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

Laure Zanna
Dept of Physics,
University of Oxford
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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

- Capillary waves
- Molecular processes
- Climate Change
- Basin-scale variability
- Rossby waves
- El Nino
- Seasonal cycle
- Barotropic Variability
- Eddies and Fronts
- Mesoscale
- Tides
- Internal waves
- Vertical turbulent mixing
- Surface gravity waves

Temporal scales:
- 0.1 sec
- 1 sec
- 1 mn
- 1 hr
- 1 d
- 1 wk
- 1 mon
- 1 yr
- 10 yr
- 100 yr
- 1000 yr

Spatial scales:
- 1 mm
- 1 cm
- 10 cm
- 1 m
- 10 m
- 100 m
- 1 km
- 10 km
- 100 km
- 1000 km
- 10^4 km

Parametrized or not represented
Ocean Processes: Temporal vs. Spatial Scales

- Capillary waves, molecular processes
- Climate Change, Basin-scale variability, Rossby waves, El Nino
- Seasonal cycle, Barotropic Variability
- Parametrized or not represented

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Spatial scale:
- 10^4 km
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- 100 m
- 10 m
- 1 m
- 1 cm
- 1 mm
Ocean Model Resolution: Moore’s Law

Resolution of Ocean Component of Coupled IPCC models

- SAR
- FAR
- TAR
- AR4
- AR5
- AR6?

First Rossby radius range

fit to median res.

fit to finest res.

Moores Law

Mesoscale-resolving

Submesoscale-resolving

Langmuir-resolving

1980 2000 2020 2040 2060 2080 2100

Year

Fox-Kemper et al 2014
A Spread of Ocean/Climate Ensembles

- Perturbed Physics: perturbations in parameters or parametrizations with the same model
- Perturbed Initial State: perturbations in initial conditions or initial background state
- Ensemble of opportunities: e.g., models participating in CMIP using different model structures but same protocol in terms of scenarios

- Explore different ensembles as a function of timescales, processes & methods
A Spread of Ensembles: (C)MIP

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

**Atlantic Meridional Overturning Circulation**

- **Observations:** \(\sim 18 \text{ Sv} \pm 6 \text{ Sv}\);
- **CMIP5:** \(\sim 20 \pm 6 \text{ Sv}\) with 23 models
Stochastically perturbed nonlinear equation of state: **Climatology**

Nonlinear equation of state for density

\[
\rho = \rho[T, S, p_0(z)]
\]

with stochastic perturbations

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

![Graph showing density vs temperature and salinity](image-url)

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)

![Map showing density difference with climatology](image)
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* hindcasts 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)

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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.:

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

- 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

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

![Figure 7. Chlorophyll a (Chl) mean and uncertainties at 20-m depth in the Mass Bay region on September 2, 1998, as hindcast by 600 Error Subspace Statistical Estimation (ESSE) ensemble members. ESSE was initialized on August 25, 1998. (Top left/right) Mean/Error Standard Deviation of Chl. (Bottom) Eight PDF estimates (normalized histograms, numbered 1 to 8) corresponding to the eight marked locations on the horizontal maps. Bars on the histograms are colored according to the center Chl value. The minimum, mean, standard deviation, and maximum values are given on each histogram (illustration by R.G. Lermusiaux, University of California, Santa Cruz).](image)
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
Understanding the “uncertainty”: CMIP

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<th>graph1</th>
<th>graph2</th>
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<tr>
<td>AMOC (Control)</td>
<td>ACC (Control)</td>
</tr>
<tr>
<td>AMOC (1%CO2)</td>
<td>ACC (1%CO2)</td>
</tr>
<tr>
<td>Zonal Ocean Heat Uptake at 2xCO2</td>
<td></td>
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<tr>
<td>Ocean Heat Uptake at 2xCO2</td>
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</tbody>
</table>
```

- Surface fluxes from CMIP
- Surface fluxes from reanalysis
- Vertical mixing parameters
- Eddy mixing parameter

MITgcm Ensemble

(individual air-sea fluxes model parameters fixed)

CMIP5 Ensemble

(heat and freshwater fluxes from reanalysis products)

MITgcm Ensemble

(ensemble-mean air-sea fluxes)

CMIP5 Ensemble

(ensemble-mean air-sea fluxes)

Huber & Zanna 2017
Understanding the “uncertainty”: CMIP

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

![Graph showing Ocean Heat Uptake at 2xCO2](image)

- 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.


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

Standard deviation of annual mean zonally averaged streamfunction, Pacific

Relative difference in variance of annual mean zonally averaged streamfunction, Pacific

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.

Sérizin 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