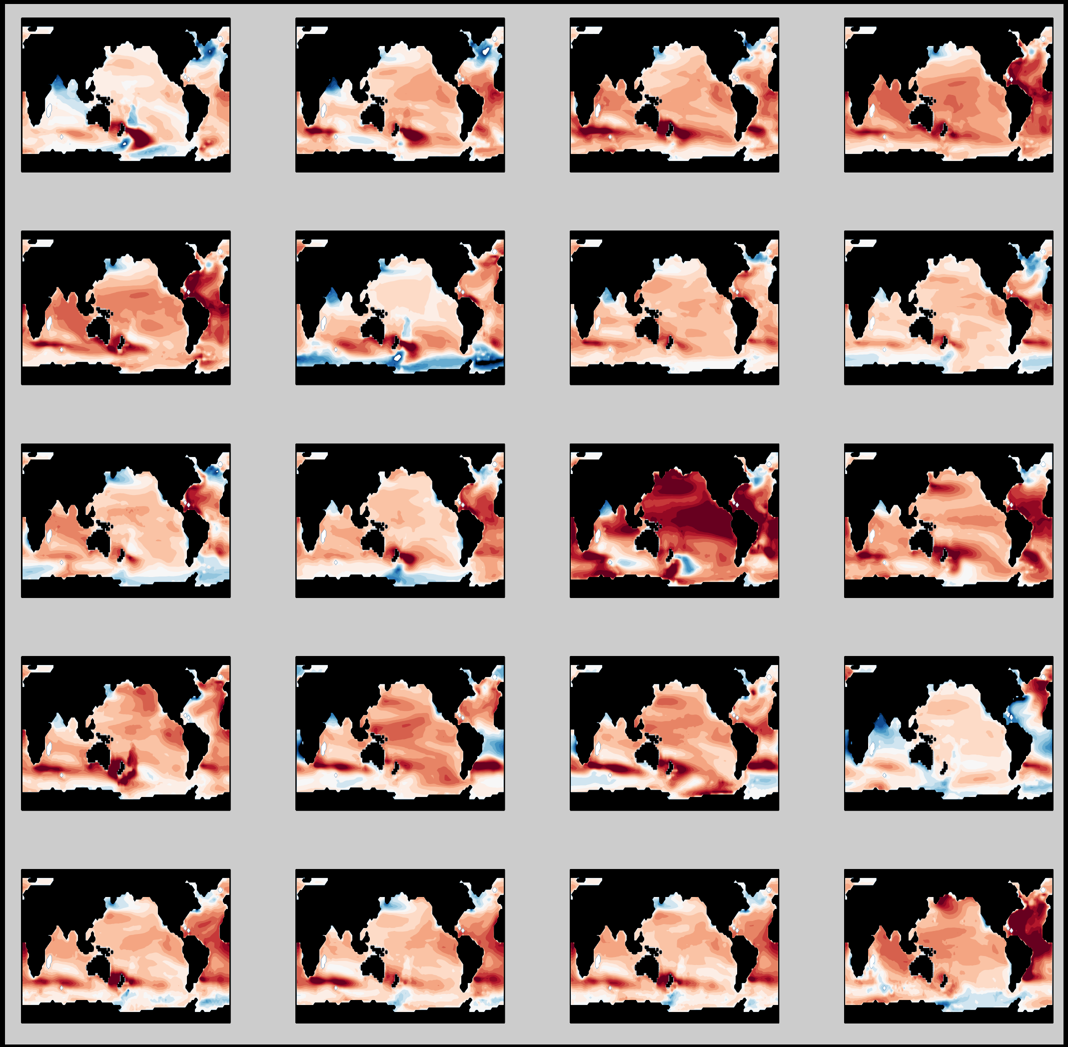
Uncertainty quantification in ocean models: from seasonal forecasts to multi-decadal predictions



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ECMWF, Annual Seminar 2017

Outline

- Overview: From ocean processes to ensembles

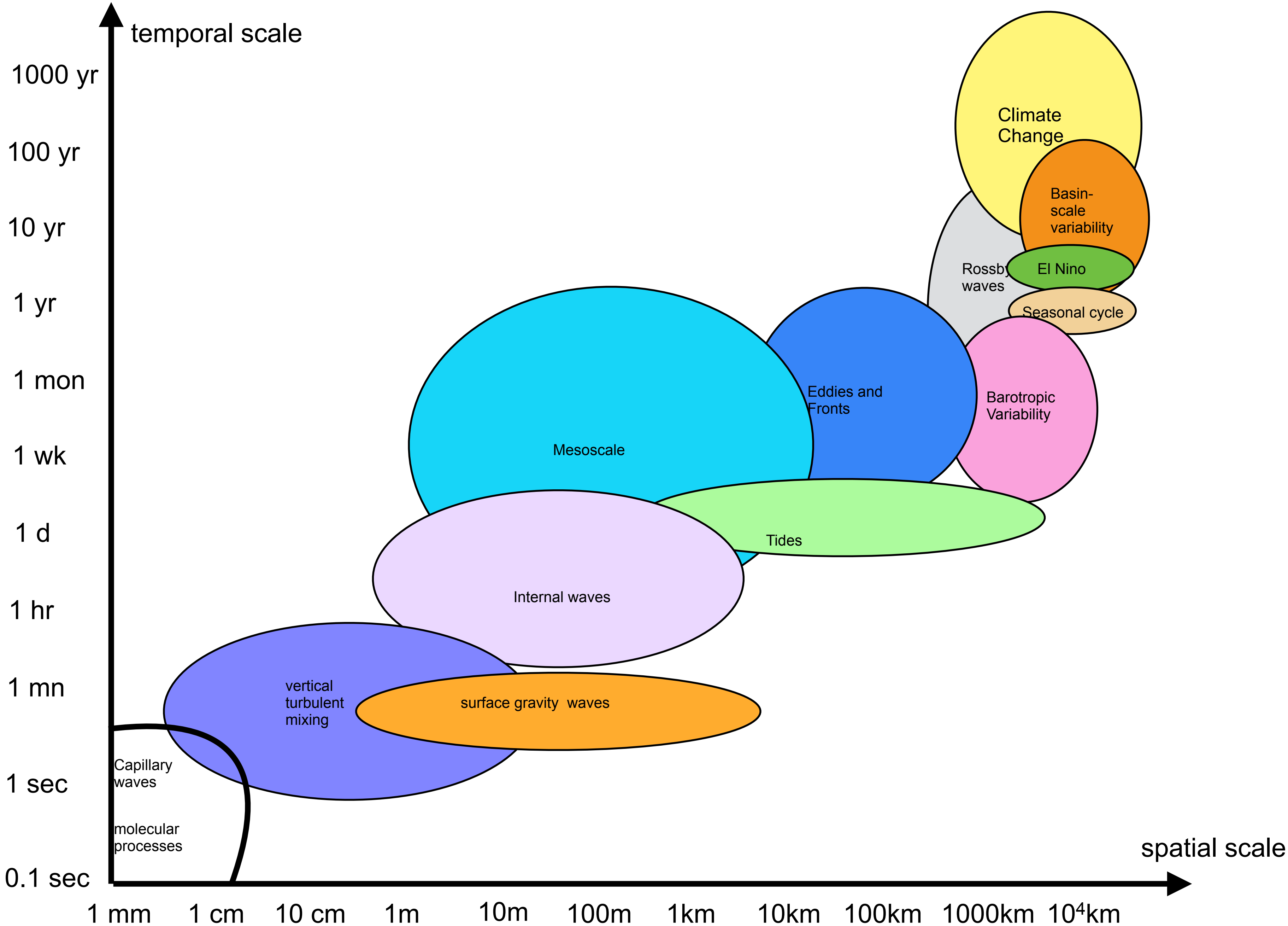
- Examples of ensembles with implicit or explicit representation of uncertainty

- Uncertainty in the ocean component: can we understand its origin and impact on the physics?

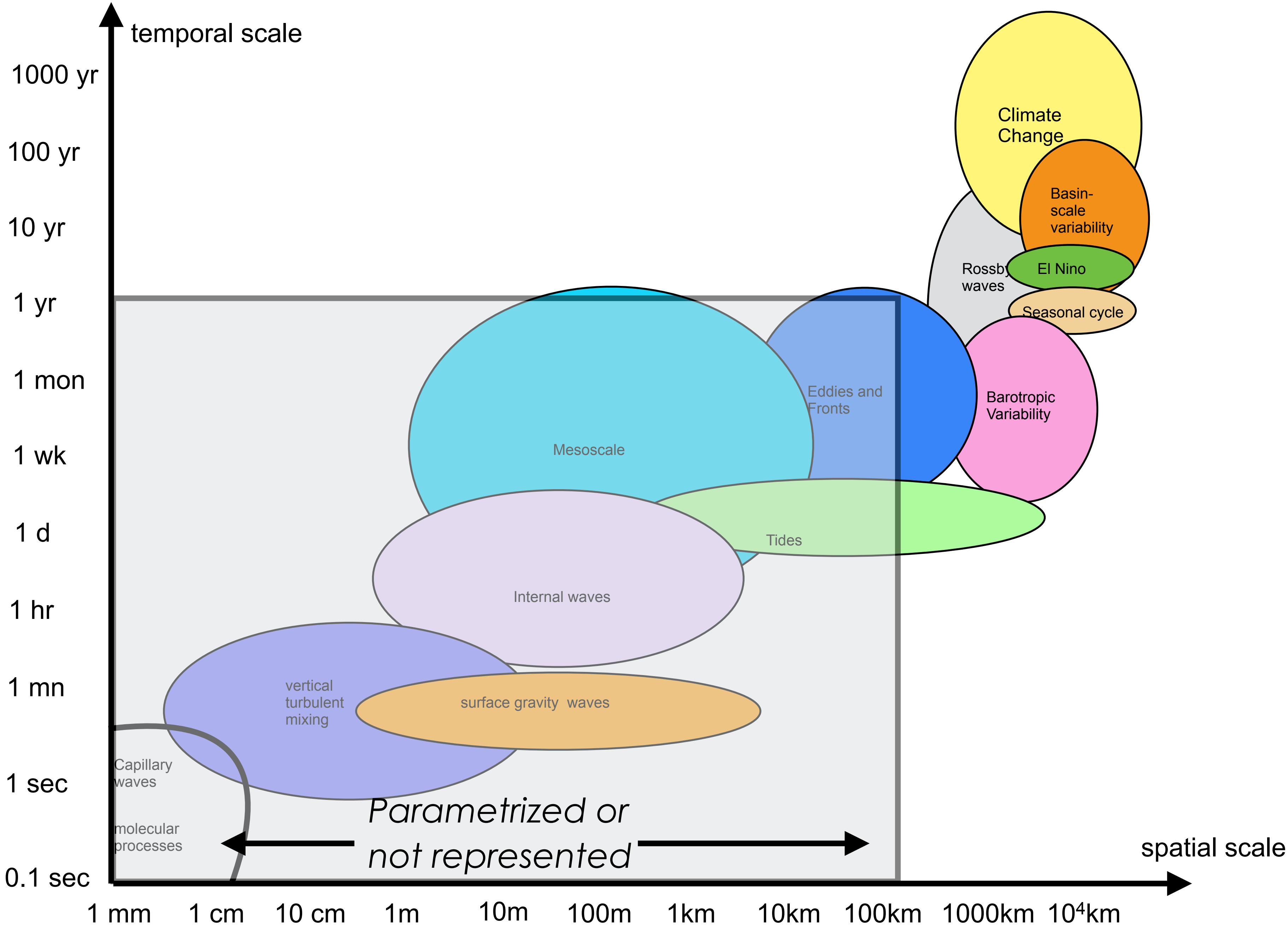
- Lessons & what's next?

