Exploring concepts in coupled atmosphere-ocean data assimilation using a low-order climate model and CMIP5 data

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Initial-value problem for decadal climate predictions

Improved decadal climate predictions require initial conditions (ICs) providing coherent & accurate descriptions of the fast (atmosphere) and slow/memory-carrying (ocean) components of the climate system. How to generate these ICs in a robust and efficient manner remains an open question.

Questions explored here:

- Is data assimilation (DA) needed?
- Is coupled atmosphere-ocean DA a fundamental requirement?
- What is the most efficient & effective approach for initializing the slow ocean?

Initialization of Atlantic meridional overturning circulation (AMOC) chosen as "canonical problem" for exploring these fundamental questions.

Initial exploration based on a simplified low-order coupled climate model, complemented by experiments based on output from a comprehensive coupled climate model (CMIP5 database).

Various initialization/DA approaches

- **Non-coupled**: recovering the AMOC by forcing ocean model with known atmospheric states (e.g. atmospheric reanalyses)
- Coupled DA with an ensemble Kalman filter (EnKF):
  - **Daily DA**, or the traditional approach: frequent assimilation of individual observations
  - Assimilation of **time-averaged observations** (Dirren & Hakim 2005; Huntley & Hakim 2010): less frequent DA & more robust sampling of atmosphere-ocean covariances
  - "**No cycling**" DA: **background** ensemble from **random draws of model states** taken from long simulation: cheapest alternative

Low-order model

Analog of the AMOC-driven North Atlantic climate system:

Idealized model composed of Lorenz (1984) wave-mean flow atmospheric model coupled to Stommel 3-box model of overturning ocean (described in Roebber 1995).

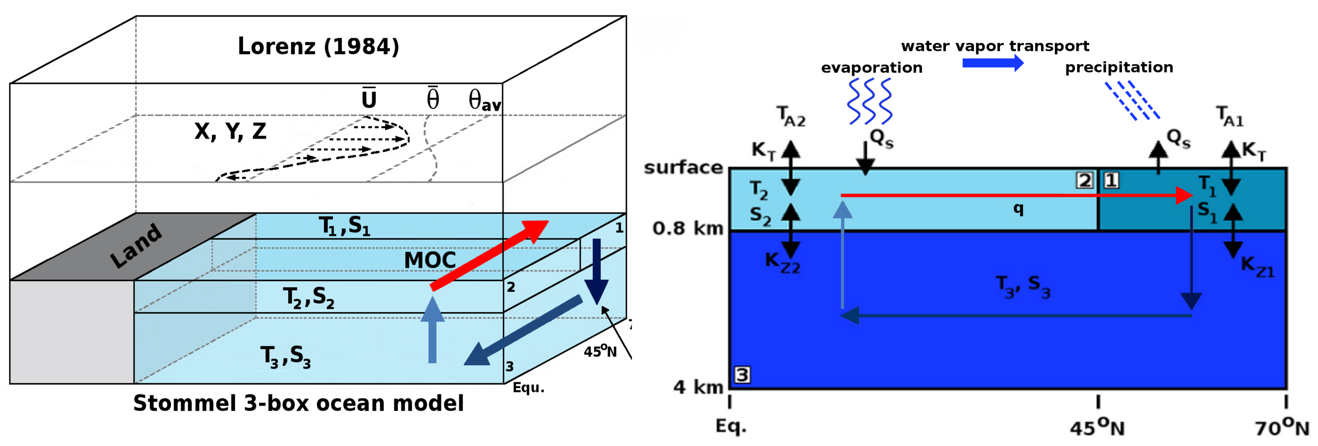

Figure 1. Schematic of the Lorenz-Stommel low-order coupled atmosphere-ocean model.

- Atmosphere -

$$\frac{dX}{dt} = -Y^2 - Z^2 - aX + F$$
$$\frac{dY}{dt} = XY - bXZ - Y + G$$
$$\frac{dZ}{dt} = XZ + bXY$$
$$T_{A1} = T_{A2} - \gamma X$$

