A Generalized Stability Analysis of the AMOC in Earth System Models: Implication for Decadal Variability and Abrupt Climate Change

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Final technical report

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Summary

The central goal of this research project is to understand the mechanisms of decadal and multi-decadal variability of the Atlantic Meridional Overturning Circulation (AMOC) as related to climate variability and abrupt climate change within a hierarchy of climate models ranging from realistic ocean GCMs to Earth system models of the CMIP5 project. Generalized Stability Analysis, a method that quantifies the transient and asymptotic growth of perturbations in the system, is one of the main approaches used throughout this project. The topics we have explored range from physical mechanisms that control AMOC variability to the factors that determine AMOC predictability in the Earth system models. In addition, we investigated the stability and variability of the AMOC in past climates.

So far, this project has resulted in 12 manuscripts, including one publication in *Nature* (Fedorov *et al.* 2013). Another publication is now under consideration at Nature Geosciences. Several other manuscripts are under preparation.

Initially this work involved a postdoctoral associate Dr. Florian Sevellec. After Dr. Sevellec accepted a faculty appointment at the National Oceanography Center at the University of Southampton, UK, a new postdoctoral associate Dr. Les Muir was hired to take his place. A graduate student Yana Bebieva (funded outside of this grant) was also involved in the project. Collaboration has continued with Dr. Sevellec as well as Drs. Eric Guilyardi and Juliette Mignot of IPSL (University of Paris, France).

During the past three years the results emanating from this project have been presented within numerous invited seminars at universities in the US and abroad including MIT, Woods Hole Oceanographic Institution, Princeton University, University of Rhode Island, University of Paris VI (France) and Institute of Geophysics and Volcanology (Bologna, Italy). The PI and the members of his research group have participated in several international conferences and workshops, including the CLIVAR US AMOC annual meetings in Boulder (2012), Baltimore (2013) and Seattle (2014), the Latsis climate symposium in Zurich (2014), and the 4th International Summit on Hurricanes and Climate Change, Greece (2013). The results have been also presented during the AGU Fall meetings in San Francisco (2012, 2013, 2014) and the EGU annual meeting in Vienna (2012). The PI was the convener of two major sessions during the Fall AGU meeting, “The Atlantic Meridional Overturning, Climate variability and change (2014)” and “Thirty years of ENSO research: dynamics, predictability, impacts (2013)”.

Some of the results of this work have being incorporated into several classes currently taught by the PI at Yale University, “Physical Oceanography”, “Climate Dynamics” and “Geophysical Fluid Dynamics”. These are graduate courses open to upper-level undergraduate students.

Particular scientific results of this project are described in more detail below.

An interdecadal AMOC mode related to westward propagation of temperature anomalies in the North Atlantic (Sevellec and Fedorov 2013a)

We have conducted analysis of continuous integrations of linearized forward and adjoint versions of a realistic ocean general circulation model (OPA) to show rigorously the existence in the system of a weakly-damped mode of oscillation centered in the North Atlantic and related solely to the dynamics of the AMOC. The period of the mode in this particular GCM is 24 years, its e-folding decay timescale is 40 years, and the mode surface manifestation is evident in the westward propagation of SST anomalies (Fig. 1).

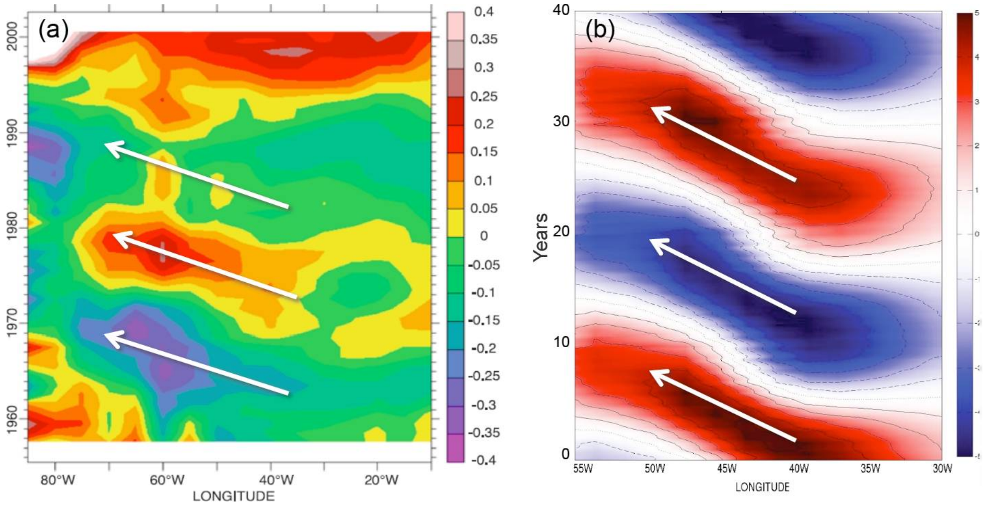

Fig. 1: Hovmoller diagrams showing westward propagation across the North Atlantic. (a) Observed temperature anomalies averaged between 300-400m and 10–60°N (XBT data) with a hint of a 20-year mode (Frankcombe *et al.* 2008). Longer observations are needed to confirm these results. (b) Simulated temperature anomalies averaged between 0-500m and 30–60°N in the leading AMOC eigenmode, with a 24-year period, in a realistic ocean GCM (Sévellec and Fedorov 2013a).

The dynamics of the mode are related to spatio-temporal temperature variations in the northern Atlantic north of 30°N in the upper ocean: these temperature variations affect the ocean density field and hence, by geostrophic balance, ocean currents which then affect the temperature field (Fig. 2). The corresponding temperature anomalies propagate westward, and the basin crossing time gives the half-period of the oscillation.

The westward propagation of temperature anomalies results from a competition between mean eastward zonal advection, equivalent anomalous westward advection due to the mean meridional temperature gradient, and westward propagation typical of long baroclinic Rossby waves. When a temperature anomaly arrives at the basin's western boundary, the ensuing geostrophic adjustment modifies the AMOC in about 2 years.