with thanks to M. Andrejczuk, T. Bolton, F. Cooper, T. David, M. Huber, S. Juricke, J. Kjellsson, L. Mana, T. Palmer, A. Weisheimer

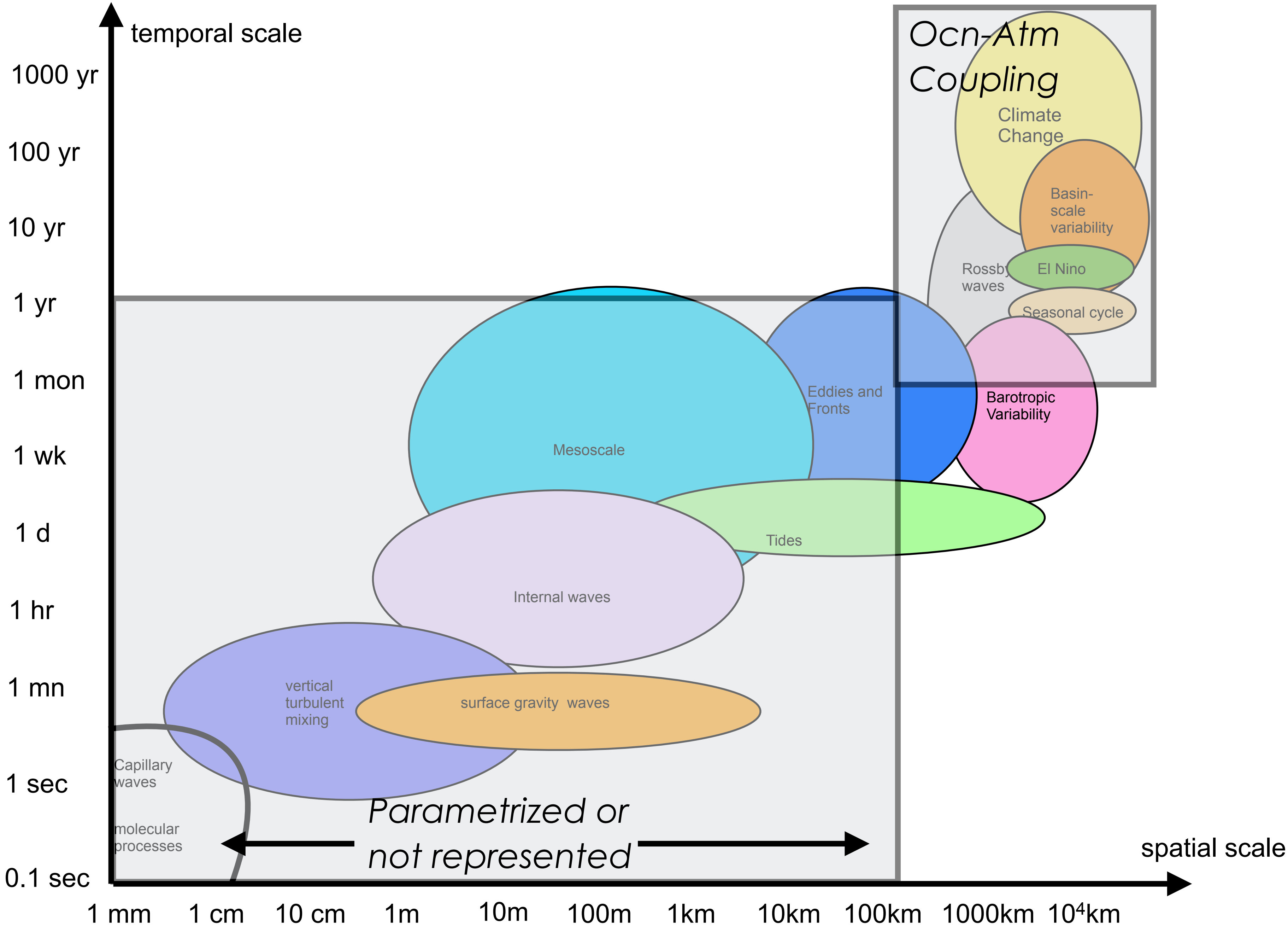
Ocean Processes: Temporal vs. Spatial Scales



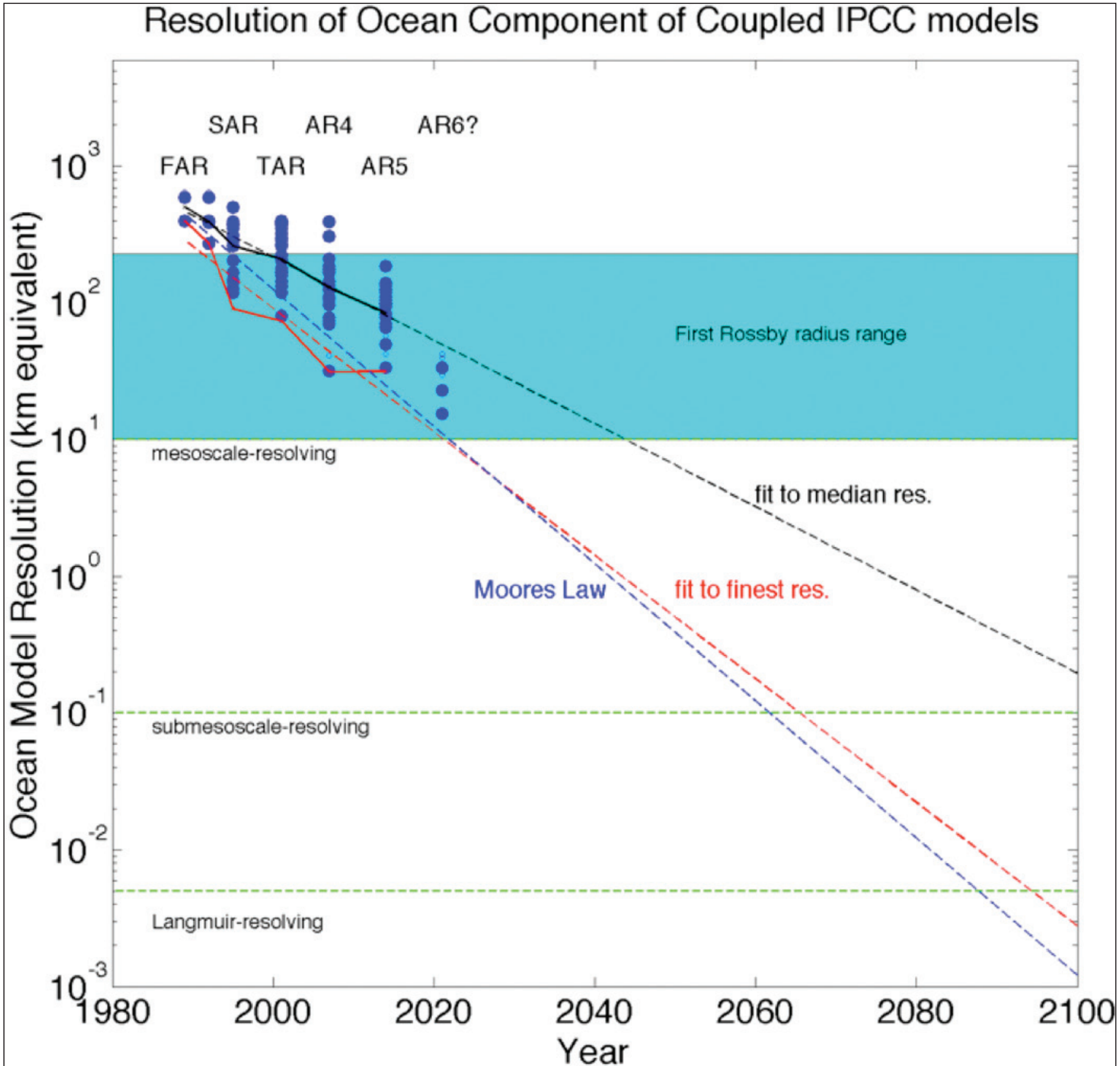
Ocean Processes: Temporal vs. Spatial Scales