X: meridional difference in tropospheric air temperature or zonal wind

Y, Z: amplitudes of cosine and sine phases of large scale transient eddies

- Ocean -

$$V_1\frac{dT_1}{dt} = \frac{1}{2}q(T_2 - T_3) + K_T(T_{A1} - T_1) - K_z(T_1 - T_3)$$
$$V_2\frac{dT_2}{dt} = \frac{1}{2}q(T_3 - T_1) + K_T(T_{A2} - T_2) - K_z(T_2 - T_3)$$
$$V_3\frac{dT_3}{dt} = \frac{1}{2}q(T_1 - T_2) + K_z(T_1 - T_3) - K_z(T_2 - T_3)$$
$$V_1\frac{dS_1}{dt} = \frac{1}{2}q(S_2 - S_3) - K_z(S_1 - S_3) - Q_s$$
$$V_2\frac{dS_2}{dt} = \frac{1}{2}q(S_3 - S_1) - K_z(S_2 - S_3) + Q_s$$
$$V_3\frac{dS_3}{dt} = \frac{1}{2}q(S_1 - S_2) + K_z(S_1 - S_3) + K_z(S_2 - S_3)$$
$$q = \mu\left[\alpha(T_2 - T_1) - \beta(S_2 - S_1)\right]$$

Coupling

$$F = F_0 + F_1\cos\omega t + F_2(T_2 - T_1)$$
$$G = G_0 + G_1\cos\omega t + G_2 T_1$$
$$Q_s = c_1 + c_2\left(Y^2 + Z^2\right)$$

← eddy energy

Idealized experiments with low-order model

AMOC evolution & predictability in low-order model

- 100-member ensemble simulation from random small amplitude perturbations around reference ICs [truth= member corresponding to reference ICs]
- **Low frequency variability**: Centennial scale dominant + weaker decadal signal

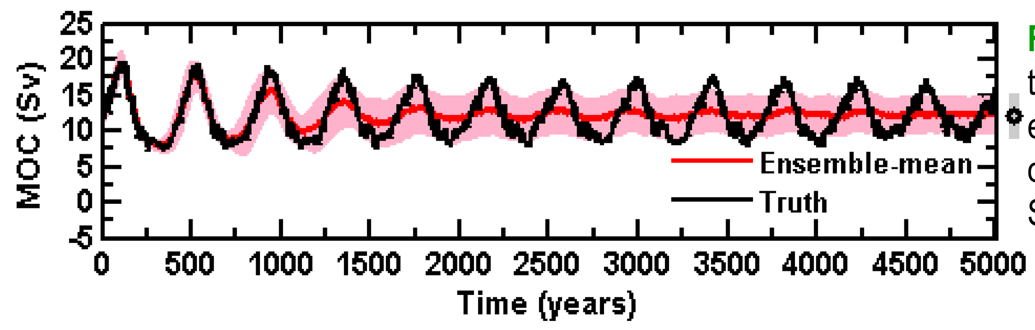

Figure 2. Evolution of the AMOC in a long ensemble simulation of the Lorenz-Stommel model.

Non-coupled init.: Forcing the ocean with known atmosphere

- **ICs** for 100-member ensemble simulation of ocean states from **random draws** of model states from 5000-yr "truth" simulation (initial ensemble contains only information on climatology)
- Free: Fully coupled simulations from initial coherent atmosphere & ocean states
- Forced: Every ocean member integrated forward **using same known deterministic atmosphere** (truth)

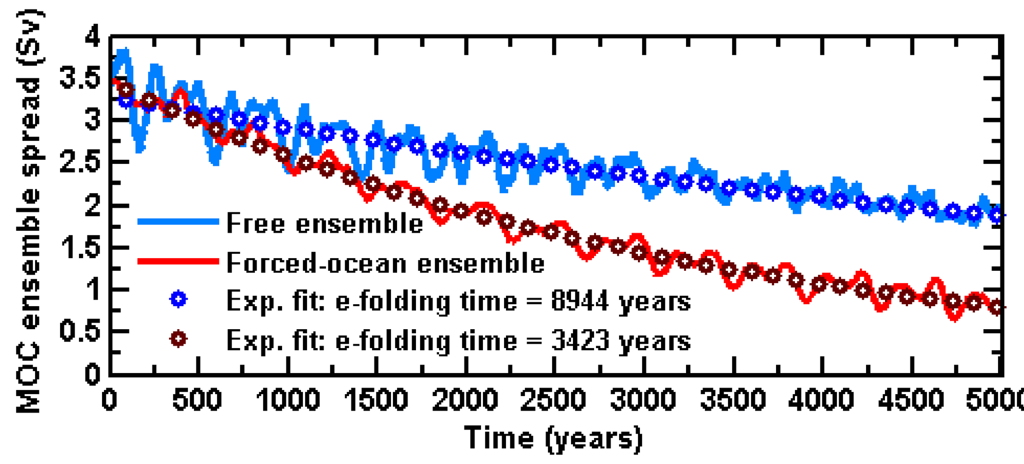

Figure 3. Evolution of AMOC ensemble spread in free and forced simulations of the low-order model.

