OPTIMAL SURFACE SALINITY PERTURBATIONS OF THE THERMOHALINE CIRCULATION. II: GLOBAL OGCM.

F. Sévellec(1), T. Huck(1), M. Ben Jelloul(1), N. Grima(1), J. Vialard(2), A. Weaver(3)

(1) *Laboratoire de Physique des Océans, Université de Bretagne Occidentale, France.*
(2) *LOCEAN, Université Pierre et Marie Curie, Paris, France.* (3) *CERFACS, Toulouse, France.*

ABSTRACT

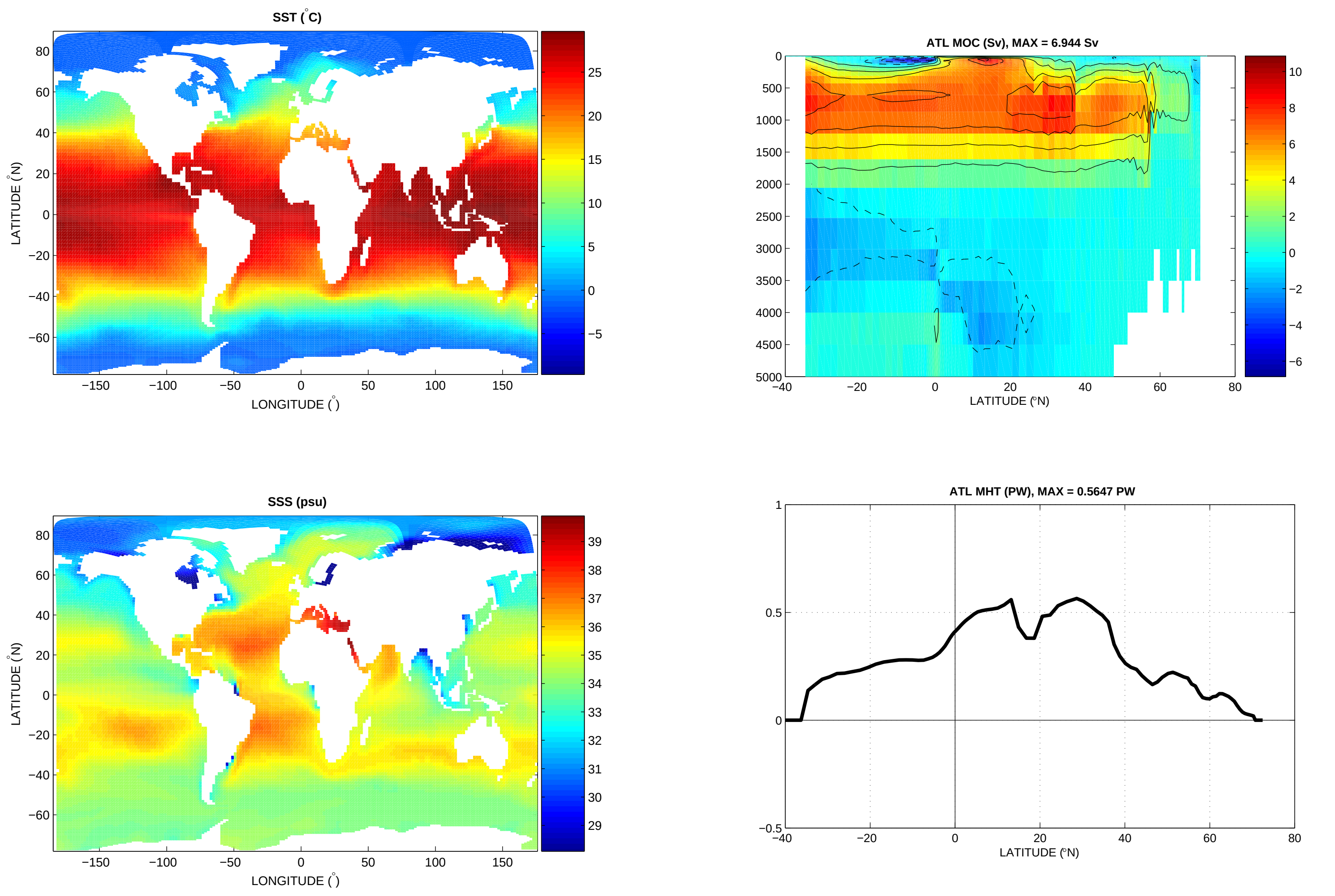
After a methodological step in a 2D zonally-averaged model (Sévellec et al., 2007), optimal initial surface salinity perturbations are computed and described for a realistic mean state of a global ocean general circulation model (OPA ORCA2°); optimality is defined with respect to the meridional overturning circulation intensity. The most efficient transient growth appears for a delay of 10.5 yr after the perturbation by the optimal surface salinity anomaly. This optimal growth is induced by an initial anomaly located north of 50°N. The optimal perturbation yields upperbound on the intensity of the MOC response: using typical amplitudes of the Great Salinity Anomalies, the upper bound for the associated variability is 0.8 Sv (11% of the mean circulation). The linear and nonlinear responses to the optimal perturbation are compared for various perturbation amplitudes.