Ocean Processes: Temporal vs. Spatial Scales

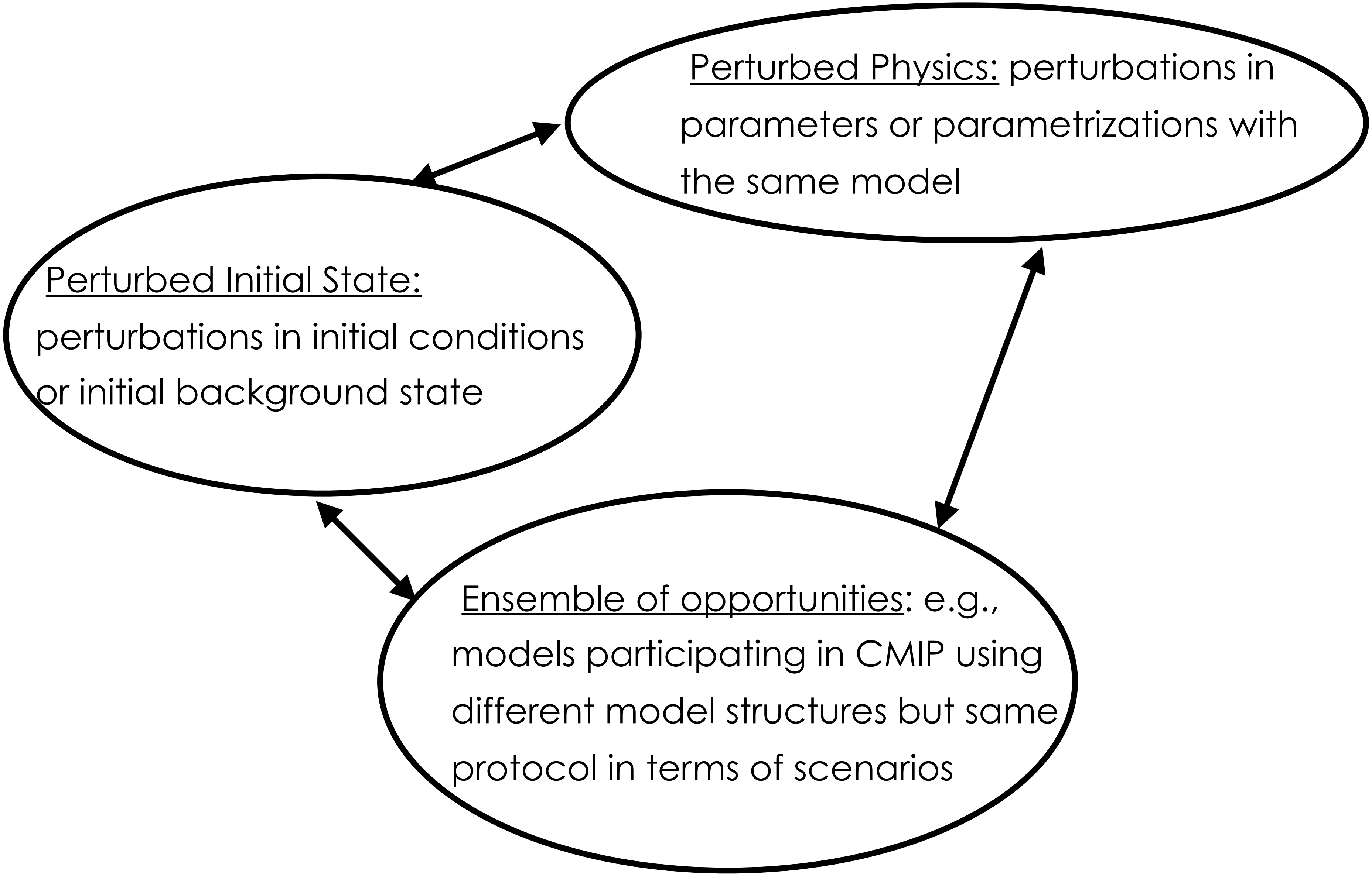


Ocean Model Resolution: Moore's Law



Fox-Kemper et al 2014

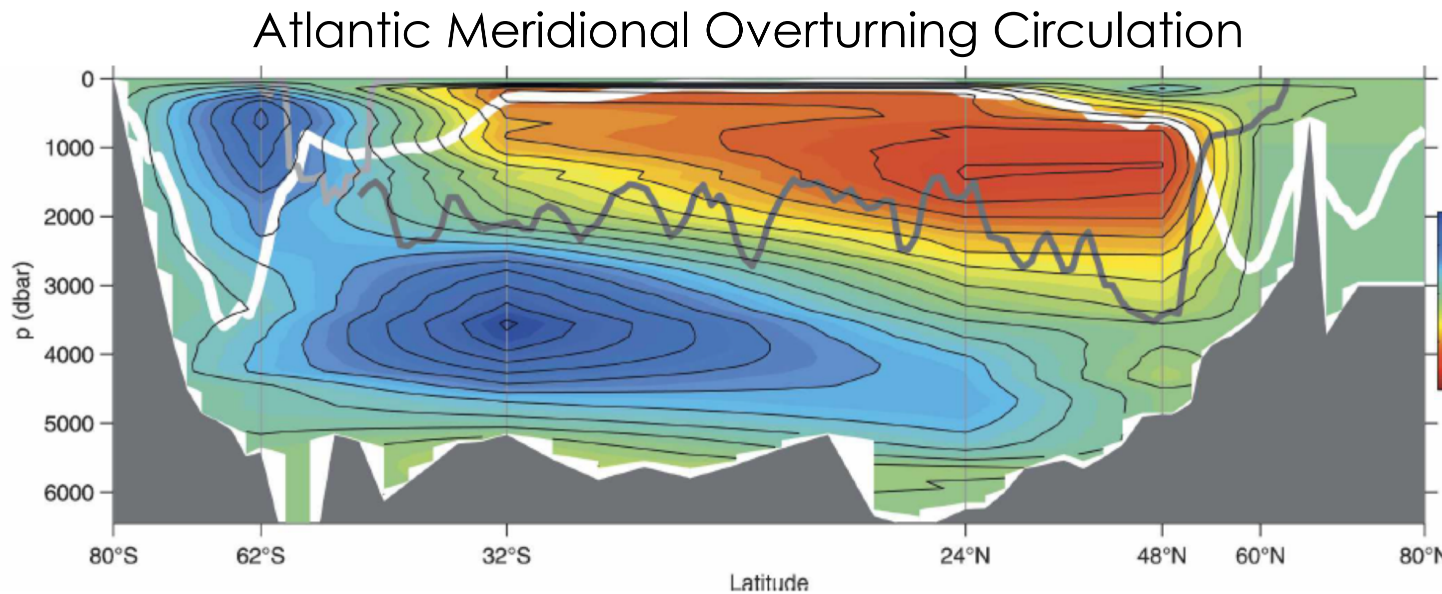
A Spread of Ocean/Climate Ensembles



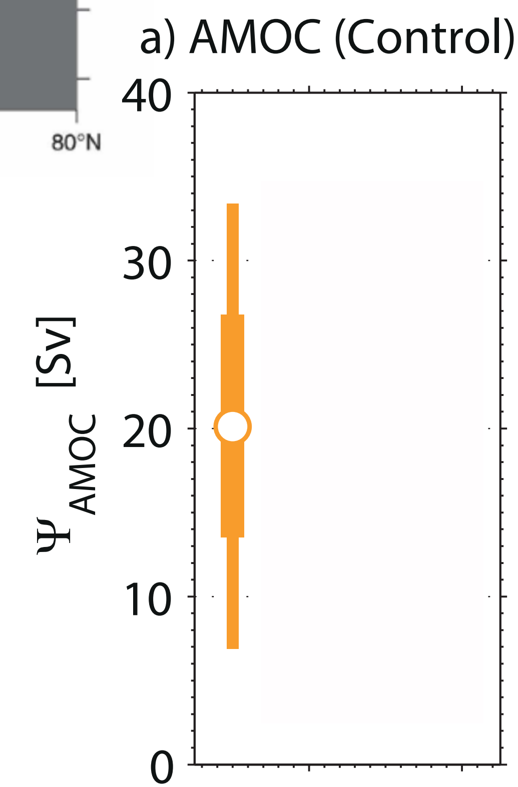
- Explore different ensembles as a function of timescales, processes & methods

A Spread of Ensembles: (C)MIP

- Ensemble of opportunity: **Climatology (multidecadal and beyond)**



Sv= 10^6 m^3/s



- **Observations:** ~18Sv +/- 6 Sv;

CMIP5: ~20 +/- 6 Sv with 23 models

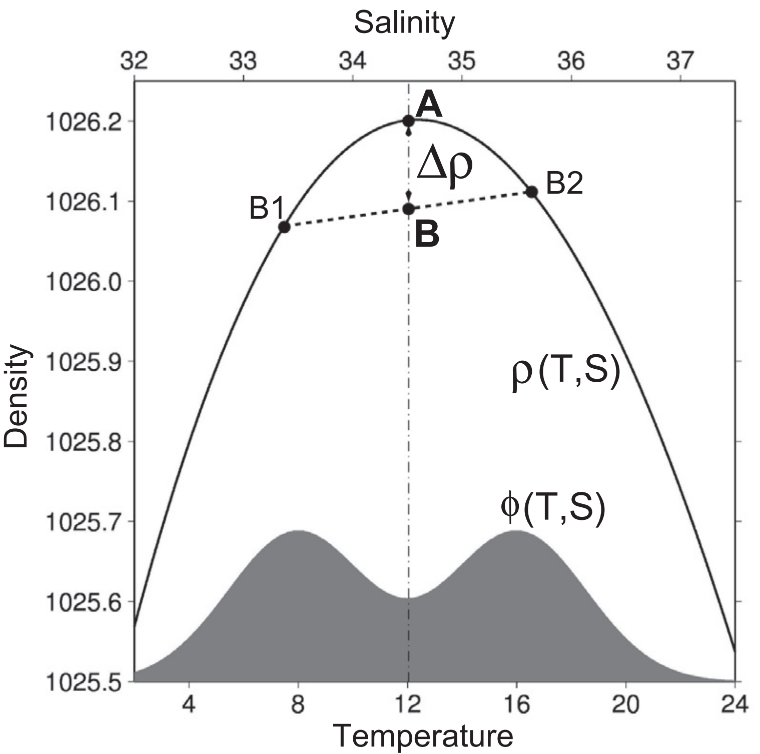
A Spread of Ensembles: Stochastic Perturbations