- Very **slow convergence** of ensemble toward truth (e-folding time > 3000 years)

Coupled assimilation: Daily DA vs. time-averaged DA & cycling vs. no cycling

- Rationale for time-averaging: **atmosphere-ocean covariability** & time scales

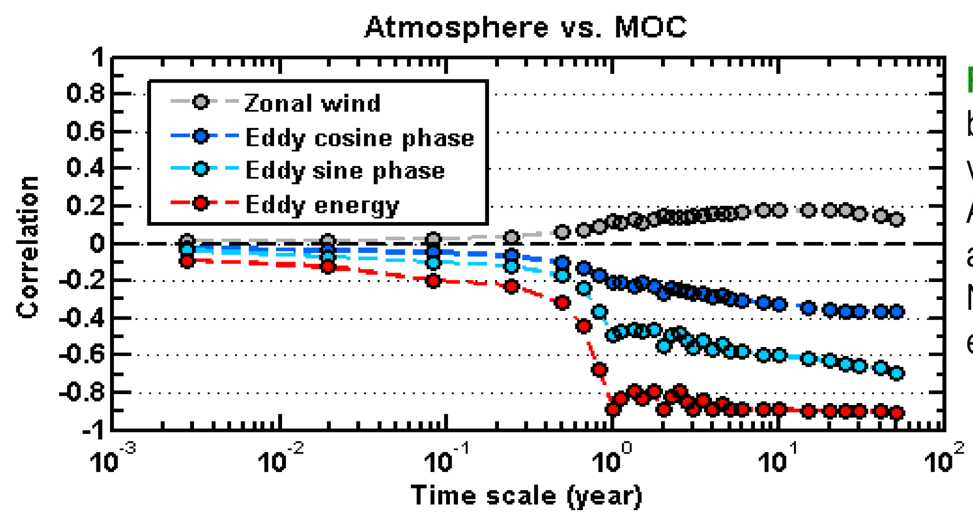

Figure 4. Correlation between atmospheric variables and the AMOC versus averaging time scale. Note: eddy energy $=Y^2+Z^2$.

- DA experiments: AMOC analyses in various data denial scenarios (progressively less assimilated ocean obs.) & initial ensemble from random draws of model states
- Assimilation of **daily obs**. versus **yearly-averaged obs**.
- Assimilation of **alternative variable** w/ stronger covariability w.r.t. AMOC: **eddy energy** (driving meridional flux of moisture in model)
- **Cycling**: 100 realizations of 100-member ensemble DA over 50-yr segments
- **No cycling**: 500-member ensemble DA over first 1000 yrs of truth simulation

Coefficient of efficiency:
$$CE = 1 - \sum_{i=1}^{N}\left(x_i^{truth} - x_i^{a}\right)^2 \Big/ \sum_{i=1}^{N}\left(x_i^{truth} - \overline{x^{truth}}\right)^2$$