INTRODUCTION

One of the expected consequences of global warming is the modification of the freshwater flux, inducing changes in the ocean salinity. Such modifications have been documented in the North Atlantic over recent decades (Josey and Marsh, 2005; Curry et al., 2003; Curry and Mauritzen, 2005). In this context, we examine herein the sensitivity of the ocean circulation to sea surface salinity perturbations through the analysis of optimal initial perturbations.

MODEL AND STEADY STATE

We use the oceanic primitive equation model OPA (Madec et al., 1997) in a global configuration with 2° resolution ORCA2 (Madec and Imbard, 1996). The model is integrated during 200 yr with annual mean forcing to obtain a steady state (leading to an autonomous problem after linearisation). Additional surface restoring is used for temperature and salinity, but has been switched off in the linearized equations.



Sea Surface Temperature and Salinity, Atlantic Meridional Overturning Circulation and Meridional Heat Transport at the steady state after a 200 yr integration of the global model.

OPTIMAL INITIAL SSS PERTURBATION

We look for the optimal sea surface salinity perturbation influencing the oceanic circulation in a linearized approach. Optimality is defined with respect to the MOC maximum (48°N). The optimal SSS for this measure is obtained by propagation of the cost function relative to the measure, through the adjoint of the linear tangent model OPATAM (Weaver et al., 2003). In addition we constrain the solution (1) to be SSS only, (2) to conserve salt and (3) to be normed (in such optimal linear problem a quadratic norm must be used). The optimal solution can be explicitly written in terms of the two constraints, the adjoint of the linear tangent model and the cost function.

$$\text{Maximisation problem:}\quad \mathrm{Max}\left(\langle F|u(\tau)\rangle\,,|u(0)\rangle\right).$$

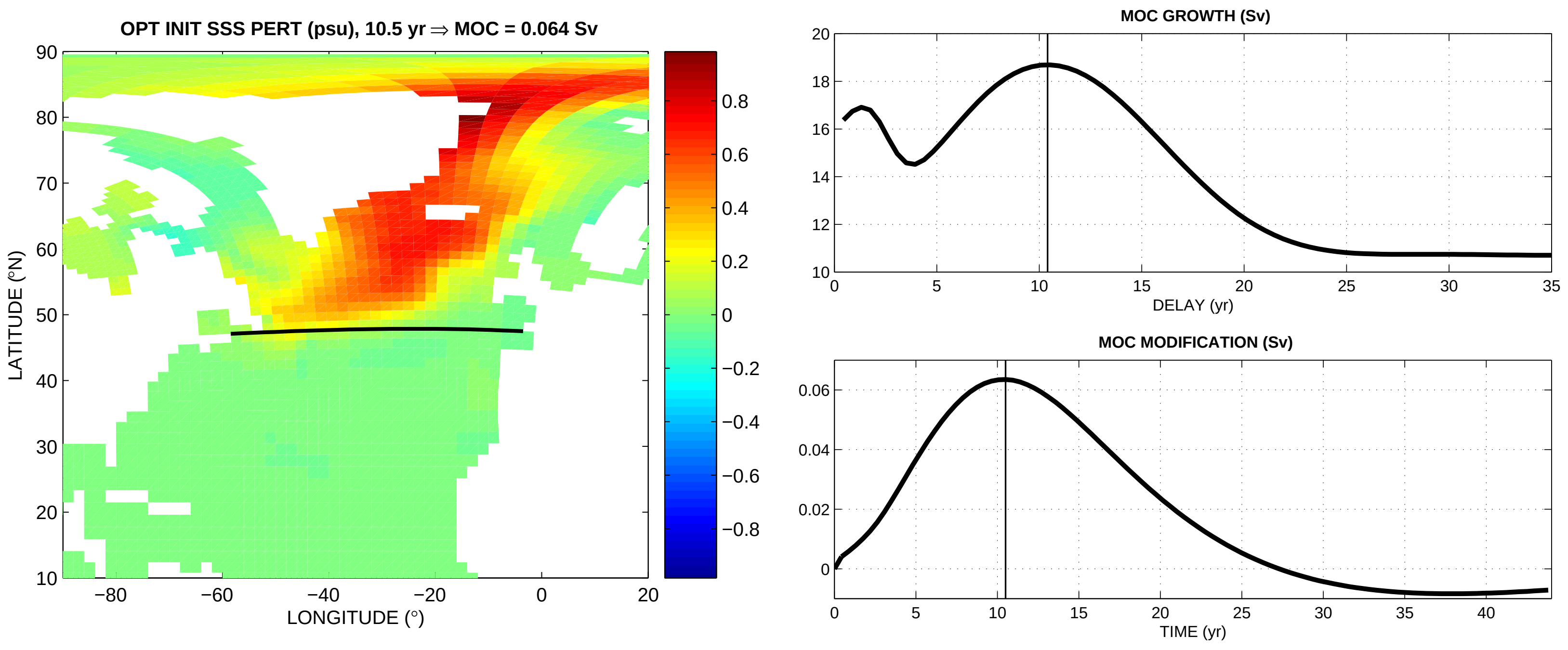
$$\text{Constraints: (1)}\;\;|u(0)\rangle=\mathbf{P}\,|u'\rangle\,,\text{(2)}\;\;\langle C|u(0)\rangle=0\text{ and (3)}\;\;\langle u(0)|\mathbf{S}|u(0)\rangle=1.$$