- Stochastically perturbed nonlinear equation of state: **Climatology**

- Nonlinear equation of state for density $\rho = \rho[T, S, p_0(z)]$

with stochastic perturbations

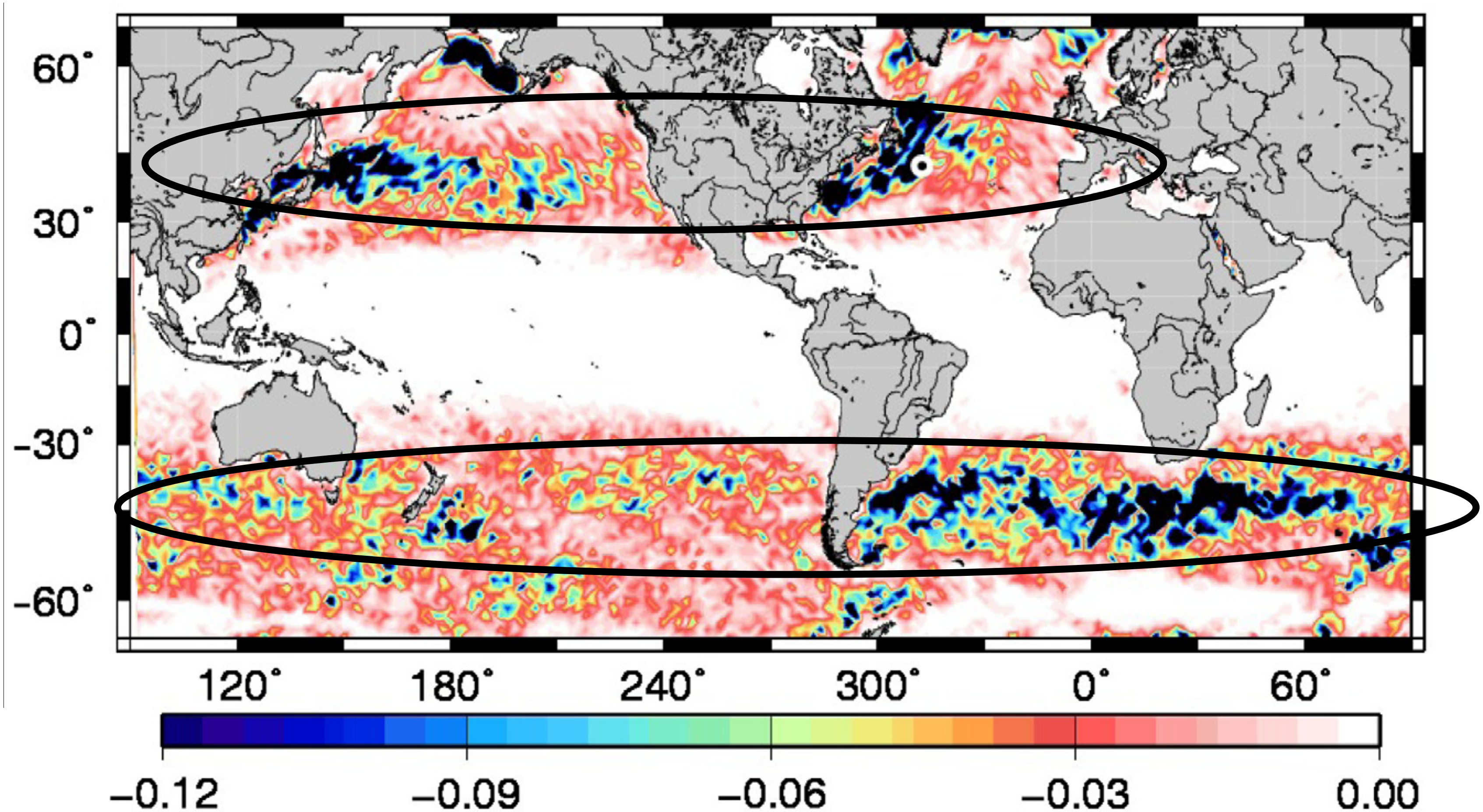
$$\rho(\mathbf{x}) = \int \rho[T(\mathbf{x}) + \delta T, S(\mathbf{x}) + \delta S, p_0(z)]\phi(\delta T, \delta S; \mathbf{x})\, d\delta T\, d\delta S$$



Brankart 2013

A Spread of Ensembles: Stochastic Perturbations

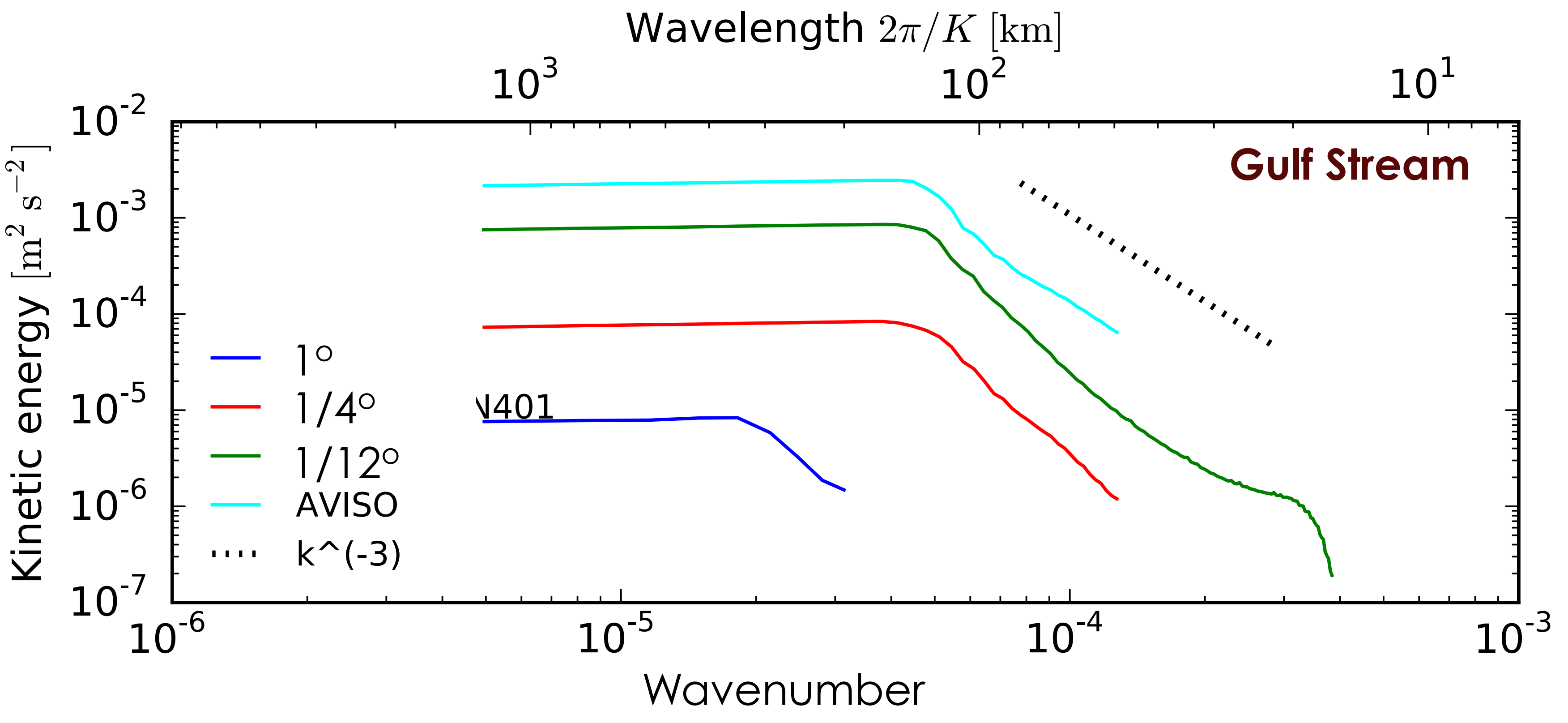
- **Climatology**: density difference between stochastic nonlinear equation of state and control in a coarse-resolution (2°) ocean-only model (NEMO)



Brankart 2013

A Spread of Ensembles: Eddy-permitting

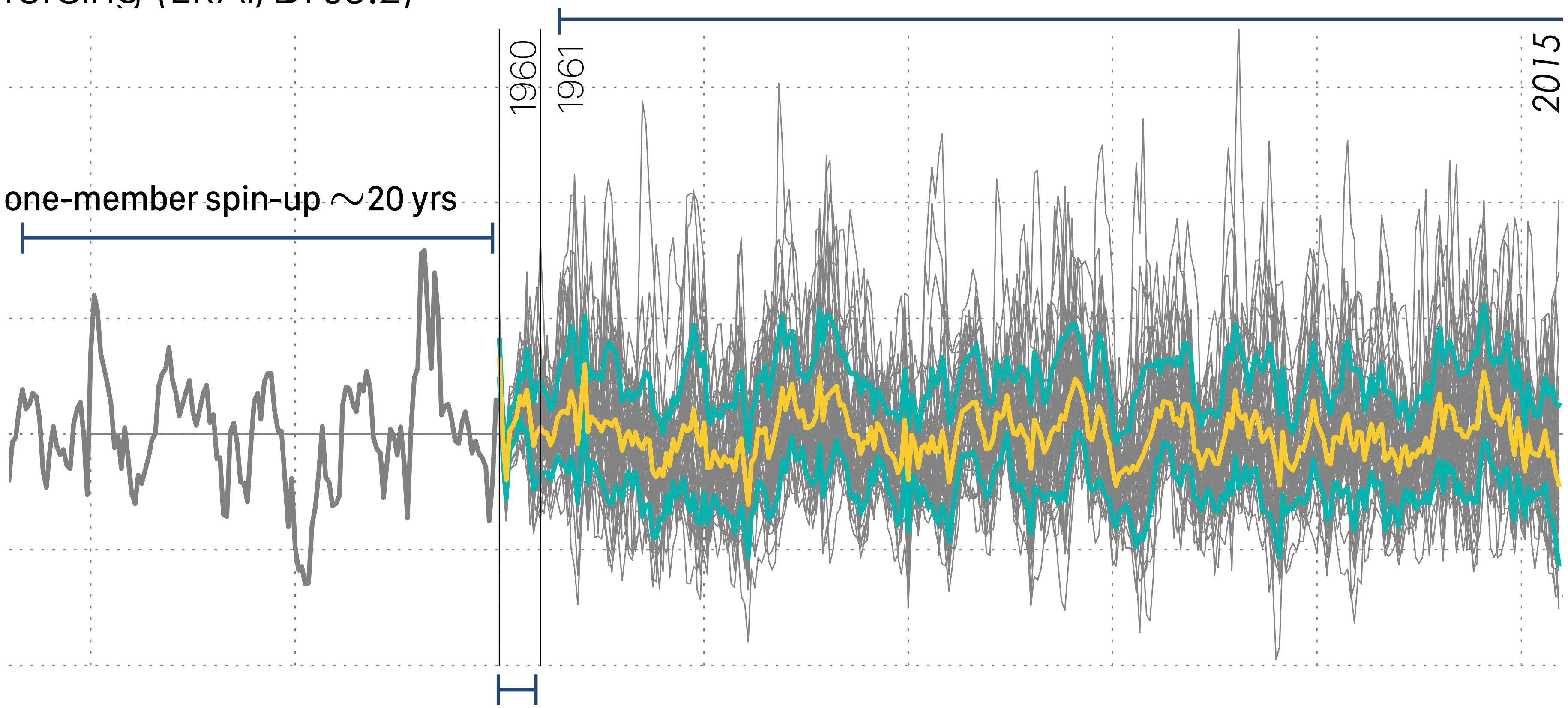
- Increased horizontal resolution, increased kinetic Energy and variance



Kjellsson & Zanna 2017

A Spread of Ensembles: Eddy-permitting + Stochastic I.P

- OCCIPUT: **Interannual** hincasts with NEMO 1/4 horizontal resolution, ocean + sea-ice, 1960-2015, 50 members (~19 million CPU h.) driven by same atmospheric forcing (ERAi/DFS5.2)



