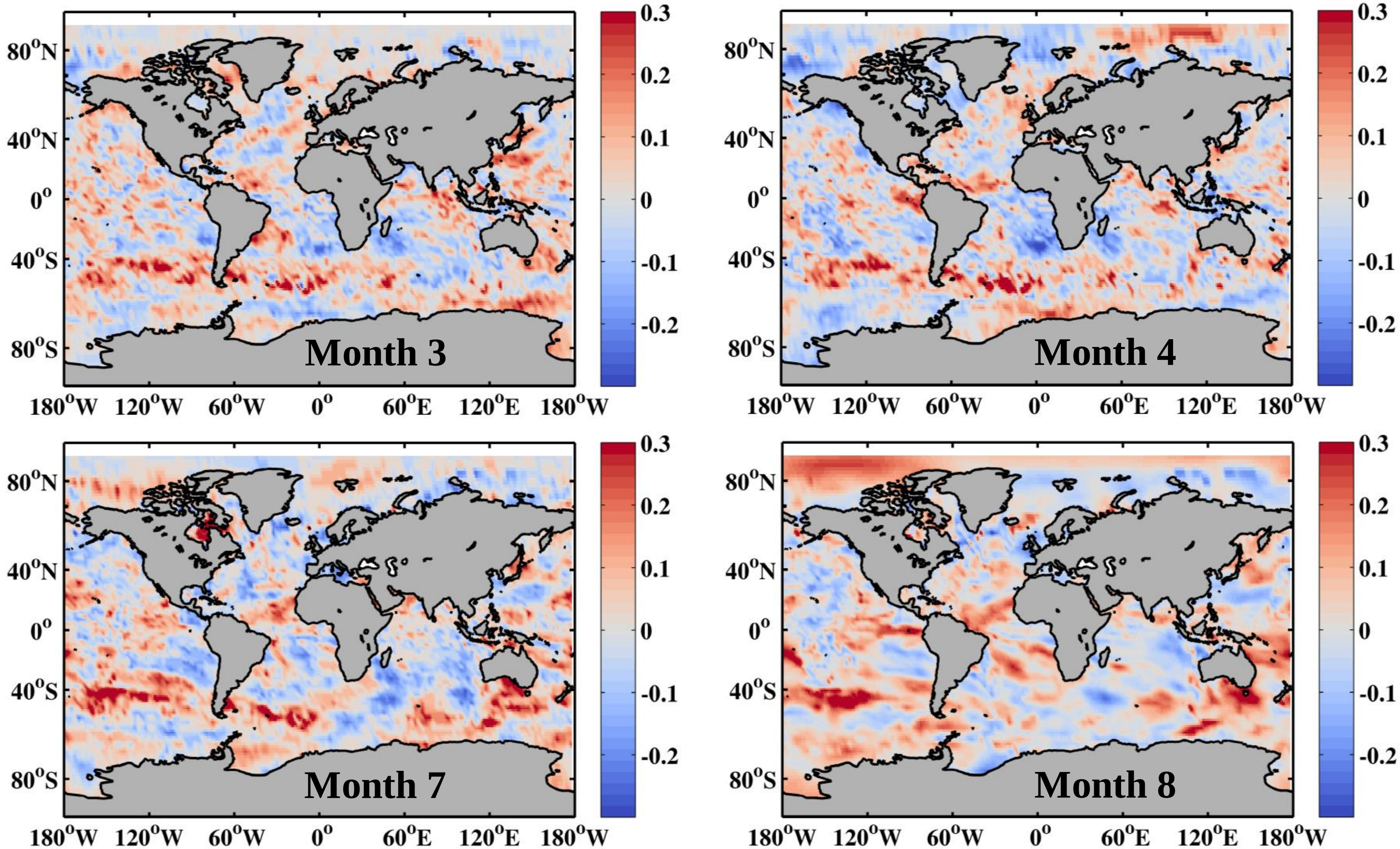
Relative change in ensemble variance for SST



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35 years, 20 ensemble members, ECMWF System 4, NEMO ORCA1L42