$$\text{Perturbation propagation:}\quad |u(\tau)\rangle=\mathbf{M}(\tau)\,|u(0)\rangle\,.$$

$$\Rightarrow \textit{Explicit solution:}\quad |u'\rangle=(2\gamma_1)^{-1}\left(\mathbf{N}^{-1}\mathbf{P}^{\dagger}\mathbf{M}^{\dagger}(\tau)\,|F\rangle-\gamma_2\mathbf{N}^{-1}\mathbf{P}^{\dagger}\,|C\rangle\right),$$

$$\text{with }\mathbf{N}=\mathbf{P}^{\dagger}\mathbf{S}\mathbf{P},\,\gamma_1=\mathrm{fct}\left(\mathbf{M}(\tau),|F\rangle\,,|C\rangle\,,\mathbf{N},\mathbf{P},\gamma_2\right)\;\text{ and }\gamma_2=\mathrm{fct}\left(\mathbf{M}(\tau),|F\rangle\,,|C\rangle\,,\mathbf{N},\mathbf{P}\right).$$

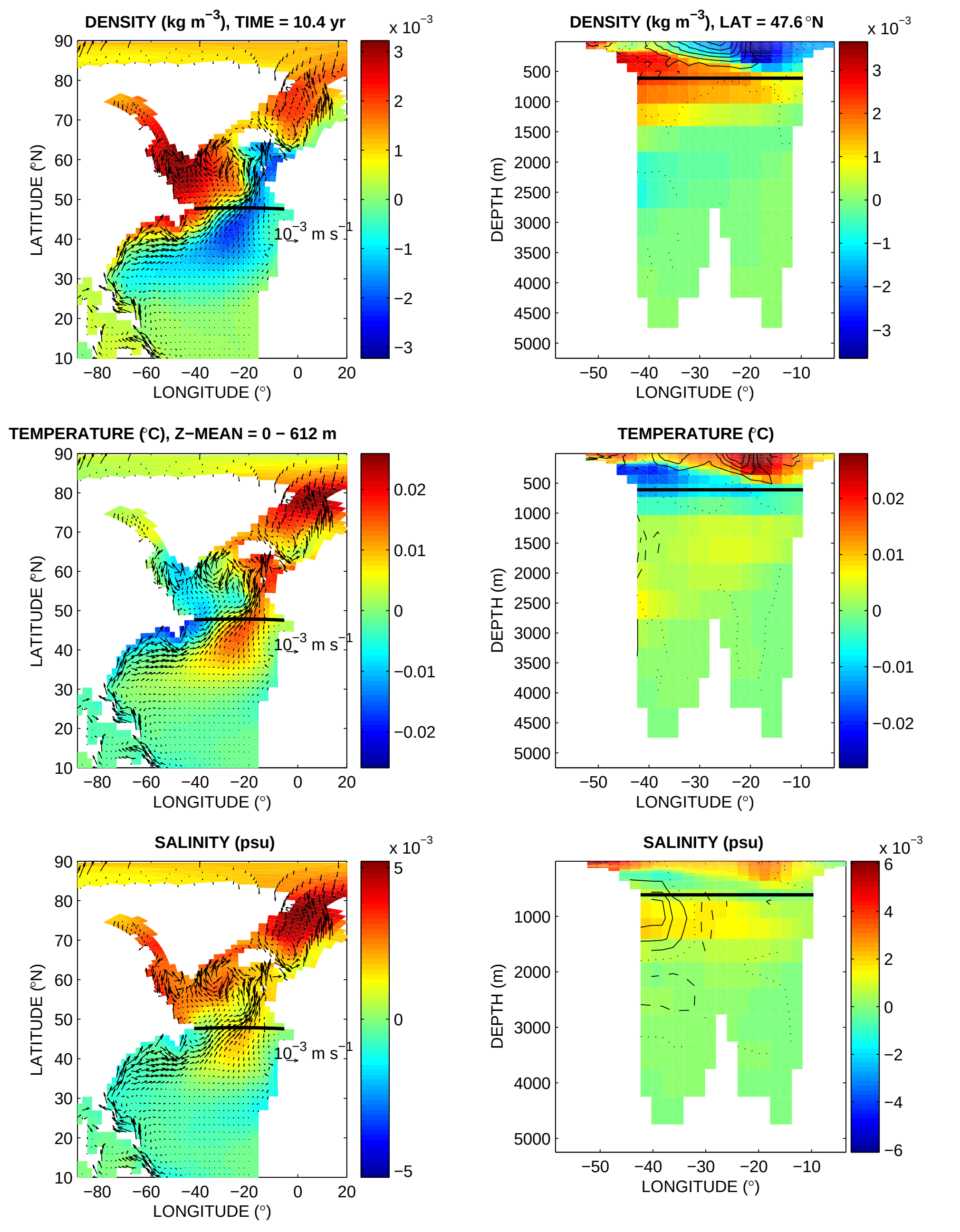
The solution depends on the integration time of the adjoint model: we choose to examine the most efficient growth in time.