Initial perturbation strategy:

50 × stochastic equation of state
applied for ONE year (Brankart et al 2013)

Sérazin et al 2017; Penduff et al 2015

A Spread of Ensembles: Stochastic Perturbations

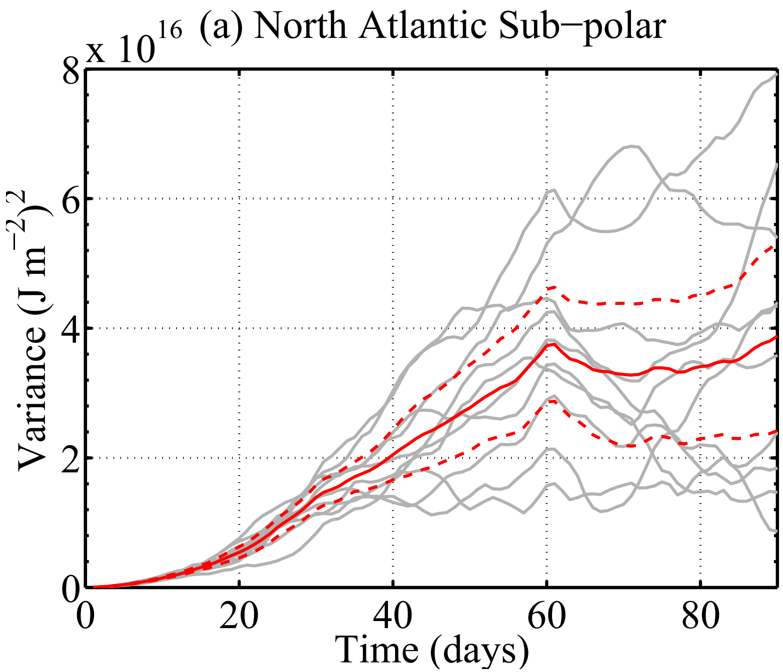
- **Perturbing subgrid parametrizations with multiplicative noise** on seasonal timescales *(*Stochastically Perturbed Physics Tendencies - *SPPT Buizza et al 1999)*: horizontal & vertical mixing, eddy diffusivity & viscosity; e.g.:

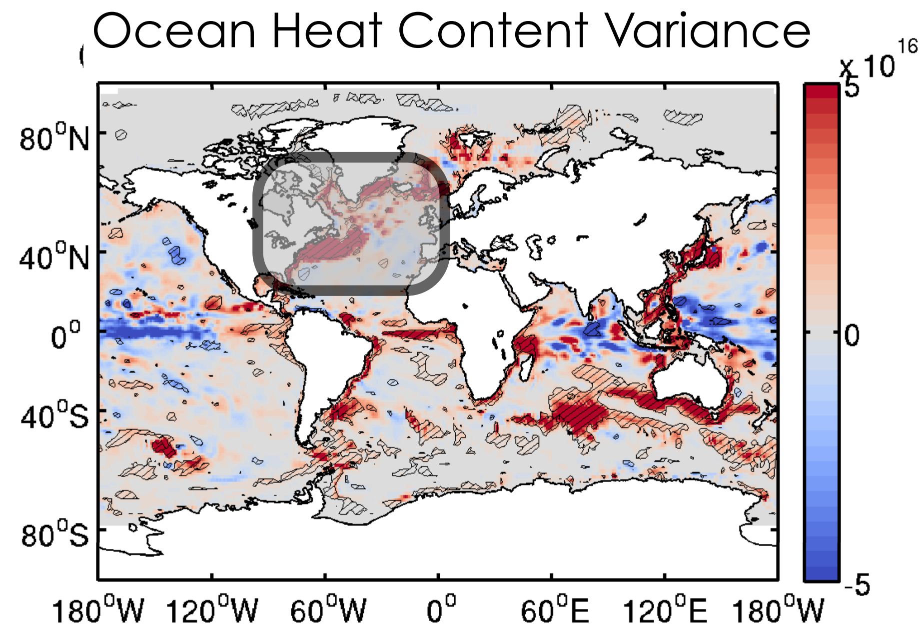
$$\frac{\partial \mathbf{U}_h}{\partial t} = -\left[(\nabla \times \mathbf{U}) \times \mathbf{U} + \frac{1}{2}\nabla\left(\mathbf{U}^2\right)\right]_h - f\,\mathbf{k} \times \mathbf{U}_h - \frac{1}{\rho_o}\nabla_h p + (\mathbf{1} + \mathbf{r})\,\mathbf{D}^{\mathbf{U}} + \mathbf{F}^{\mathbf{U}}$$

- Represent (1) structural (model parametrization) uncertainty; (2) increase the spread of the ensemble & variability; (3) potentially reducing biases?

A Spread of Ensembles: Stochastic Perturbations

- Large spread in model heat content on **seasonal timescale** using SPPT in coarse-resolution 1° coupled model



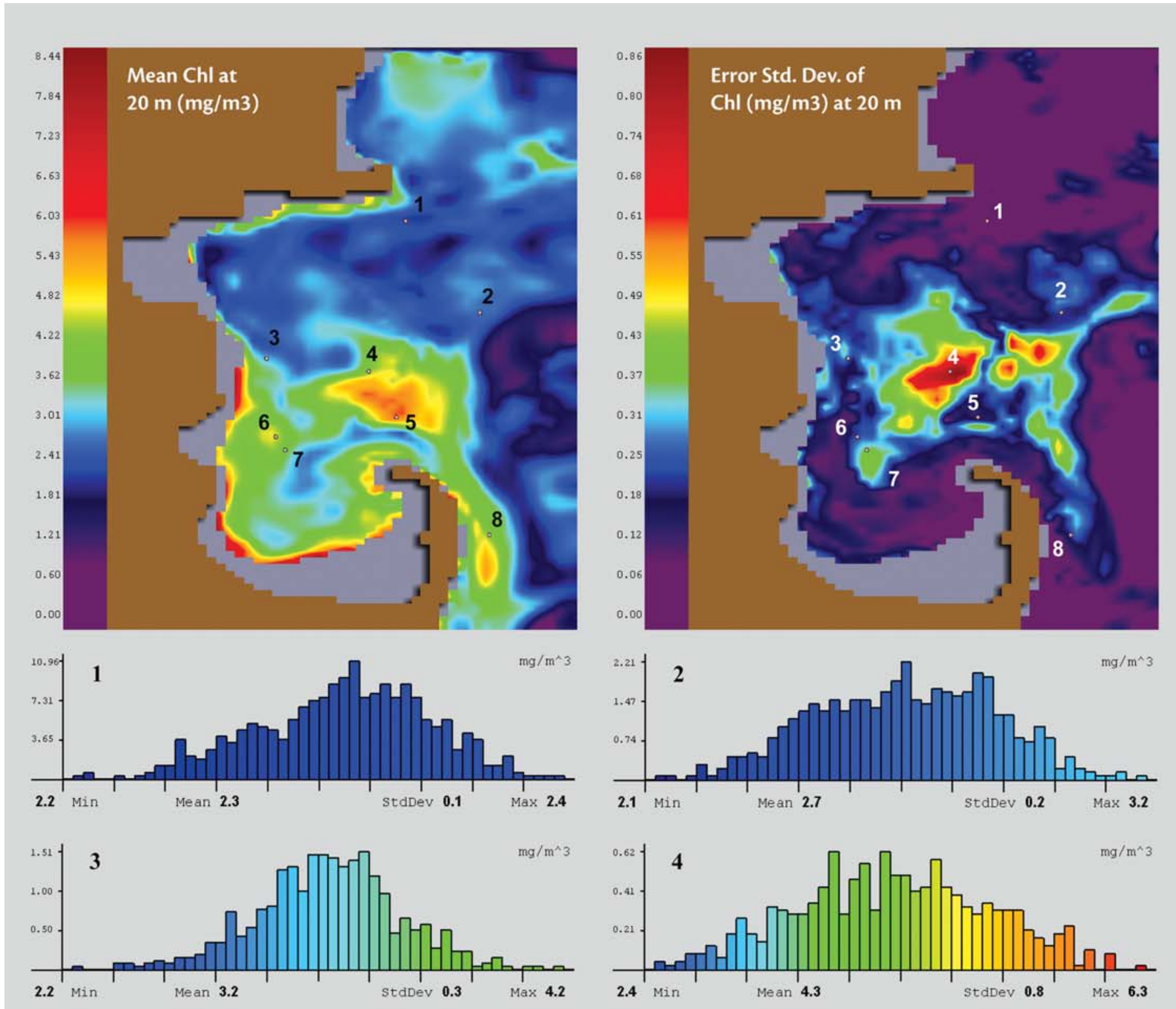


Andrejczuk, Cooper, Juricke, Palmer, Weisheimer & Zanna, MWR, 2016; Juricke, Palmer, Zanna, J. Clim. 2017.

See also Brankart et al 2017 for a NEMO-SPPT; Grooms 2017 for stochastic eddy Gent-McWilliams.

A Spread of Ensembles: Regional (inc. nested) Models

- Regional models initialized, and perturbed with stochastic forcing weighted by observation-based (EDA or observations) variability



Lermusiaux et al, 2006

A Spread of Ensembles

- Many models with different parametrizations, different resolutions

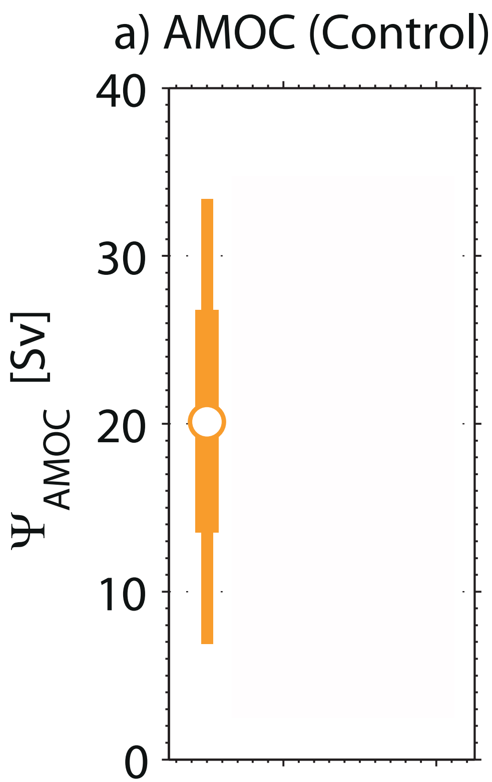
- Many ways to represent model errors: stochastic physics, perturbed parameters, multi-models

- Better representation of uncertainty on a range of timescales but

- Do we learn anything from these experiments?