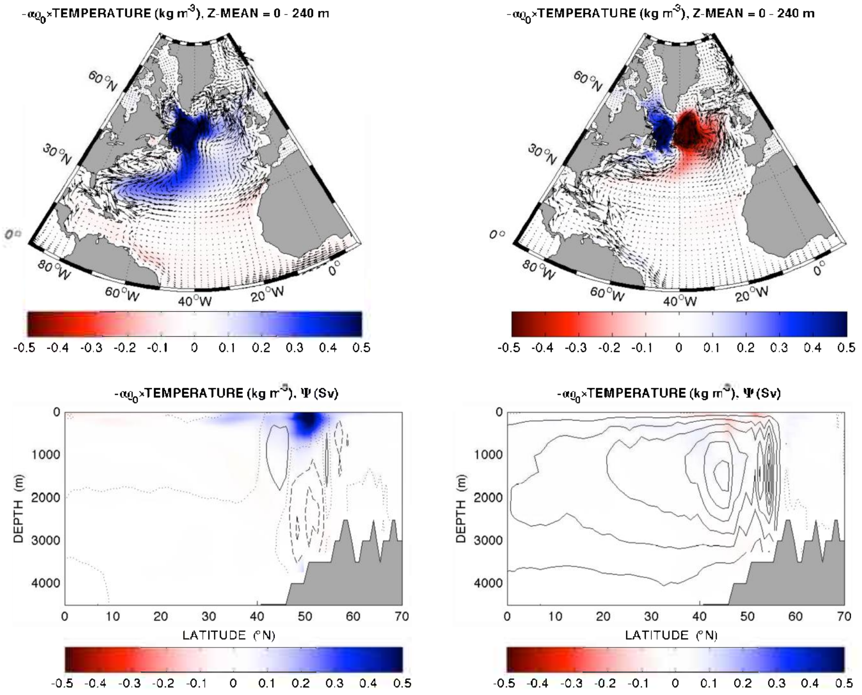

Fig. 2: The spatial structure of the dominant oscillatory AMOC mode in a realistic ocean GCM (OPA): anomalies in (top) upper-ocean temperature and surface currents and (bottom) meridional streamfuction and zonally-averaged temperature for two phases of the oscillation separated by a quarter-period (left and right columns, respectively). Temperature variations are given in terms of density. The ocean fields in the left and right columns are separated by roughly a 6-year interval. The full period of the mode is 24 years (Sevellec and Fedorov 2013a).

The AMOC mode related to westward propagation of temperature anomalies in Earth system models of CMIP5 (Muir and Fedorov 2015)

We have been conducting a comprehensive analysis of the CMIP5 Earth system models, looking at the characteristics of AMOC variability in different models in the decadal to multi-decadal range. It is evident that a large majority of these climate models exhibit a strong AMOC variability in this frequency band (Fig. 3), especially in the interdecadal range between 15 and 35 years. However, the major characteristics of this variability vary greatly from one model to the next, including the typical oscillation period, and the amplitude and spatio-temporal characteristics of the dominant modes.

We have explored the key mechanisms of this interdecadal AMOC mode in CMIP5. Apparently, this mode in CMIP5 models is related to the exact same ocean dynamics described previously, in which westward-propagating upper-ocean temperature anomalies are coupled to AMOC variations. Several examples of this westward propagation of temperature anomalies and corresponding variations in the AMOC volume transport are shown in Fig. 4. Roughly one third to a half of these models appear to exhibit a strong interdecadal AMOC mode associated with the westward propagation of temperature anomalies in the North Atlantic.

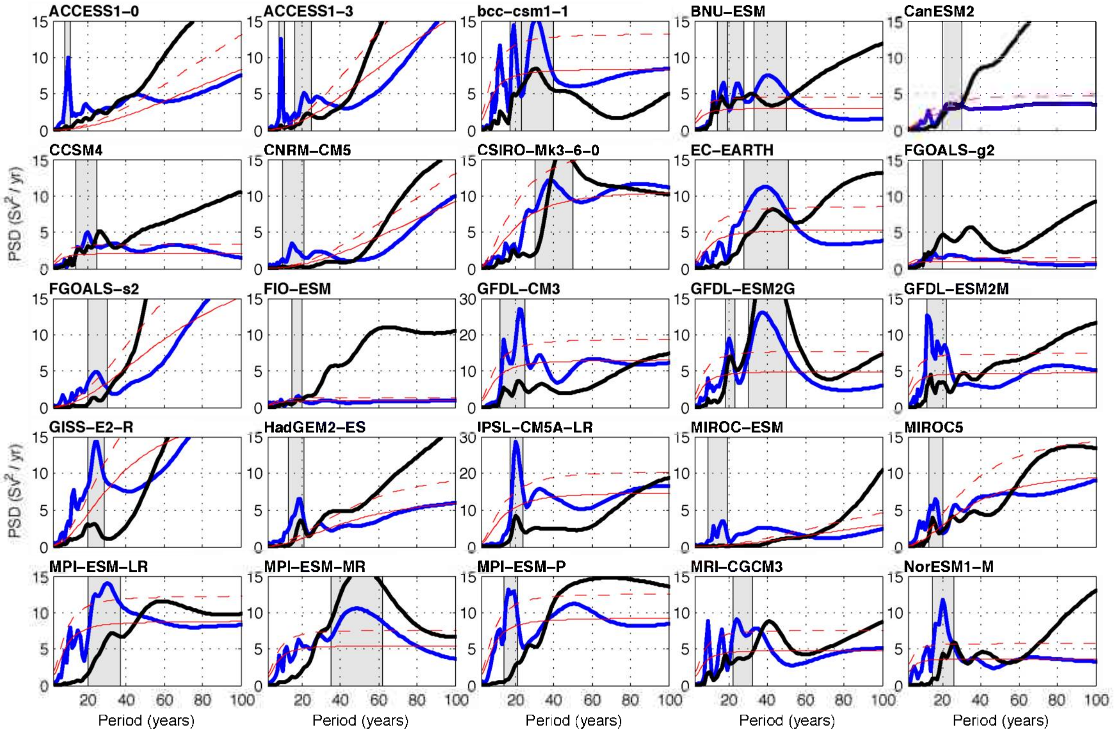

Fig. 3: The power spectral density (blue line), the red noise estimate (solid red line) and the 95% red noise estimate (dashed red line) of the 45°N AMOC index in the 25 models investigated. The solid black line is the normalized Northern Atlantic mean density 200-2000m, 300-360E. 40-60N. Shaded bands indicate spectral peaks (Muir and Fedorov 2015).

