On the mechanism of the centennial thermohaline oscillations

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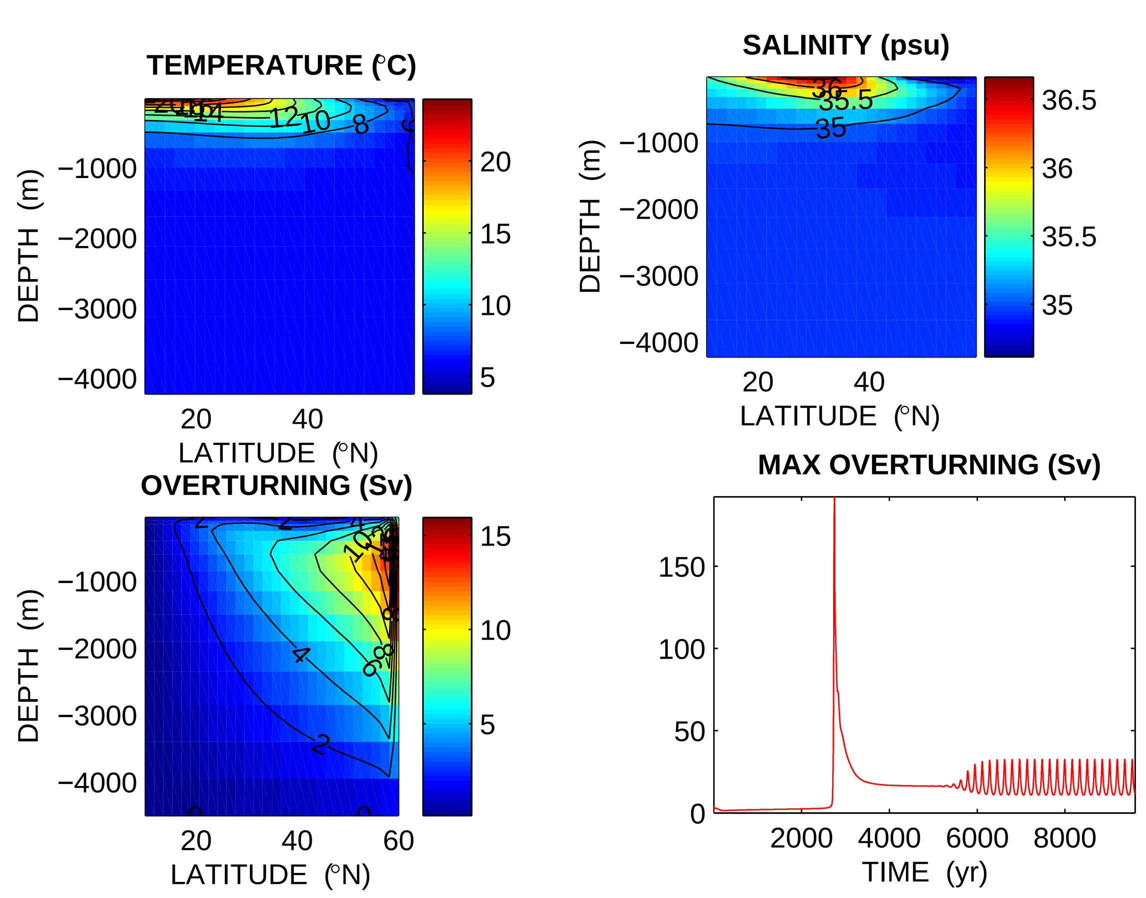
INTRODUCTION

Centennial scale variability is ubiquitous in historical records of temperature and proxy records in sediments and ice cores. As the slow component of the Earth's climate system, the ocean circulation is a potential candidate for generating oscillations on such long time scales. We developp this idea through the analysis of the stability of the ocean circulation in a hierarchy of simplified ocean models (one- and two-dimensional), using linear stability analysis and density variance budgets in order to better understand the oscillation mechanism.

LATITUDE-DEPTH MODEL

$$\partial_t T = -J(\psi, T) + K_H \partial_y^2 T + K_V \partial_z^2 T + \mathcal{C}, \quad \text{Temperature evolution}$$
$$\partial_t S = -J(\psi, S) + K_H \partial_y^2 S + K_V \partial_z^2 S + \mathcal{C}, \quad \text{Salinity evolution}$$
$$\kappa v = -\rho_0^{-1} \partial_y P, \quad \text{Linear friction equation (Wright and Stocker, 1991)}$$
$$\partial_z P = -\rho g, \quad \text{Hydrostatic equation}$$
$$\partial_y v + \partial_z w = 0, \quad \text{Continuity equation}$$
$$\int_{-H}^{0} P dz = 0, \quad \text{Baroclinicty condition}$$
$$\rho = \rho_0 \left[1 - \alpha(T - T_0) + \beta(S - S_0)\right], \quad \text{Density equation}$$
$$K_V \partial_z T(y) = \gamma h_m \left(T^*(y) - T(y)\right), \quad \text{Temperature boundary condition}$$
$$K_V \partial_z S(y) = FW(y), \quad \text{Salinity boundary condition}$$

