A Linear Analysis of AMOC Dynamics in GFDL-ESM2M and CCSM4

Cécile Penland[1], Douglas MacMartin[2], Chesley McColl[3,1], Laure Zanna[4], Leslie Hartten[3,1], and Eli Tziperman[5]

[1] *NOAA/ESRL/Physical Sciences Division, Boulder, CO*; [2]*California Institute of Technology, Pasadena, CA*; [3]*CIRES, University of Colorado, Boulder, CO*; [4]*University of Oxford, Oxford, UK*, [5]*Harvard University, Cambridge, MA*

Introduction:

- The representation of the Atlantic Meridional Overturning Circulation (AMOC) differs greatly among individual coupled General Circulation Models (GCMs). Physical reasons for these differences are still poorly understood.

- We consider two such GCMs, ESM2M and CCSM4, and their simulation of the AMOC as defined by the anomalous streamfunction minus the Ekman component (ψ_{NoEk}: see depth-latitude slices below). For this study, we use annually averaged model output.

- In particular, we investigate what role, if any, surface fresh water flux (**FW**: see latitude-longitude plots below) and surface heat flux (**HF**) in the same geographical area as **FW** (see plots below), play in the interannual evolution of the AMOC.

Methodology:

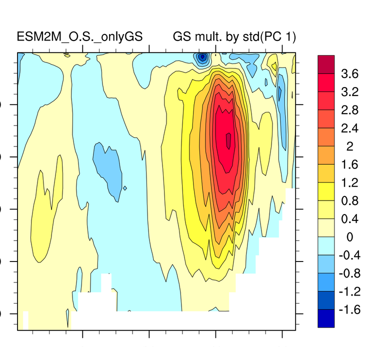
For each model, we consider two classes of state vector $\boldsymbol{x}$, consisting either of the 10 leading Principal Components (PCs) of ψ_{NoEk} alone, or of the 10 leading PCs of each field, (ψ_{NoEk}, FW, HF), normalized so that the 30 time series are about the same size but the relative variance of the PCs within any single field is preserved. We apply *Linear Inverse Modeling* (*LIM*) to these fields. That is, we use lagged and contemporaneous statistics to derive the best fit linear model of the form

$$\frac{d\boldsymbol{x}}{dt} = \mathbf{L}\boldsymbol{x} + \boldsymbol{\xi}$$

where $\mathbf{L}$ is a constant matrix and $\boldsymbol{\xi}$ is a vector of white noise. With this *ansatz*, the most probable prediction of $\boldsymbol{x}(t+\tau)$ given $\boldsymbol{x}(t)$ is $\mathbf{G}(\tau)\,\boldsymbol{x}(t)$, where $\mathbf{G}(\tau) = \exp(\mathbf{L}\tau)$. Further, the initial condition evolving during time τ into the pattern having the largest possible amplitude of, say, ψ_{NoEk}, is the leading eigenvector of $\mathbf{G}^{\mathrm{T}}(\tau)\mathbf{W}\mathbf{G}(\tau)$, called the *optimal structure*. $\mathbf{W}$ is a weighting matrix ensuring that the amplitude of ψ_{NoEk} is what is maximized. If $\boldsymbol{x}$ consists of ψ_{NoEk} only, then $\mathbf{W}$ is the identity matrix.

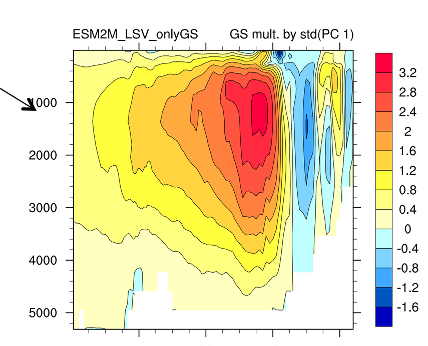
Comparison of ESM2M and CCSM4 when x consists only of ψ_{NoEk}:

ESM2M:

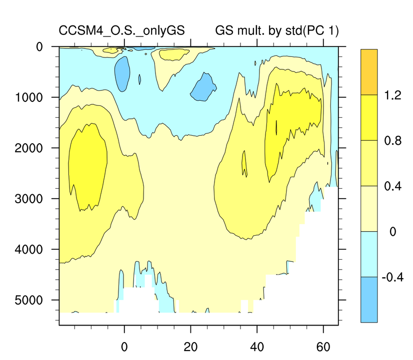


This initial condition evolves into this in 3 years.