Understanding the "uncertainty": CMIP

- CMIP: many models, many parameters & parametrizations and several components (ocean, atmosphere, ice, land …)
- Designed an ocean-only ensemble: 1) forced by CMIP fluxes and 2) with perturbed physics ensemble



Huber & Zanna 2017

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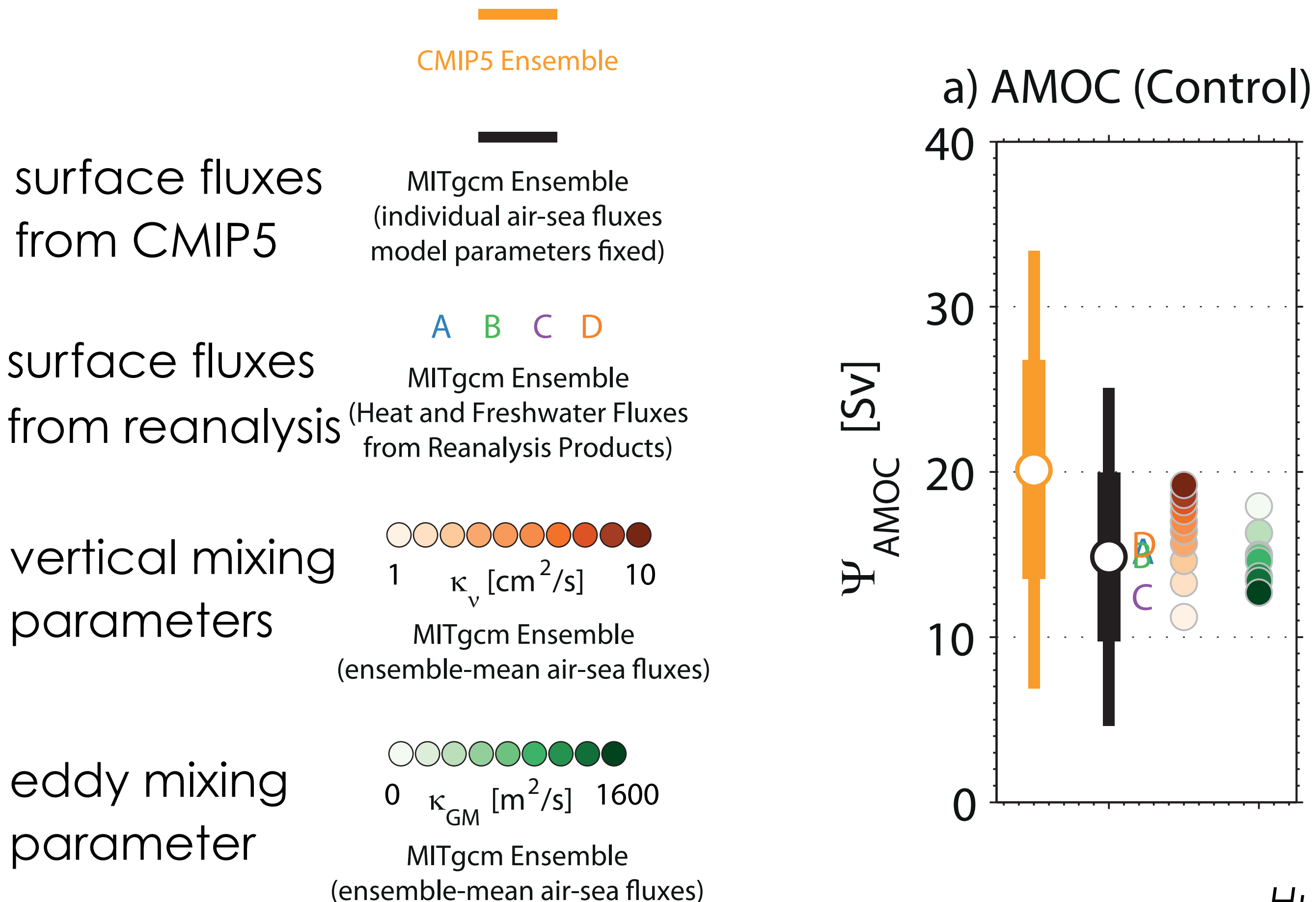
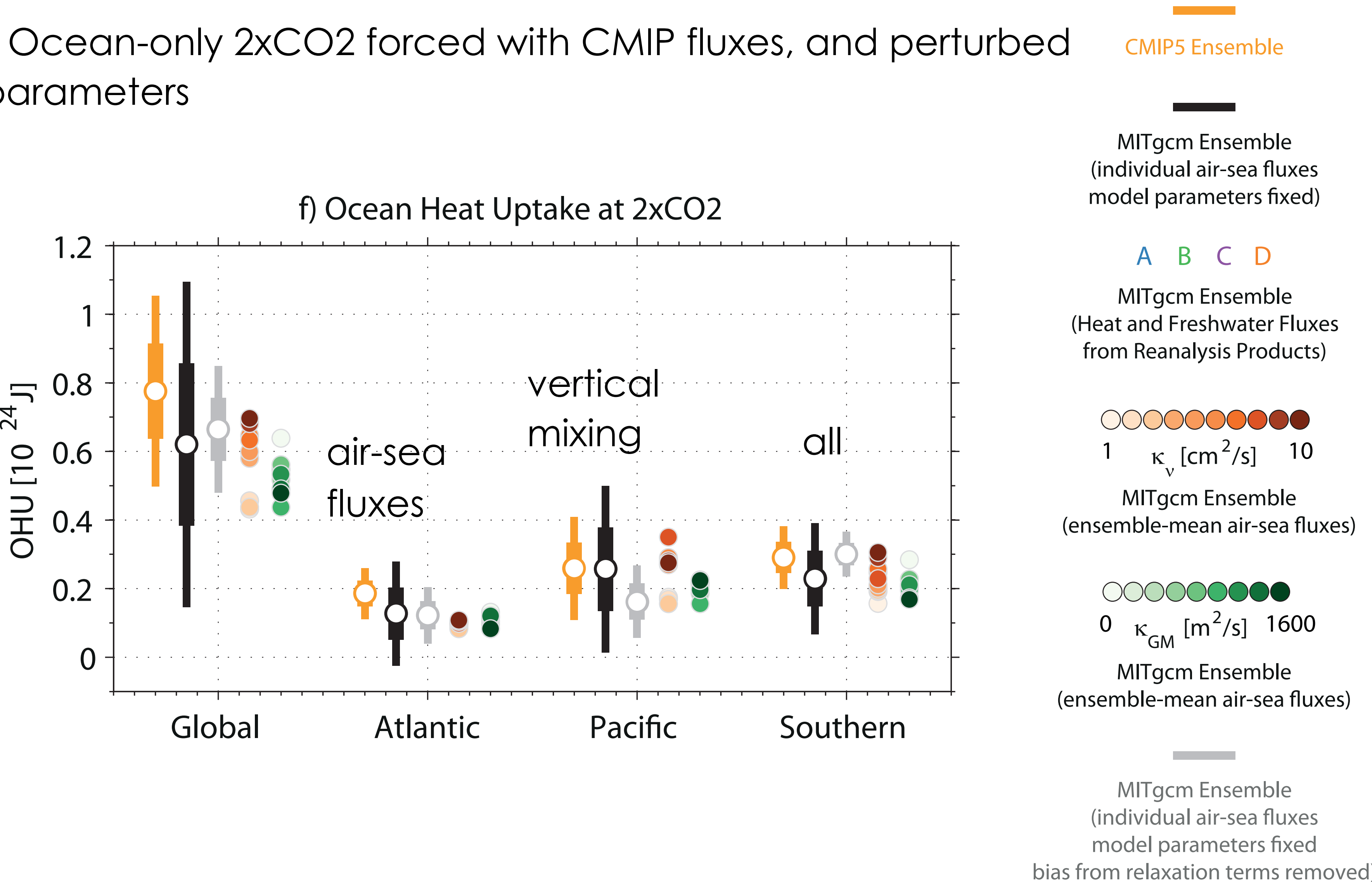


Huber & Zanna 2017

Understanding the "uncertainty": CMIP

- Ocean-only 2xCO2 forced with CMIP fluxes, and perturbed parameters

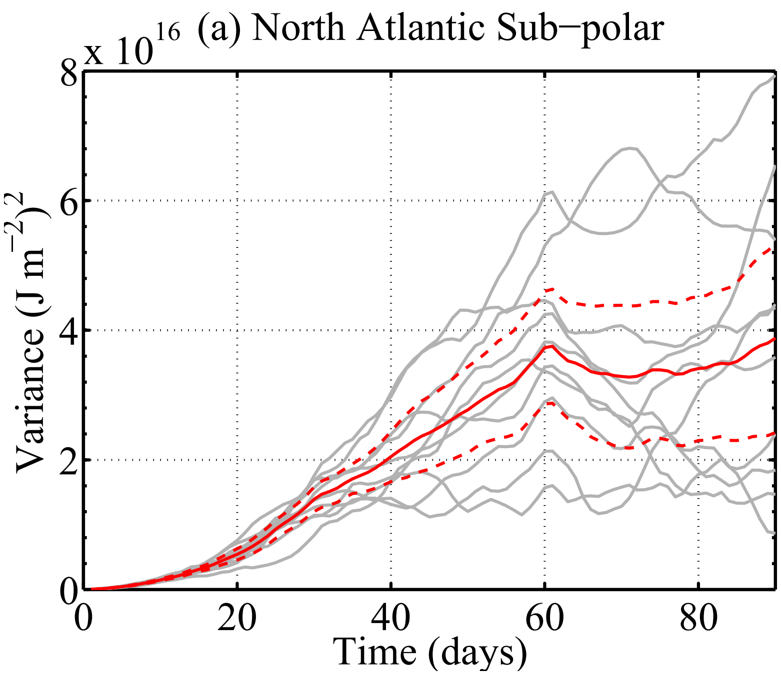


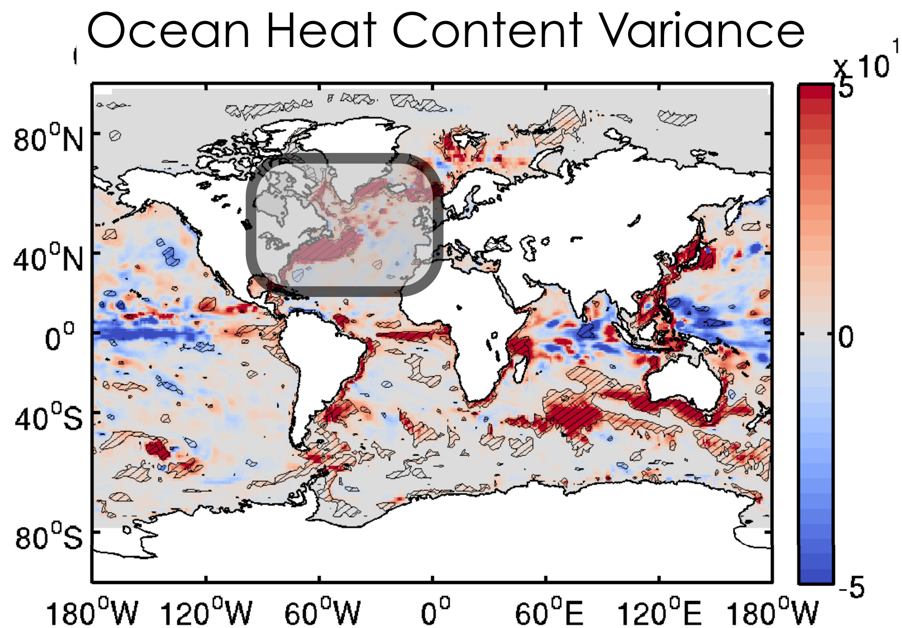
➡ **important implications for thermometric sea level predictions**