Optimal SSS structure modifying the MOC. The response has a maximum at 10.4 yr, confirmed by the integration of the linear tangent model with the optimal structure for initial conditions.

FINITE TIME GROWTH MECHANISM

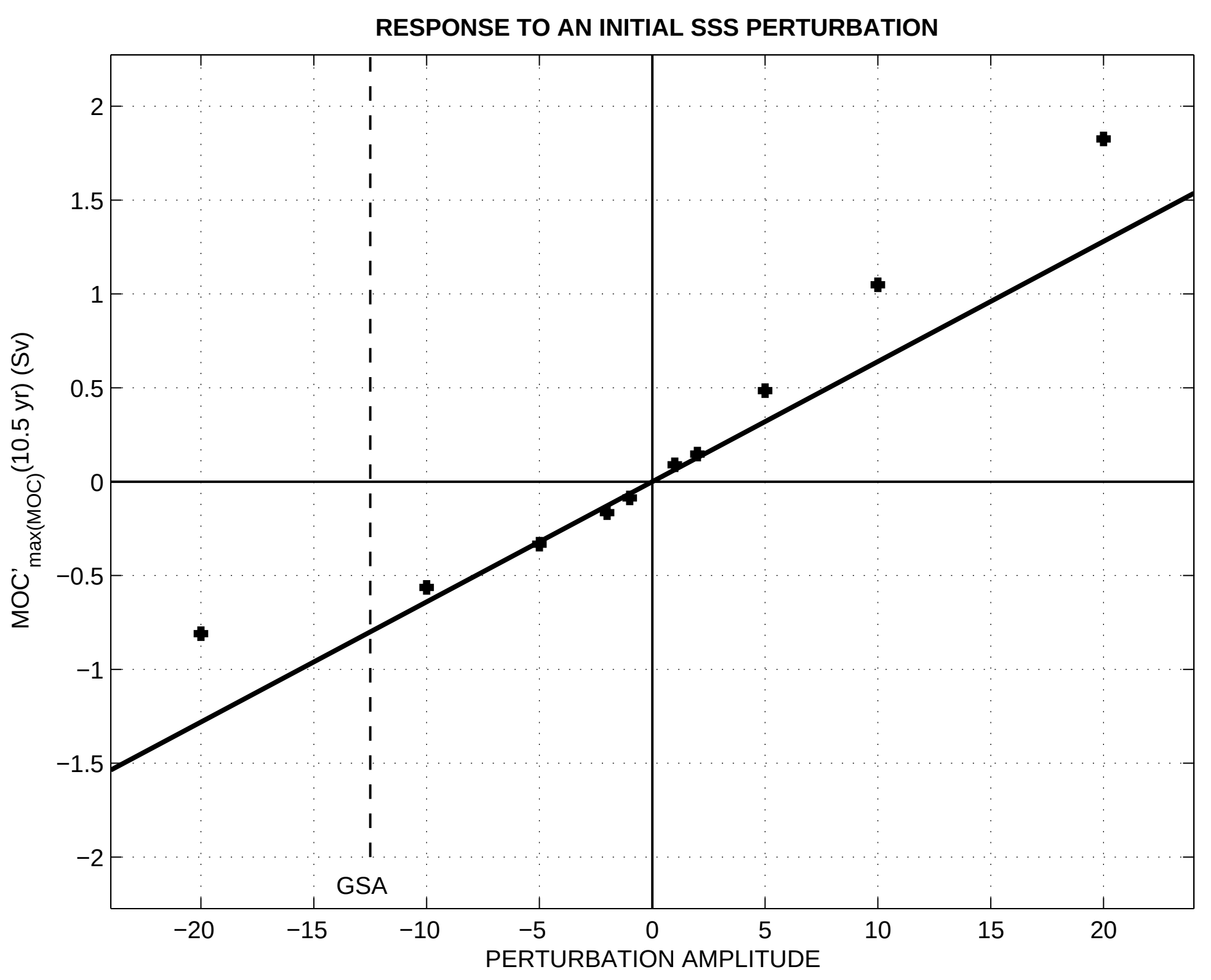
The salinity anomaly in the Irminger sea creates a strong meridional density gradient in the first 1000 meters. This gradient is increased during 10.4 yr by the salty water stored in the Artic sea which supplies in salt the Irminger Sea through the Denmark Strait and Iceland-Scotland ridges. The meridional density gradient created in the North Atlantic induces eastward velocities at the latitude of the MOC maximum. The associated advection, by interaction with the mean zonal temperature gradient, generates an eastward temperature anomaly gradient, that produces northward surface and southward bottom circulation through the thermal wind relation. A similar mechanism is invoked for interdecadal oscillations (Colin de Verdière and Huck, 1999; Te Raa and Dijkstra, 2002).