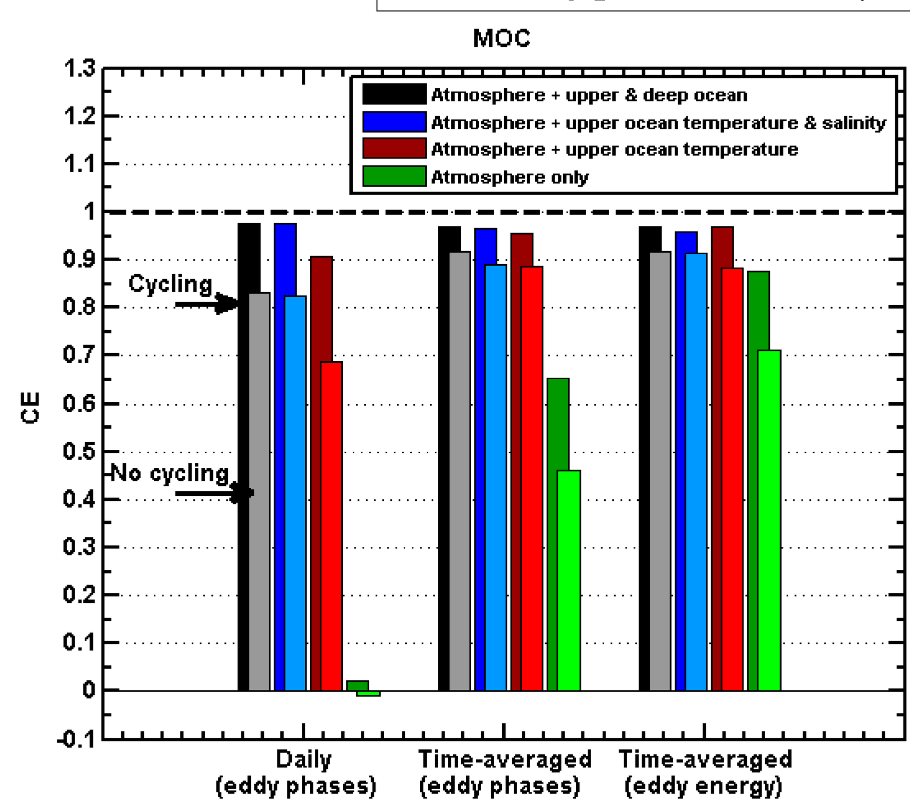

Figure 5. CE values of **AMOC analyses** obtained with various DA configurations (daily vs. yearly-averaged observations) under various scenarios of data availability in the ocean.

DA experiments using CMIP5 data

Motivation: Are findings obtained with simplified low-order model (e.g. value of assimilating time-averaged observations) applicable to more realistic prediction systems?

- "No cycling" DA idealized "perfect model" experiments can easily be performed using output from long simulations from comprehensive atmosphere-ocean general circulation models (AOGCMs).
- **Monthly** output from **CCSM4** "last millennium" CMIP5 simulation is used
- Focus on AMOC: analysis variable = maximum value of meridional overturning streamfunction

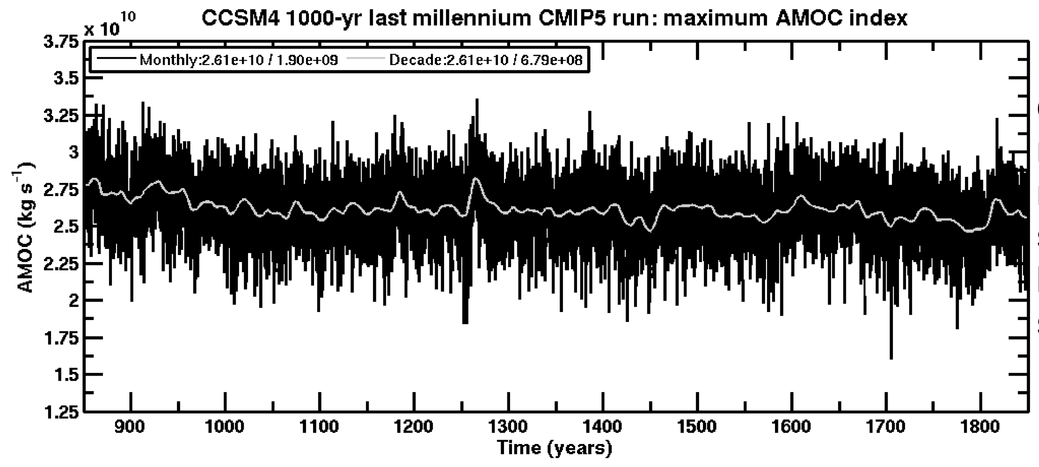

Figure 6. Temporal evolution of the maximum value of meridional overturning streamfunction in the last-millennium CCSM4 simulation.

Low-order variables & covariability w/ AMOC in CCSM4

- Monthly AOGCM gridded output "coarse grained" to low-order variables: average over subtropical & subpolar boxes (atmosphere & upper ocean) & deep ocean box
- Daily output of sea level pressure, near-surface temperature & water vapor used to estimate eddy amplitude & meridional heat and moisture eddy fluxes at 40°N following method presented in Chang et al. (2013)