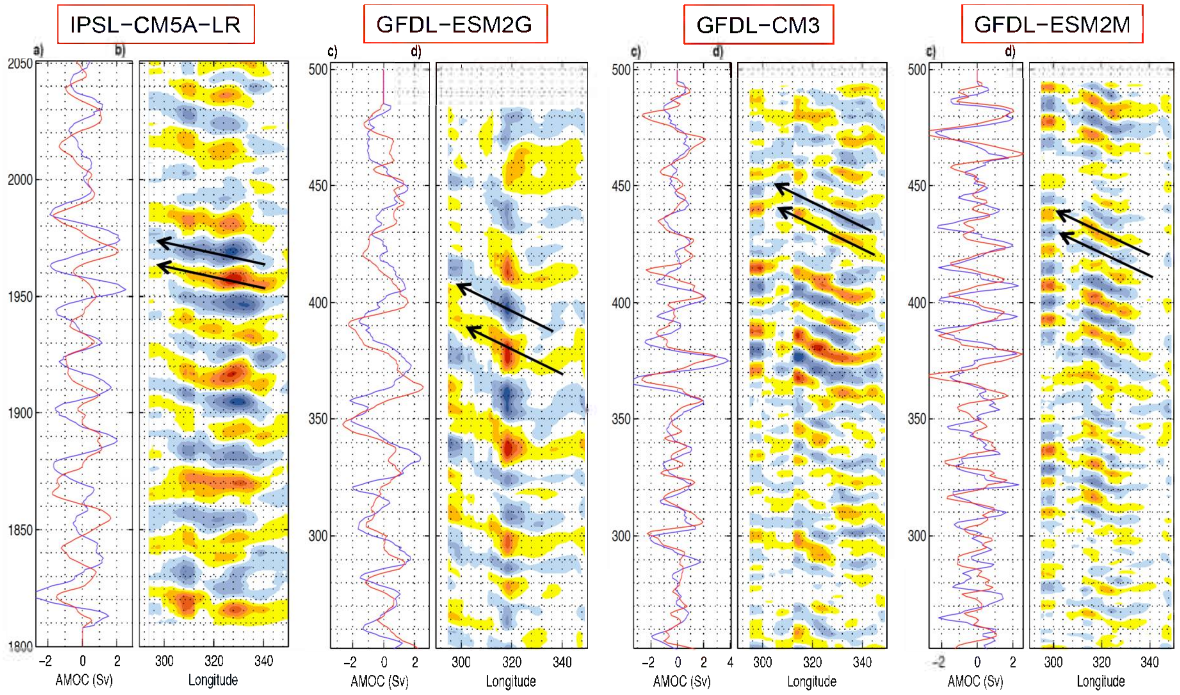

Fig. 4: Examples of westward-propagating temperature anomalies in Earth System Models in CMIP5 and the corresponding AMOC variations (Muir and Fedorov 2015).

Excitation of AMOC variability by optimal initial perturbations in ocean GCM (Sevellec and Fedorov 2014a)

While the previous analyses concentrates on the internal natural mode of the AMOC, a characteristic of asymptotic oscillatory properties of the system, the next step is to investigate how this mode can be excited. In particular, in this part of the project we described the excitation of variability of the Atlantic Meridional Overturning Circulation (AMOC) by optimal initial perturbations in surface temperature and salinity. Our initial approach is based on a generalized stability analysis within a realistic ocean general circulation model, which extends the conventional linear stability analysis to transient growth. Unlike methods based on singular value decomposition, our analysis invokes an optimization procedure using Lagrangian multipliers, which is a more general approach allowing us to impose relevant constraints on the perturbations and use linear measures of the AMOC (meridional volume and heat transports).

We find that the structure of optimal perturbations is characterized by anomalies in surface temperature or salinity centered in the Subpolar regions of the North Atlantic off the east coasts of Greenland and Canada, just south of the Denmark Strait (Fig. 3).

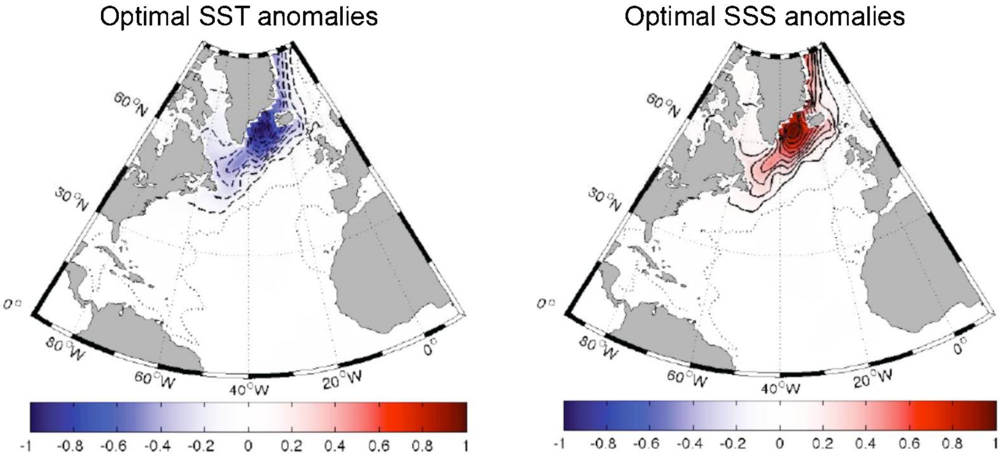

Fig. 5: The spatial structure of optimal initial perturbations in SST (left) and SSS (right) for the most efficient time delay. The units are °C for temperature and psu for salinity but could be multiplied by an arbitrary constant (Sevellec and Fedorov 2014a).