Linear model integration of the optimal SSS perturbation after 10.4 yr. (left) Density, temperature, salinity, and velocity perturbations in the upper 600 m. (right) 48°N section with contoured fields of zonal, merididional and vertical velocities; CI respectively 5×10^{-5} and 10^{-9} m s^{-1}.

LINEAR VS NONLINEAR TIME INTEGRATIONS

In order to validate the linear approach, we have compared the linear and nonlinear time integrations initialized by the optimal SSS perturbation for different amplitudes ranging from -20 to 20 psu (confined in the upper 10 m). Relative differences in MOC response are between 4% and 58%. The nonlinear integrations show an asymmetry between positive and negative perturbations, that increases with the perturbations amplitude: this may be due to the feedback of density anomalies on the vertical mixing (i.e. positive anomalies enhance vertical mixing, hence deep water formation, resulting in stronger MOC than in the linear model). This comparison ensures that the nonlinear evolution of the linear optimal perturbation can be approximated by the linear model in such amplitude range, but not that this pattern is the optimal perturbation in the full nonlinear problem (Mu et al., 2004).



Optimal response of the meridional overturning circulation intensity, as a function of the optimal initial perturbation amplitude (maximum SSS anomaly in psu), according to the linear (solid line) and the nonlinear time integrations (crosses). The vertical dashed line corresponds to a typical amplitude of Great Salinity Anomalies (Belkin et al., 1998).

CONCLUSIONS

Optimal initial surface salinity perturbations modifying the Atlantic Meridional Overturning Circulation have been obtained, and the associated finite time growth has been described. The optimal pattern corresponds to an anomaly in the Artic and Irminger seas and leads to an 0.8 Sv MOC modification for a salinity perturbation equivalent to Great Salinity Anomalies (0.5 psu on 250 m). Because we have studied the optimal perturbation, we know that this finite time growth is the upper bound for modification of the MOC. In addition, we have shown that for such perturbations, the linear model response is a good approximation of the nonlinear evolution. To better understand the optimal structure, delay and growth mechanism, we are now looking for the eigenmodes of the linear and adjoint models. Note that the the optimal pattern and delay are very different when computed for maximizing the poleward heat transport (Sévellec et al., 2008).

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Florian Sévellec, Yale University, Dept. of Geology and Geophysics, New Haven, CT 06520-8109, USA – florian.sevellec@yale.edu – http://www.locean-ipsl.upmc.fr/∼fsevlod/