ψ_{NoEk} variance increases by a factor of 3.0.

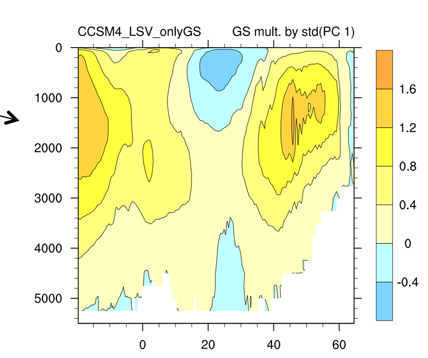


CCSM4:



This initial condition evolves into this in 1 year.

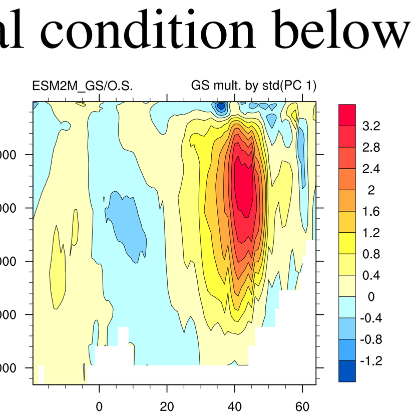
ψ_{NoEk} variance here increases by a factor of 2.9.

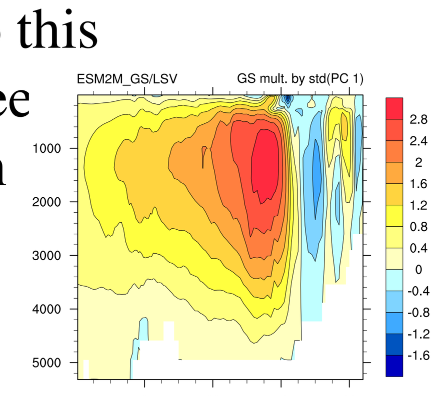


Comparison of ESM2M and CCSM4 when x consists of (ψ_{NoEk}, FW, HF):

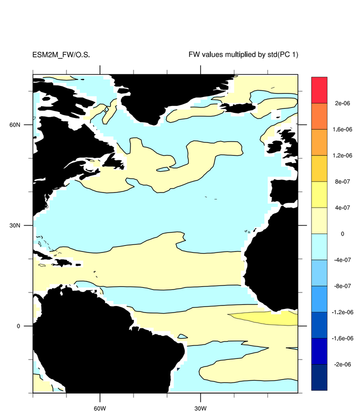
ESM2M: The three-component initial condition below causes ψ_{NoEk} (left column) to evolve into this pattern in three years, with an amplification factor of 2.9.