The maximum impact of such perturbations on the AMOC is reached after 7 to 9 years. Simple estimates show that typical changes in salinity or temperature in the upper ocean (such as those due to the Great Salinity Anomaly) can induce AMOC variations of several Sverdups via this mechanism, up to 20% of the mean overturning. Stronger temperature or salinity changes can potentially induce an abrupt climate change with a significant slowing down or a temporary shut-down of the AMOC.

Our study has several implications for decadal predictability of the ocean meridional overturning circulation in the Atlantic. Firstly, our results imply that the spread in predictions of the volume and heat transports by the AMOC is affected most by the same physical process: the excitation of zonal dipole-like SST patterns by density anomalies. Secondly, the spatial patterns of the optimal initial perturbations can serve as precursors of future changes in the AMOC - only those SST and SSS perturbations that have a nonzero projection on the optimal perturbations will be able to impact the AMOC after a time delay. This implies that to anticipate AMOC changes approximately one decade in advance we should carefully monitor surface density changes in the Atlantic north of 50°N. Similarly, to fully explain the weakening of the AMOC in the winter of 2009/2010 for example, one would need to search for causes a decade earlier.

Excitation of AMOC variability by optimal initial perturbations in Earth System Models (work in progress)

We continue use this approach, but now applying the same analysis to oceanic components of Earth system models of CMIP5. Using generalized stability analysis we find initial optimal perturbations in upper ocean temperature and salinity that excite the AMOC the most in these models. We find that these optimal perturbations do excite the system and lead to a strong change in the AMOC over a decade or so. Our preliminary computations for several different models, including GFDL's CM3 (Fig. 6), reveal optimal perturbation patterns still localized mainly in the Subpolar gyre region.

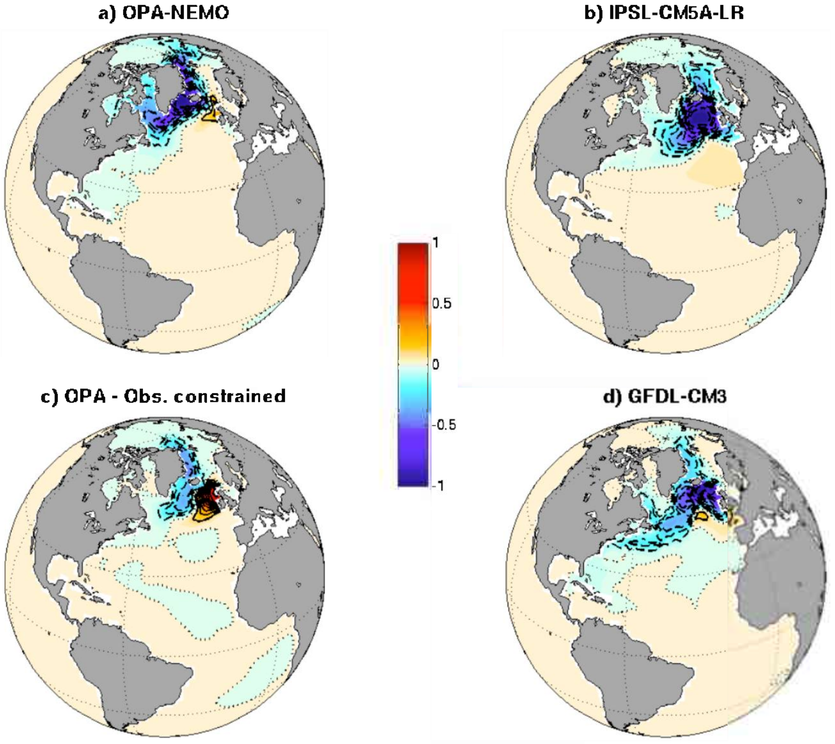

Fig. 6: Examples of oceanic optimal initial patterns in the upper-ocean temperature field, or the optimal initial perturbations, that affect the AMOC the most in four different models. (Top left) NEMO-OPA, an ocean-only model, *cf.* Fig. 5; (Bottom left) NEMO-OPA, but constrained with the observed climatological cycle; (Top right) IPSL-CM5, an Earth system model with the same oceanic component as NEMO-OPA; (Bottom right) GFDL-CM3.

Climate impacts of AMOC variability in CMIP5 (Muir and Fedorov 2014).

We further investigated how variations of the Atlantic meridional overturning circulation (AMOC) affect climate, and sea surface temperature (SST) in particular, within the simulations of CMIP5. In particular, we have explored whether the SST response is interhemispheric in nature, specifically as reflected in the Atlantic SST Dipole index, or whether the response is localized more in the North Atlantic Ocean. In the absence of direct observational data, this Dipole index has been proposed to approximate AMOC variations over the duration of the instrumental temperature record.

We find that typically, on timescales between decadal and centennial, even for the models with the highest correspondence between the AMOC and the Dipole index, the correlation between the two variables is controlled mainly by SST variations in the North Atlantic (Fig. 7), not the South Atlantic, both for the model control and historical simulations. Consequently, in nearly all models, the North Atlantic SST provides a better indicator of AMOC variations than the Atlantic Dipole.