Huber & Zanna 2017

Understanding the "uncertainty": Stochastic Physics

- Large spread in model heat content on **seasonal timescale** using SPPT but **often small compared to atmospheric variability in coarse-resolution models**





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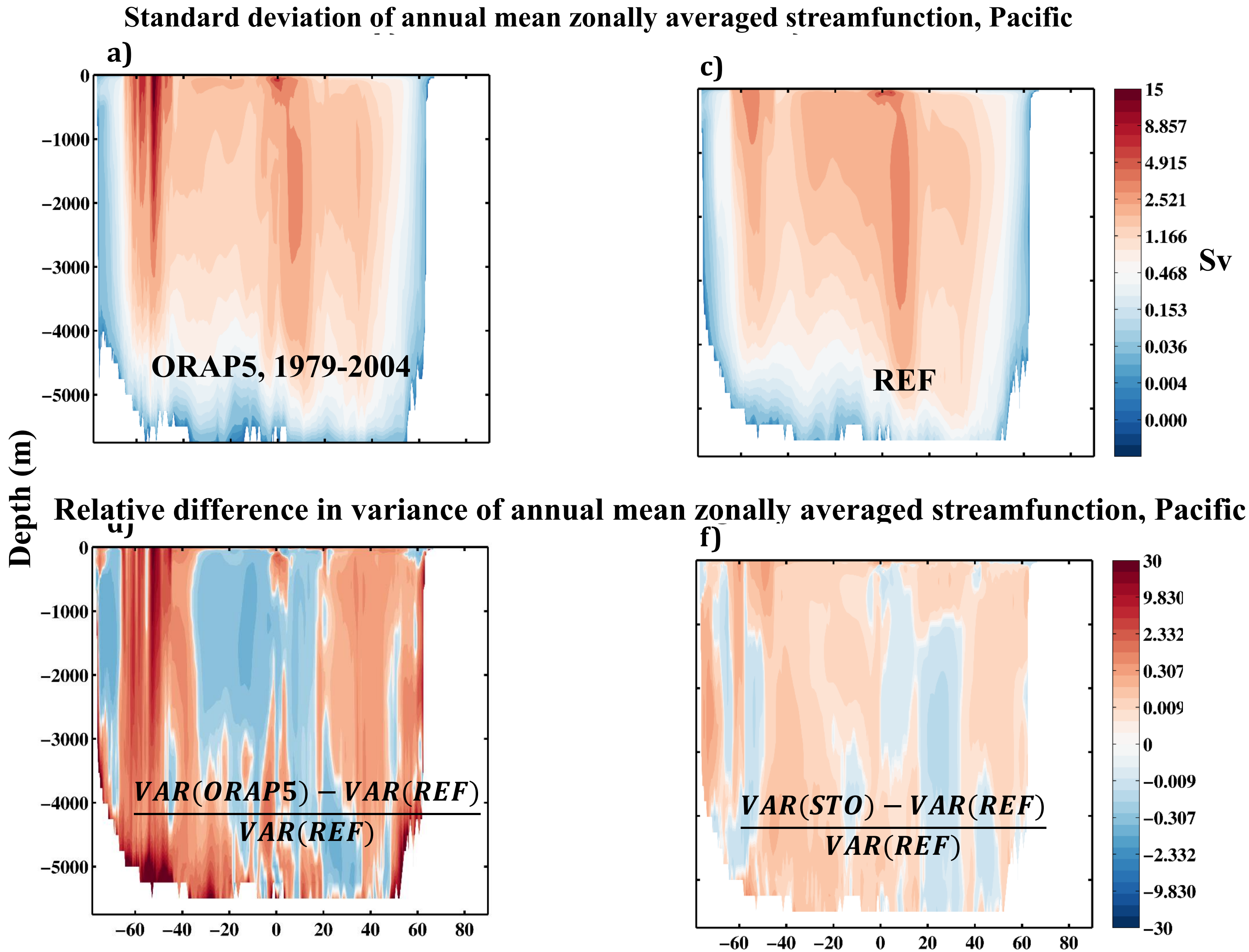
See also Brankart et al 2017 for a NEMO-SPPT; Grooms 2017 for stochastic eddy Gent-McWilliams.

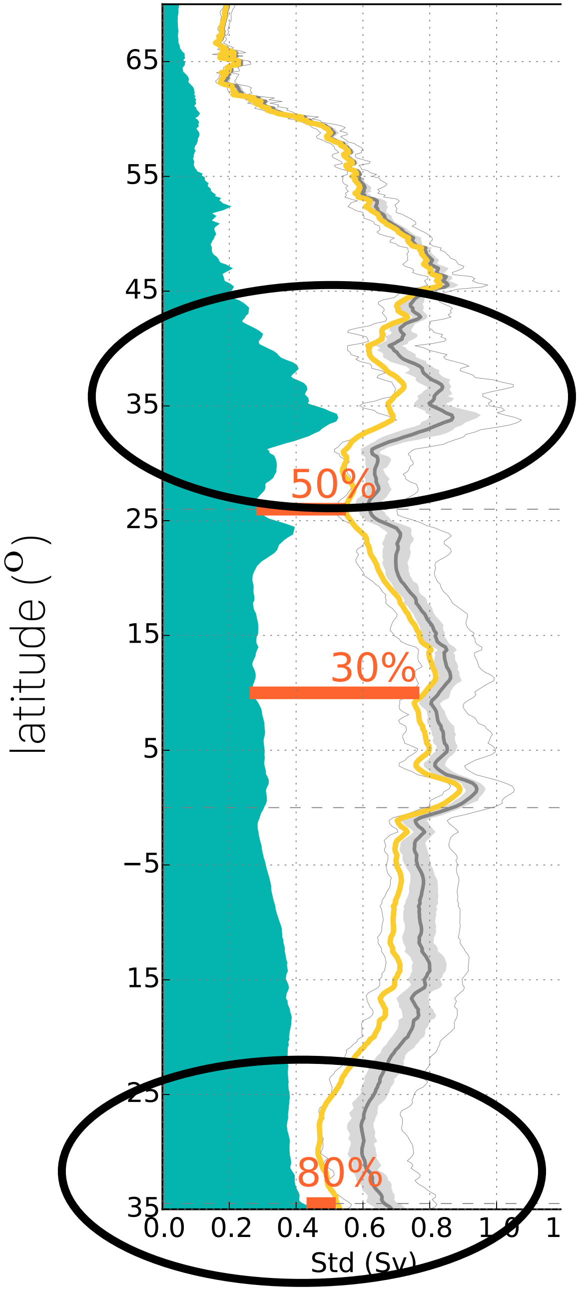
Understanding the "uncertainty": Stochastic Physics

- Impact on low-frequency variability at coarse-resolution 1° due to eddies



Juricke, Palmer, Zanna J. Clim. 2017

Understanding the “uncertainty”: hindcasts + stochastic

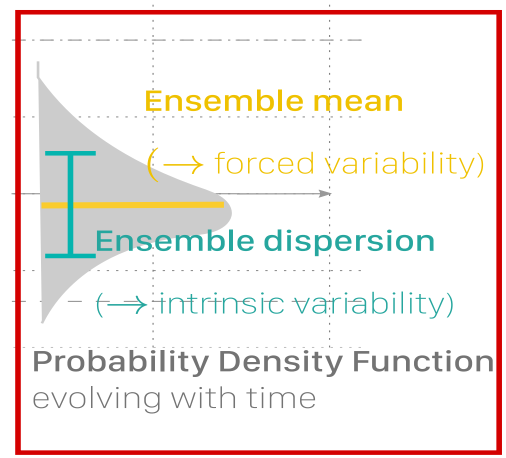


- Atlantic MOC interannual variability at eddy-permitting (1/4) resolution

Time-Std of the ensemble-mean: **forced variability**.

Ensemble-Std (averaged over 1960-1999): **intrinsic variability**

— Distribution of the 50 individual total Time-Std (mean, min, max, q25, q75): **total variability.**



- Influence is stronger at mid-latitudes, where ocean eddy energy is strongest & where differences in density perturbations are largest too.