ψ_{NoEk}

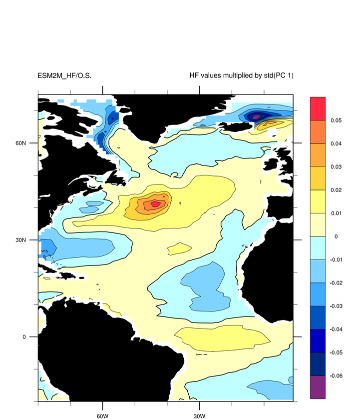




FW

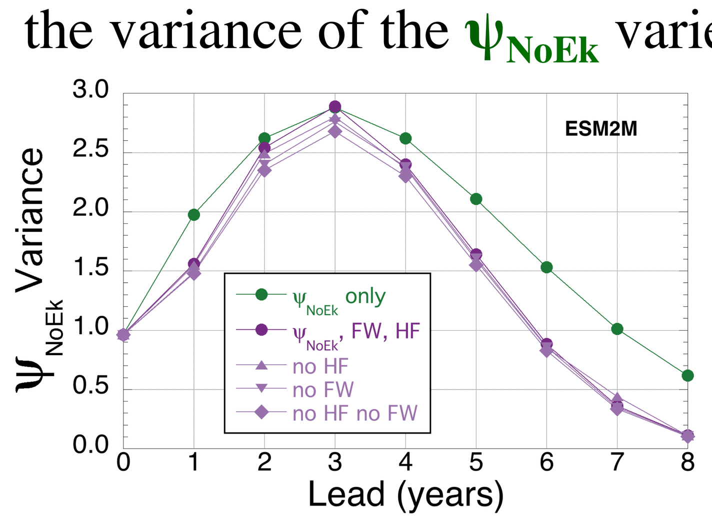


HF



Do FW and HF actually play any role in the evolution of ψ_{NoEk} for ESM2M?

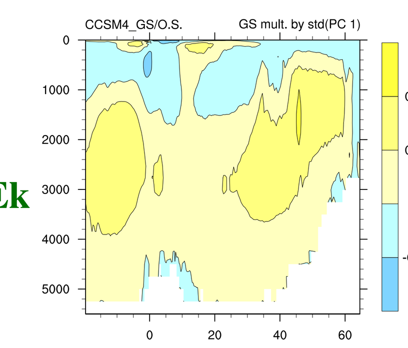
We zero out contributions from **FW** and **HF** in the propagator matrix $\mathbf{G}(\tau)$ and look at how the variance of the ψ_{NoEk} varies. It seems that **FW** and **HF** play very little role in the predictable evolution of ψ_{NoEk}.

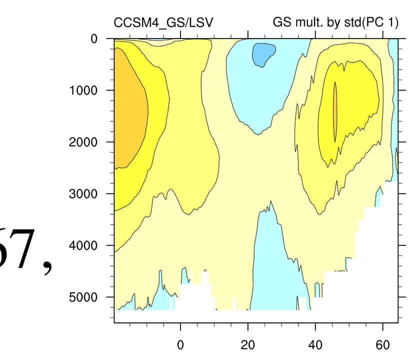


ψ_{NoEk} accounts for 96% of the 3-field optimal structure (O.S.) variance.

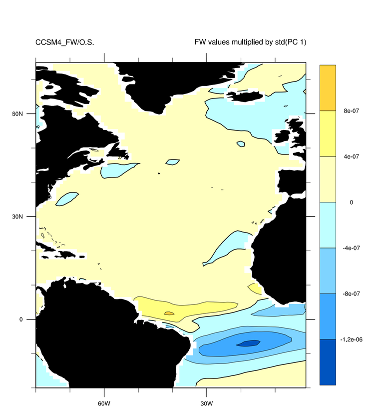
CCSM4: The three-component initial condition below causes ψ_{NoEk} (left column) to evolve into this pattern in one year with an amplification factor of 2.6/.67, or 3.9.