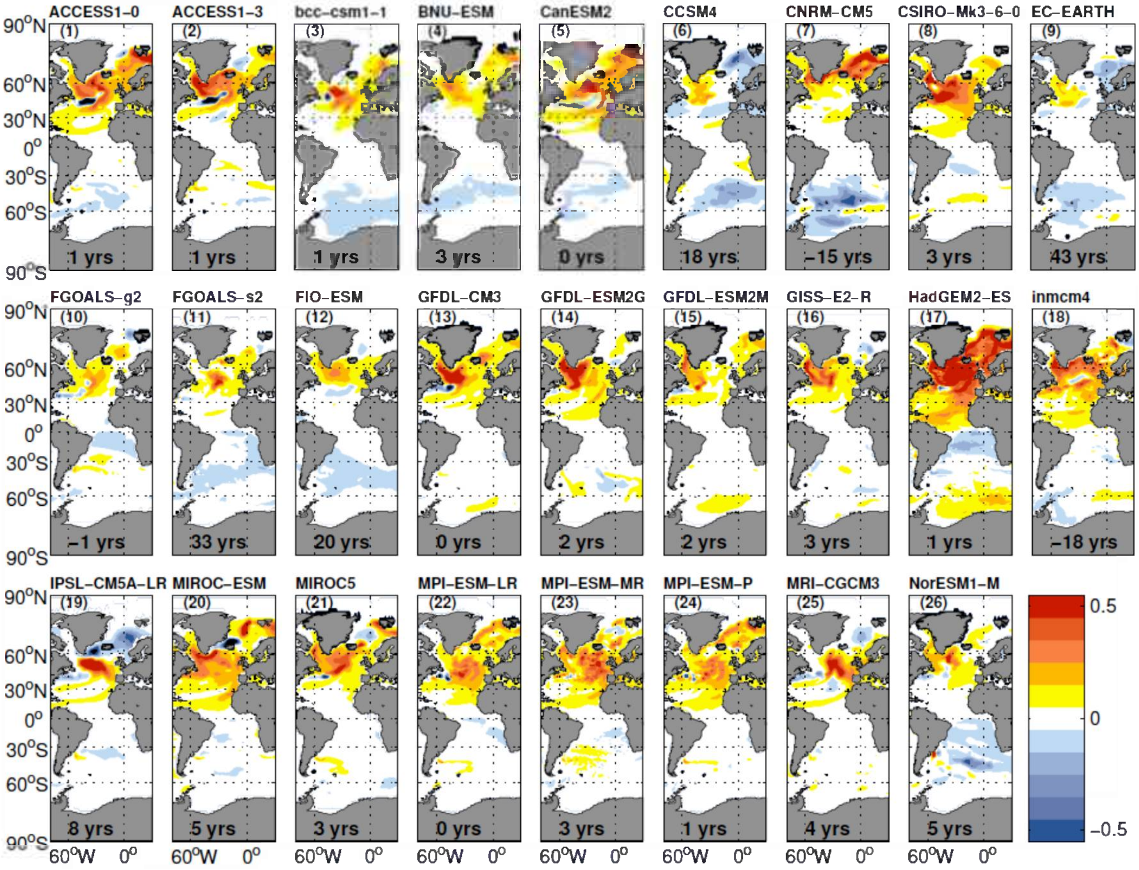

Fig. 7: Regressions of SST onto the AMOC index (evaluated at 30°N) at the lag corresponding to the maximum correlation between the AMOC and the Atlantic Dipole (the best lag). SST changes for a 1 Sv increase in the AMOC are shown. Numbers at the bottom of the panels indicate the lag (in years) of the Dipole Index with respect to AMOC variations. Units are $^{\circ}$C Sv^{-1}. The maximum SST response is found in the northern Atlantic, typically between 40 and 60°N. The Southern Atlantic exhibits no or week signal (Muir and Fedorov 2014).

Thus, on decadal to centennial timescales AMOC variability affects mainly the North Atlantic Ocean (Fig. 7), with the sensitivity of the North Atlantic SST between 40-60°N, given by the multi-model average, of about 0.3° C per 1 Sv of AMOC change, explaining roughly one third of the SST variance.

Another question concerns the connection between the AMOC and the Atlantic Multidecadal Variability (AMV, also called the AMO). Our results support the notion that a significant, albeit not too large a fraction of the AMV should be related to AMOC variations. In fact, we find that the region of the maximum SST response to AMOC simulated by the models, south of Iceland and Greenland and east of Canada, generally coincides with the region of the strongest AMV signal in the observations.

Deep ocean and decadal climate predictability (Sevellec and Fedorov 2013b)

In parallel, we looked into the problem of what controls the limits of decadal climate variability from the perspective of ocean dynamics. A closely related problem is the issue of model global bias. Even when forced with observed fields at the surface, ocean models develop global biases in temperature and salinity (as compared to the Levitus dataset, for example), and such biases typically amplify in coupled models. Here, we asked two complimentary questions related both to decadal prediction and model bias. (1) Can we temporarily reduce the bias and potentially improve climate prediction by slightly perturbing the initial conditions used for model initialization? (2) How fast will such initial perturbations grow? To answer these questions we computed initial optimal perturbations in temperature and salinity that could reduce the model bias most efficiently during a given time interval, again on decadal timescales. We find that to reduce the bias, especially pronounced in the upper ocean, initial perturbations should be imposed in the deep ocean (especially in the Southern Ocean), Fig. 8.