Results: Seasonal

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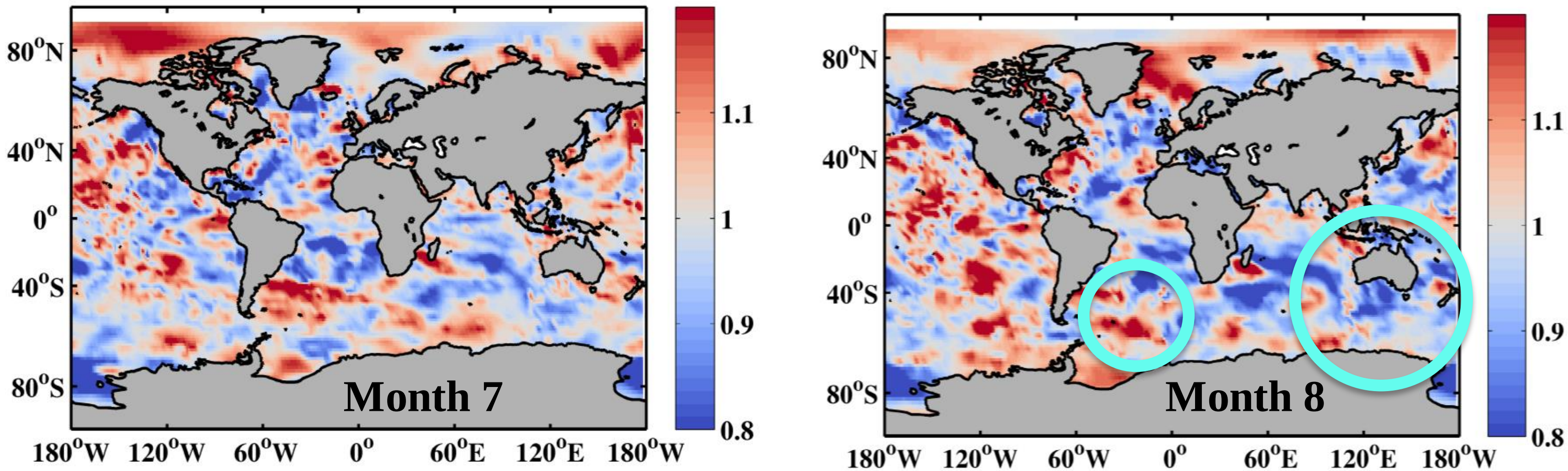
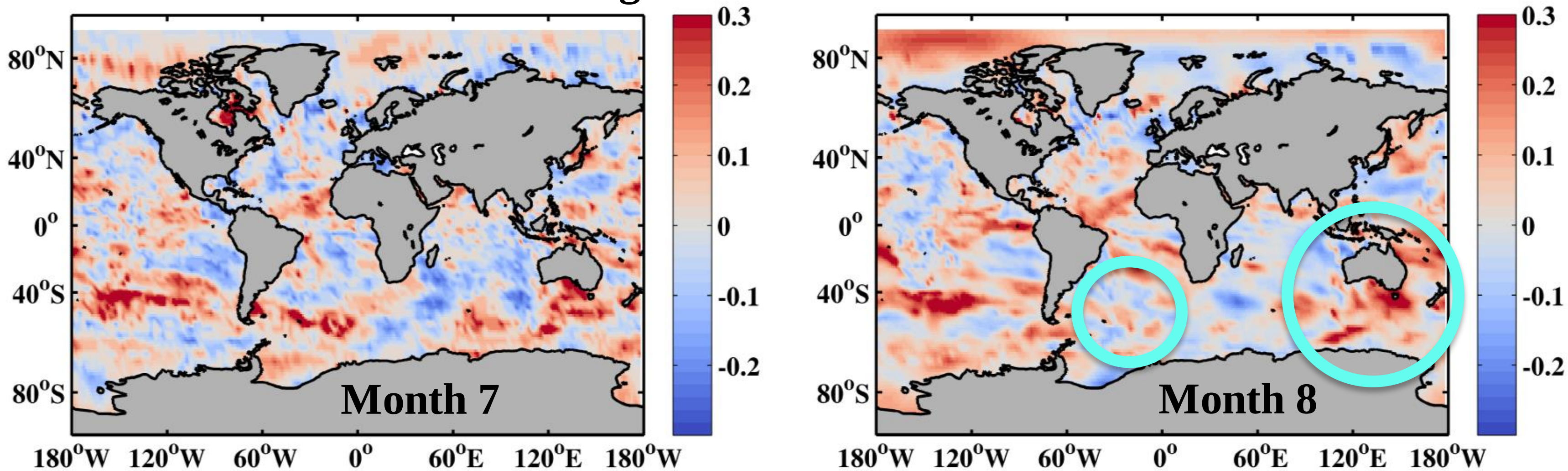
RMSE ratio (STO/REF) for SST



Relative change in ensemble variance for SST



Conclusions

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- **Stochastic mixing schemes introduced to represent sub-grid scale variability and model uncertainty**
- **Improvement in low frequency variability (compared to OBS and reanalysis) of circulation as well as sea surface height (up to 20 to 30% increase in variance)**
- **Potential improvements on representation of low frequency climate modes → Improved mean, variance, and response to forcing without the computational cost of higher resolution**
- **The basics physical principles are not violated (adiabatic, non-divergent GM for example)**
- **Increase in ensemble variance for seasonal forecasts (around 30%)**

Outlook

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- **Further investigate impact on seasonal forecasts**
- **Investigate impact in coupled climate models**
- **Test schemes in higher resolution simulations (potentially develop new schemes)**
- **Estimate parameters for amplitude, temporal and spatial correlations of noise from high resolution simulations and observations**