ψ_{NoEk}

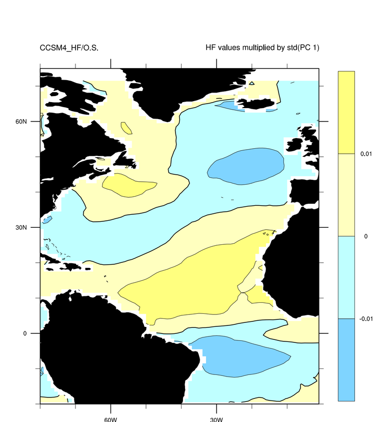




FW

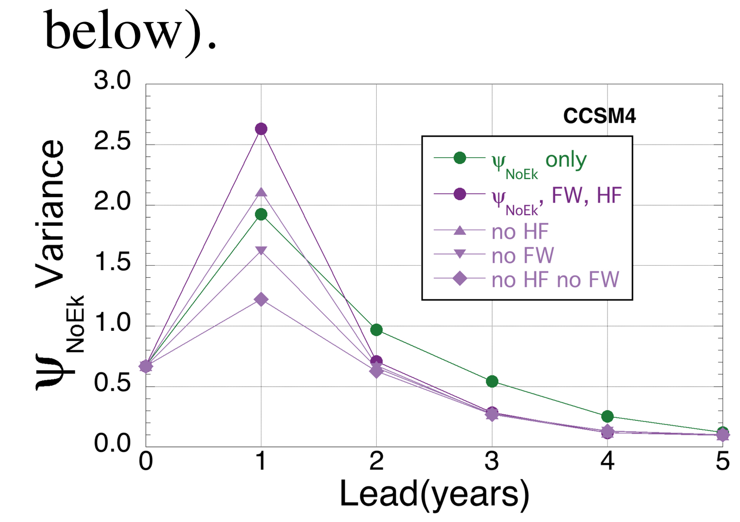


HF



Do FW and HF play any role in the evolution of ψ_{NoEk} for CCSM4?

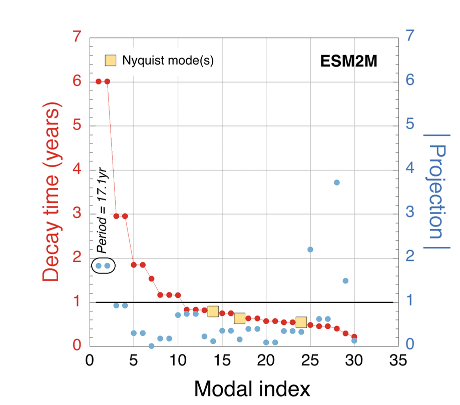
Modified Green function matrices $\mathbf{G}(\tau)$ show that **FW** and **HF** are very important (see plot below).

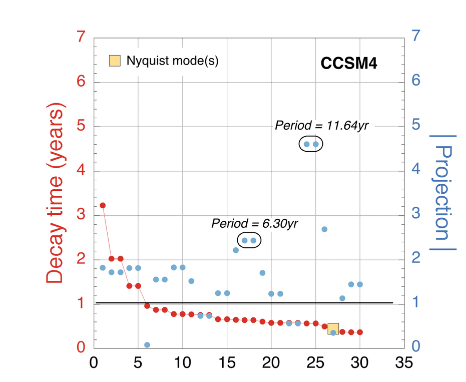


ψ_{NoEk} accounts for 67% of the 3-field optimal structure (O.S.) variance. ψ_{NoEk}-only O.S. is scaled accordingly.

Conclusions

- Evolution of ψ_{NoEk} in ESM2M appears to be due to an internal oscillation. Only 5 eigenvectors of $\mathbf{L}$ (i.e., "modes"), including a resolved (decay time > 1yr) oscillating pair, project significantly (> 1) on the ψ_{NoEk} optimal structure. The 3-year optimal growth interval is consistent with an oscillation of 12-17 years.





- Evolution of ψ_{NoEk} in CCSM4 appears to depend heavily on interactions with **FW** and **HF**. The ψ_{NoEk} optimal structure significantly projects onto a large number of modes, most of them with decay times less than the output resolution (1yr).
- Unresolved (and, therefore, highly biased) modes project most strongly onto the ψ_{NoEk} optimal structure. We defer analysis of modes themselves to subsequent work with monthly model output.
- These results are consistent with Transfer Function Analysis (talk with D. MacMartin).

Future work

- Develop verification method based on data
- Use monthly output to identify stochastic forcing
- Analyze other GCMs