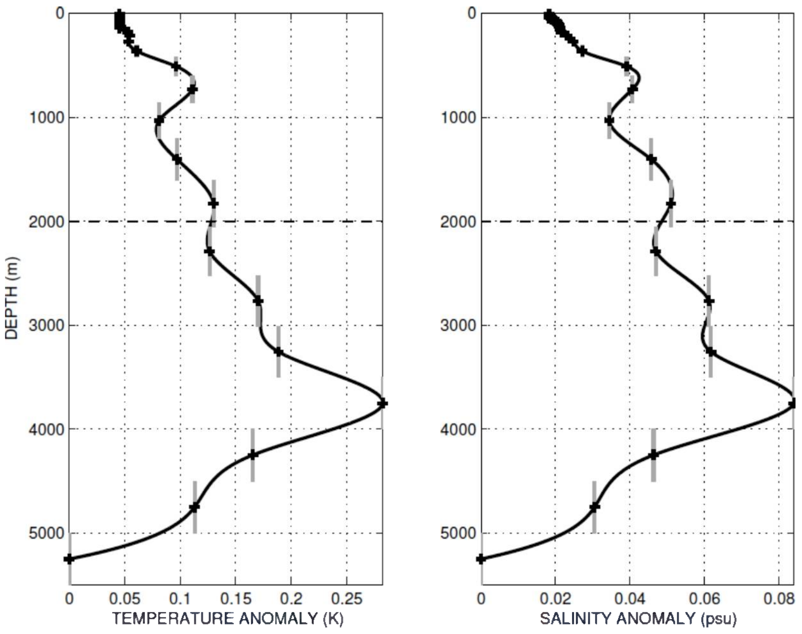

Fig. 8: Sensitivity of the upper-ocean temperature to (right) temperature and (left) salinity anomalies located at different depths for the global ocean. The strongest sensitivity is found at 3700m. Induced SST anomalies are proportional to this sensitivity. The model data are shown as small crosses connected with a black solid line. Short grey vertical lines indicate the thickness of each model level; the horizontal dot-dashed line – the typical depth limit of ARGO floats (Sevellec and Fedorov 2013b).

Our main result here is that on decadal timescales, a 0.1°C perturbation in the deep ocean can induce an SST anomaly on the order of several °C, which would partially reduce the bias. The growth of such initial perturbations peaks after about 14 years. A corollary of these results is that very small errors in model initialization in the deep ocean (Fig. 8) can potentially produce large errors in the upper-ocean temperature after a decade or two of numerical simulations, which could be interpreted as a decadal predictability barrier associated with ocean dynamics.

Prediction of the North Atlantic ocean state (Sevellec and Fedorov 2015a).

Subsequently, we investigated the decadal predictability of the ocean climatic state focusing on the North Atlantic. To assess this oceanic predictability, we compute optimal initial perturbations and estimate the maximum impact of these disturbances on ocean dynamics. As the metrics of the ocean state we use four different measures: the Meridional Volume Transport (MVT), the Meridional Heat Transport (MHT), the mean Sea Surface Temperature (SST), and the Oceanic Heat Content (OHC), all in the North Atlantic.

Similar to the previous study, these results also suggests that initial errors less than 0.1°C can lead on a decadal timescale to an error of several °C in North Atlantic mean sea surface temperature estimates. This transient error growth is maximal after about 17 years and can be interpreted as a decadal predictability barrier, which generally agrees with our previous computations completed in a different context. The maximum sensitivity here is found for 1200m, but there is still important sensitivity associated with the deep ocean (Fig. 8).

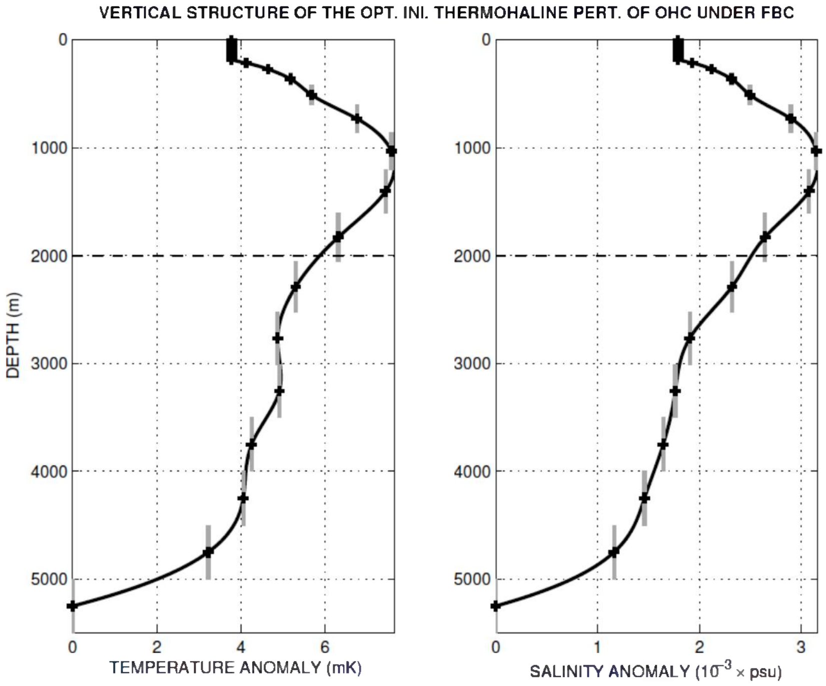

Fig. 8: The same as in Fig. 7, but only for the North Atlantic. The maximum sensitivity is at 1200m.

The relation between poleward heat transport and the AMOC (Sevellec and Fedorov 2015b)

The connection between the AMOC and oceanic poleward heat transport is another important aspect of the problem. It is typically assumed that oceanic heat transport is positively correlated with the Atlantic meridional ocean circulation (AMOC). In numerical "water-hosing" experiments, for example, imposing an anomalous freshwater flux in the northern hemisphere leads to a slow-down of the AMOC and a corresponding reduction of the northward heat transport. In this part of the project, using generalized stability analysis, we study the sensitivity of the heat transport to surface freshwater and heat fluxes and find that, while the direct relationship between the AMOC and heat transport holds on shorter time scales, it can completely reverse on timescales longer than 500 years or so (Fig. 9). That is, a reduction in the AMOC volume transport can actually lead to a stronger heat transport on long timescales, which results from the gradual increase in ocean thermal stratification.