Sérazin et al 2017; Penduff et al 2015

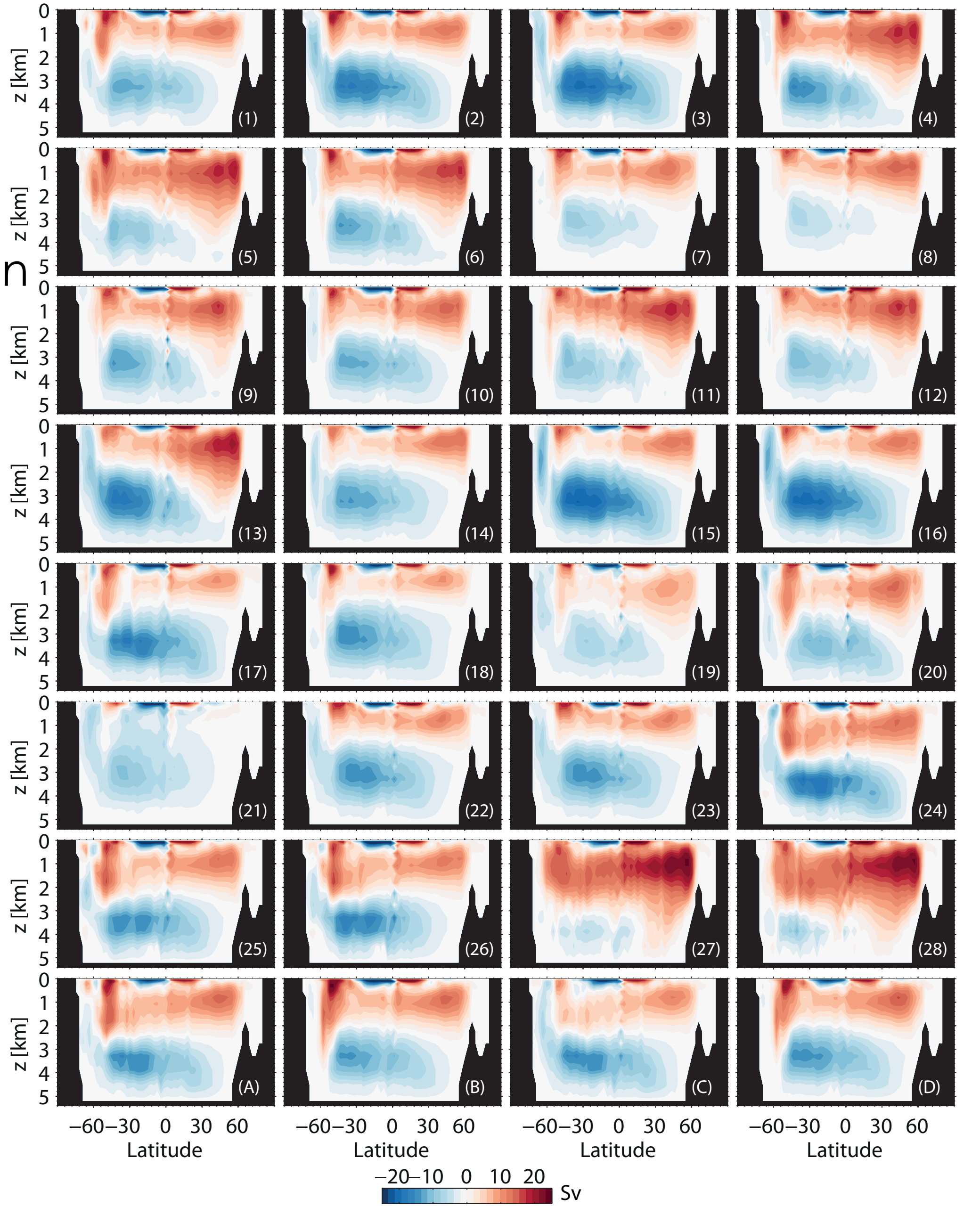
Lessons:

Lessons: 1. Importance of Air-sea fluxes

A strong influence of the air-sea coupling on all timescales.

Important for

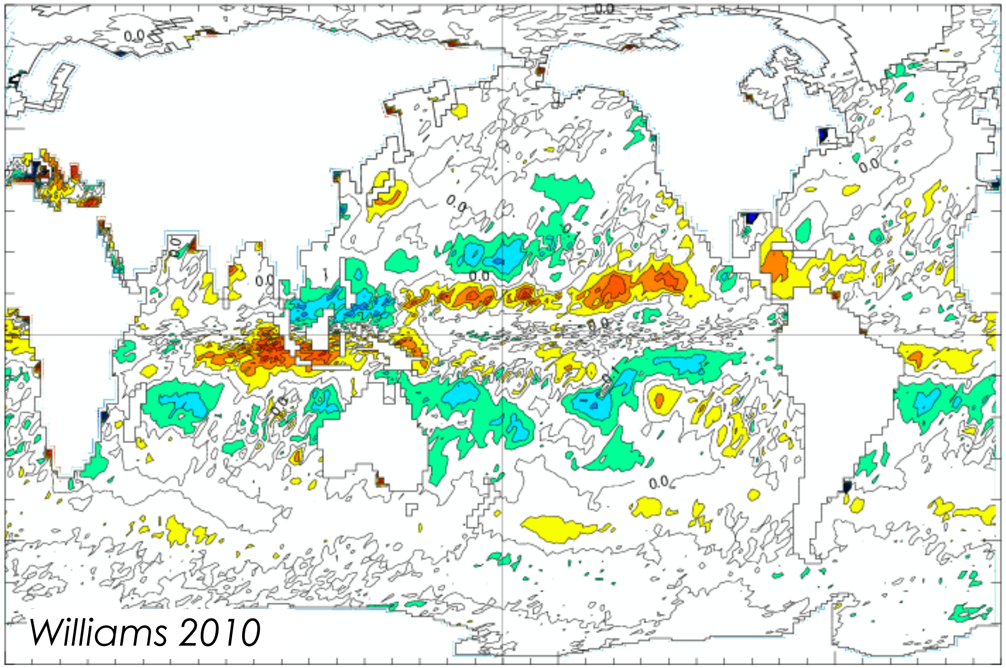
- Meridional Overturning Circulation (figs driven by CMIP5 fluxes)
- Heat content change
- Oceans feedback onto the atmosphere



Lessons: 1. Importance of Air-sea fluxes

- Need for improvements in parametrizations of air-sea fluxes and representation of uncertainty
- All parametrizations are simple bulk formulae - new approaches combining upper ocean processes & air-sea interaction are needed
- Representation of uncertainty: one preliminary approach based on SPPT in a coarse resolution model (Williams 2010), more research is required

Anomaly in net upward water flux (mm/day)



Lessons: 2. Eddies

Eddies impact the mean & variability on all timescales especially in mid-latitudes: e.g.,

- Stratification in Southern Ocean and heat uptake
- Variability in overturning circulation in the North Atlantic

- Eddy mixing is parametrized using a simple representation of baroclinic instability (via Gent-McWilliams) and turbulent kinetic energy budgets

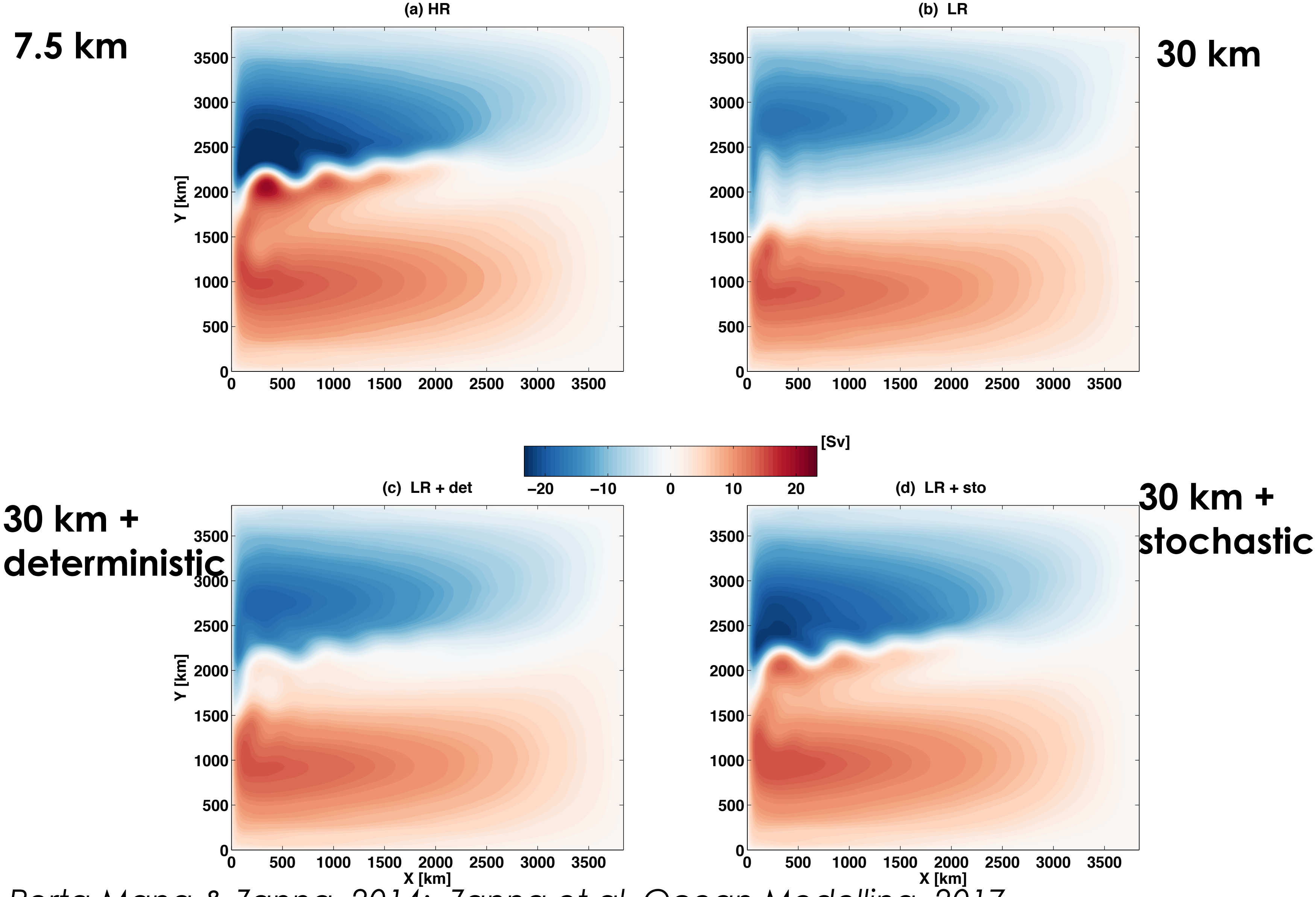
- SPPT-like representation of uncertainty for mixing shows mixed results
- Improvements should include

 - perturbations derived from observations/EDA
 - test in eddy permitting models where the model is less dissipative

- Many processes such as energy backscatter are not currently represented in ocean models; need to develop diverse parametrization

Lessons: 2. Eddies at eddy permitting resolution

- Eddy permitting: energy backscatter using non-Newtonian fluid tensors



Porta Mana & Zanna, 2014; Zanna et al, Ocean Modelling, 2017

Concluding remarks

- New era: Increased computational resources but far for resolving all important processes
- Need (diverse) parametrizations, especially focusing on upper ocean & interaction with the atmosphere
- Better two-way links between theory/idealised modelling & implementation in state-of-the-art models
- Representation of model uncertainty should link the physics of the model to the observed physics (scaling perturbations using EDA)
- Linking short to long timescales when thinking about ocean uncertainty