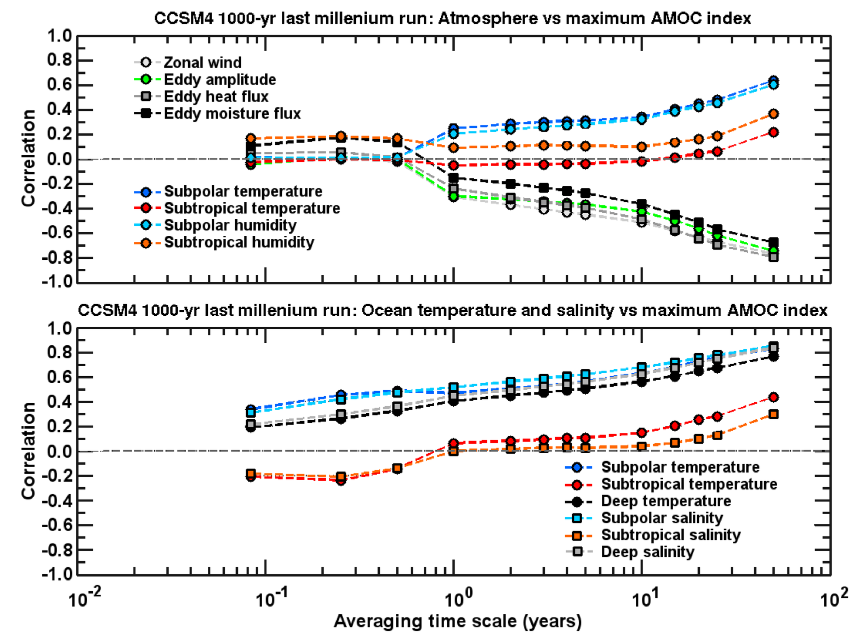

Figure 7. Correlations between atmospheric (upper frame) & oceanic (lower frame) low-order variables & the AMOC index in the CCSM4 last-millennium CMIP5 simulation.

- Progressively stronger covariability between most variables & AMOC as averaging interval is increased : potential for more effective DA at longer scales

"No cycling" DA results: 1000 years of AMOC analyses

- State vector: low-order variables; truth = Fig. 6; obs. = perturbed truth
- Monthly DA compared to assimilation of time-averaged obs. (various avg. scales)
- Ensemble size = number of "independent" samples in 1000-yr simulation (12000 for monthly DA down to 20 for DA of 50-yr averaged obs.)

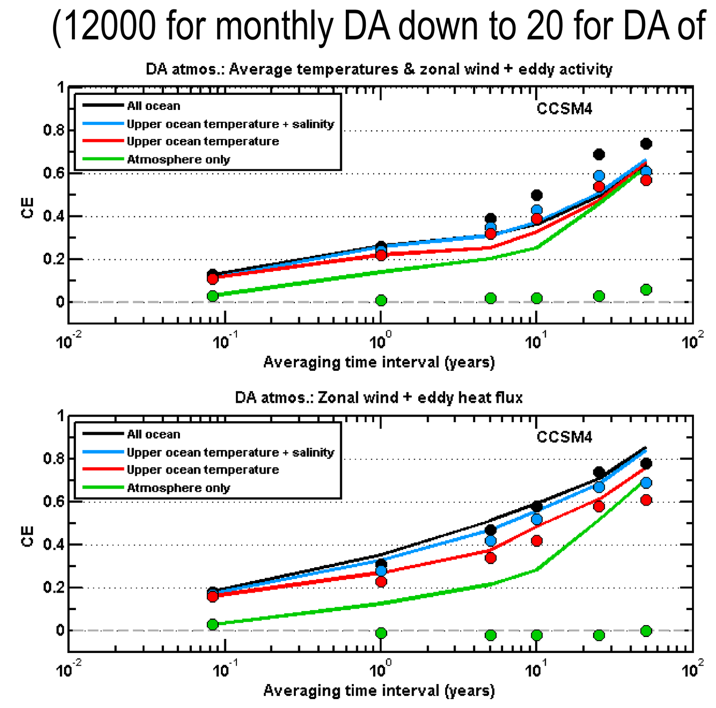

Figure 8. CE values for AMOC analyses obtained from monthly DA (leftmost data points on graphs) vs assimilation of time-averaged observations (avg. intervals from 1 yr to 50 yrs), with assimilation of eddy amplitude (upper frame) or eddy heat flux (lower frame), under contrasting scenarios of availability in oceanic observations, based on CMIP5 CCSM4 model data (solid lines). Note: Dots correspond to CE values of time-averaged monthly AMOC analyses.

Summary

- Q1: **DA needed**! More effective at initializing low frequency component of ocean
- Q2: Continuum behavior in ocean DA vs coupled atmosphere-ocean DA: **Frequent ocean DA most effective** when **ocean is well-observed**, but **coupled assimilation** of **time-averaged obs.** becomes **critical** when ocean is **poorly observed** (e.g. hindcasts initialized prior to availability of sufficient obs. in ocean)
- Q3: "**No cycling**" assimilation of time-averaged obs. slightly less accurate but **viable** & **cheap** alternative
- Q4: **Generality** of main conclusions from study using simplified model **confirmed** using data from **comprehensive AOGCM**.