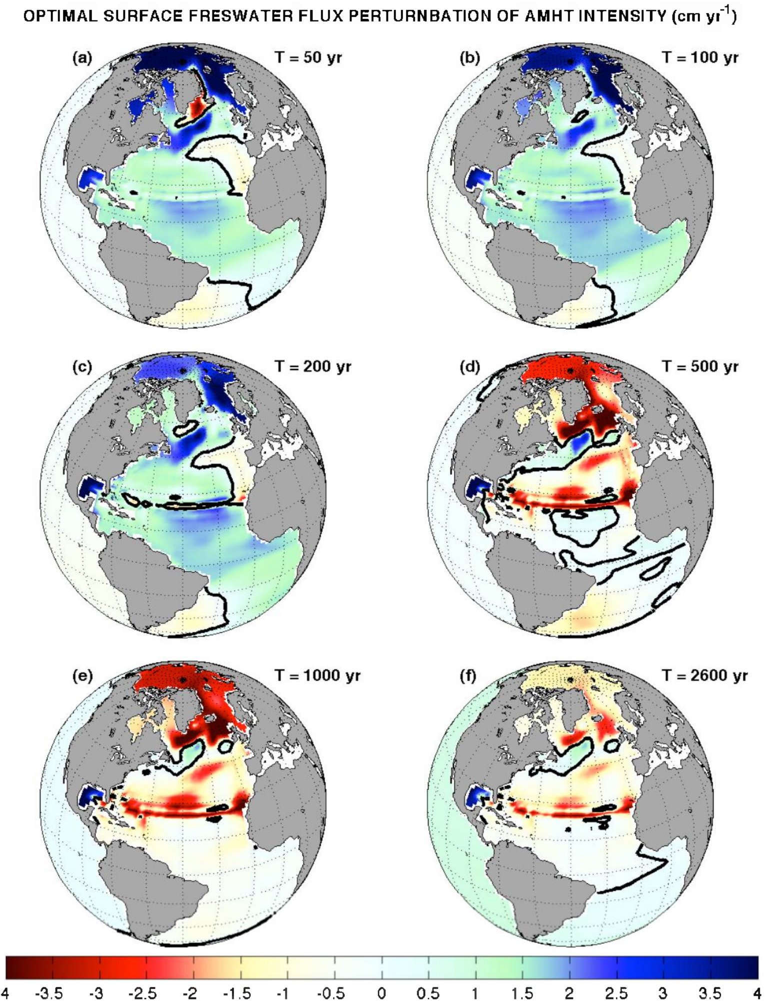

Fig. 9: The shape of optimal perturbations in steady freshwater flux, influencing the most the Atlantic poleward heat transport, for different time spans *T*= 50, 100, 200, 500, 1000, 2600 years. Note the reversal of the sign at around 500 years.

We discuss the implications of these results for the problem of steady state (statistical equilibrium) in ocean and Earth system models and to paleoclimate problems related to abrupt climate change.

Predictability of the AMOC collapse in an idealized ocean model (Sevellec and Fedorov 2014b, Sevellec and Fedorov 2015c)

In a complimentary study, we have used an idealized AMOC model as a test bed for using generalized stability analysis as a tool for evaluating the predictability of the AMOC collapse. Formulating this idealized model, we have introduced an additional degree of freedom to the classical Howard-Malkus loop, which activated AMOC chaotic dynamics on timescales ranging from decadal to centennial to millennial (Fig. 10). Using optimal perturbations we study the stability of the AMOC in this model.

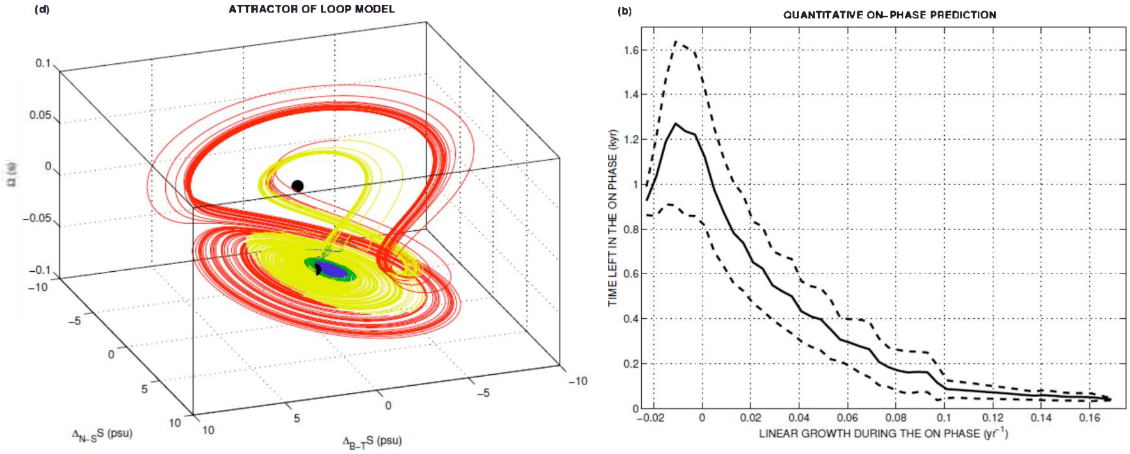

Fig. 10: (Left) the chaotic attractor of the idealized model and (right) the time left until the AMOC collapse as a function of the magnitude of the perturbation growth. Depending on the state of the system, the time until the AMOC collapse can vary from thousand years to several decades (Sevellec and Fedorov 2014b).

Accurate representation of AMOC variability in the model allows us to define predictive indices for the phase change of the overturning circulation. These indices, describing the growth of perturbations in the system, depend mainly on the ocean vertical stratification, and their magnitude gives accurate predictions for the moment when the overturning circulation can potentially collapse. Thus, monitoring particular indices of the ocean state could serve as a means for predicting a shutdown of the AMOC.

Pliocene climate as an analogue for future global warming (Fedorov *et al.* 2013, Fedorov et al. 2015, Burls et al. 2015):

In a complimentary study, we have analyzed the available proxy data on climate evolution over the past 5 Myrs in different regions of the ocean as well as changes in atmospheric CO_2 concentrations (Figs. 11 and 12).

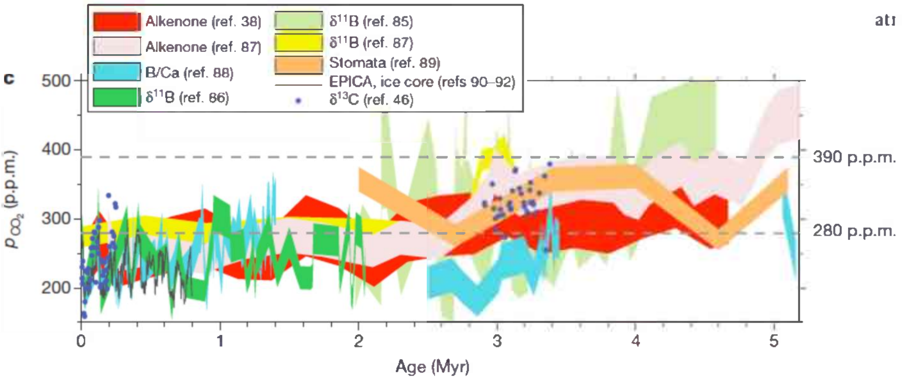

Fig. 11: Changes in atmospheric CO₂ concentration over the past 5 million years from different proxy methods. The present-day (390pppm in year 2010) and preindustrial (280 ppm) CO₂ levels are also shown. This compilation suggests that we have already exceeded CO₂ concentrations prevailing over 5 million years (Fedorov *et al.* 2013 and references therein).

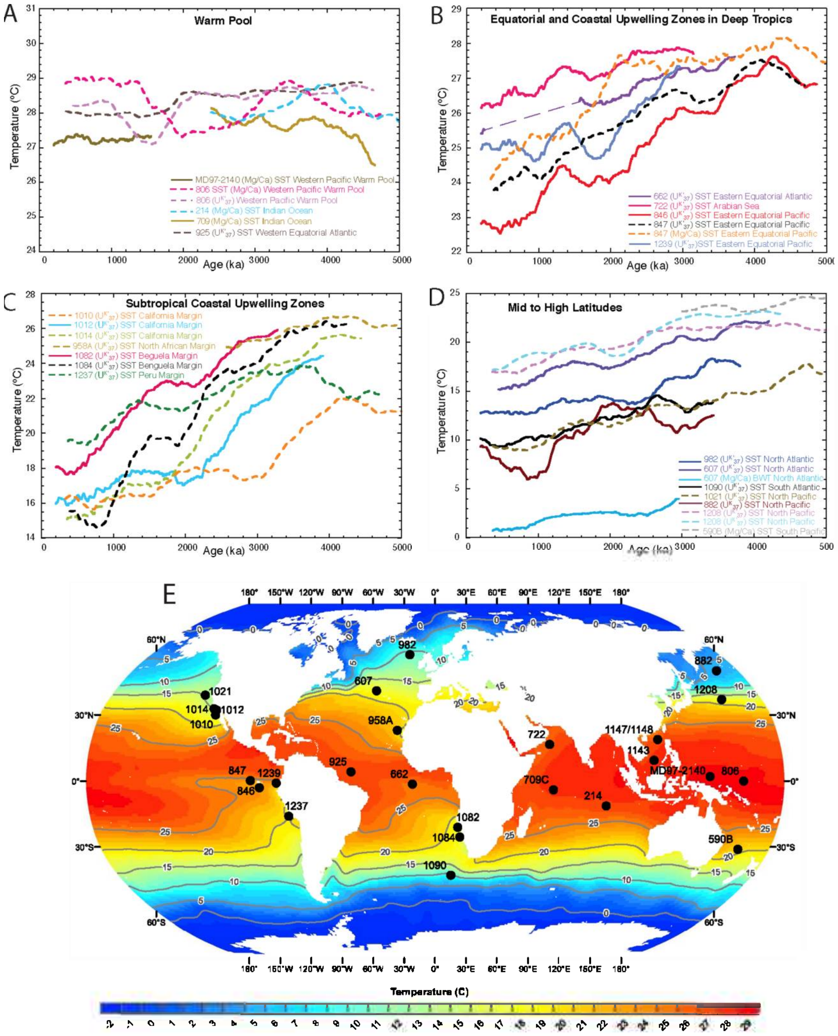

Fig. 12: Climate evolution over the past 5 million years. (A, B, C, D) Surface temperature trends from paleodata in different regions of the ocean. (E) The site locations superimposed on a map of modern ocean surface temperature. Note a significant cooling from 5My ago to the present in most of the sites, except for those in the tropical warm pool (panel A), Fedorov *et al.* 2013.

After carefully analyzing data uncertainty and potential errors we concluded that, with very similar to today's elevated levels of CO_2 4-5million years ago, in the early Pliocene epoch, Earth climate was significantly warmer and had substantially reduced zonal and meridional temperature gradients. Using a comprehensive Earth system model (CESM) we compared potential mechanisms that could have maintained such a climate, and concluded that modifications of the model physics are required, since neither high CO_2, nor changes in oceanic gateways produce a structural climate change comparable with the observations. Our results suggest that changes in cloud properties affecting planetary albedo appear to be the most important factors besides CO_2 concentration.

The next step, especially relevant to the current project, is to understand the role of the AMOC and, potentially, changes in its dynamics and stability that accompanied this climate evolution. We find that in such a warm climate as the early Pliocene, the AMOC weakens by some 20-30%, but does not collapse. The weakening of the AMOC provides a week negative feedback for the warming of the North Atlantic. In another surprised finding we observe an establishment of the Pacific Meridional Overturning circulation (PMOC), a counterpart of the AMOC in the Pacific. This study will be submitted to *Nature* shortly (Burls et al. 2015). Whether contemporary global warming can result in similar oceanic changes is now being explored.

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