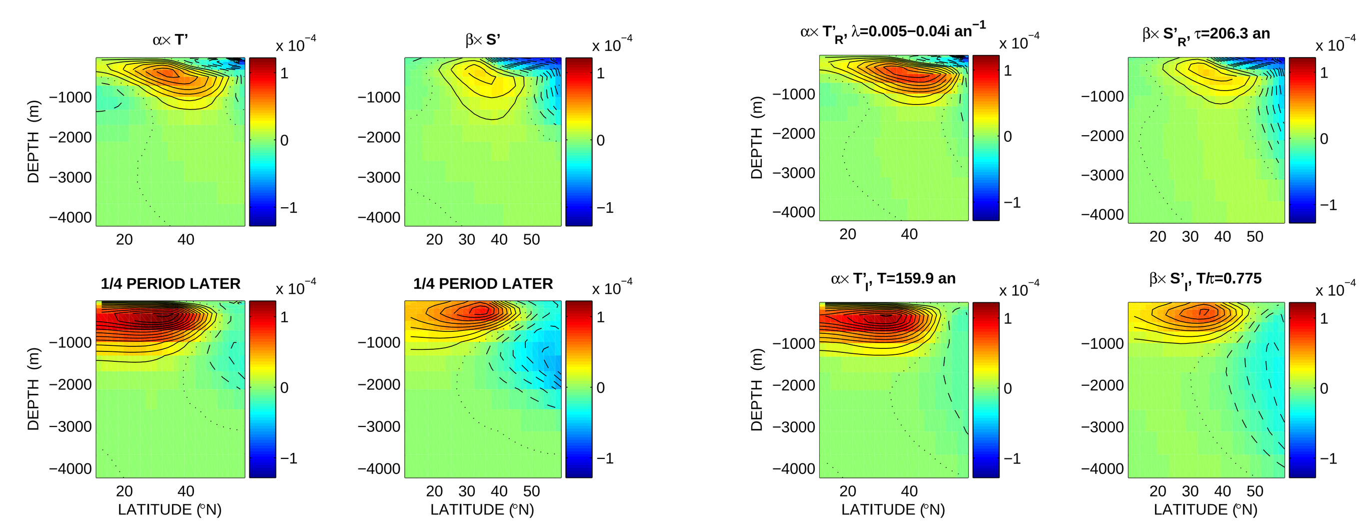
Our control parameter for the direct integration experiments is the freshwater flux intensity (F_0). We explored the range 70–100 cm yr^{-1}. After a Hopf bifurcation (around 79 cm yr^{-1} without convection and 92 cm yr^{-1} with convection) the direct integration of our model reveals centennial variability, this variability persists with and without convection (in the following presentation we deal with the case without convection).



Temperature, salinity and overturning averaged over the period; time series of the maximum of the overturning streamfunction. There is perpetual oscillation for the case without convection at F_0=80 cm yr^{-1} of freshwater flux intensity.

Temperature and salinity anomalies are well correlated. However the density is dominated by the salinity. It is mainly advected by the mean flow; the period is 171 yr with a growing time scale of 206 yr.

The linear stability analysis reveals that the most unstable eigenmode has the same properties. The eigenvalue corresponds to a 160 yr period and a 206 yr growing time scale.

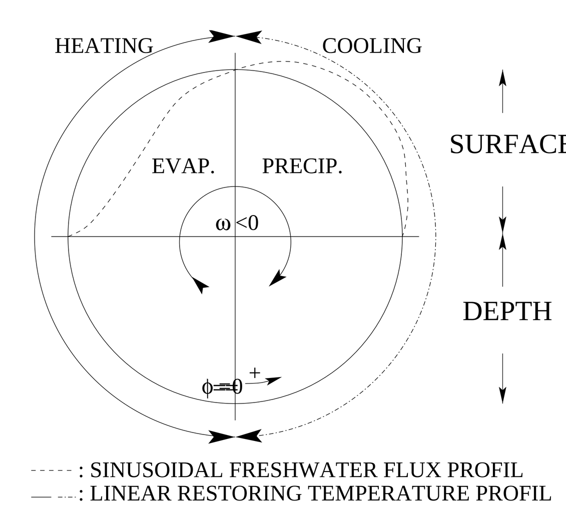


(left) Temperature and salinity anomalies of the 171 yr oscillation of the nonlinear model integration (both in density units). Snapshots are given at a time and a quarter-period later.(right) Most unstable linear eigenmode (evolving as: $X_R \rightarrow X_I \rightarrow -X_R \rightarrow -X_I \rightarrow X_R$, with $X = \{T', S'\}$). Spatial structure and time evolution are very similar to the nonlinear anomaly.

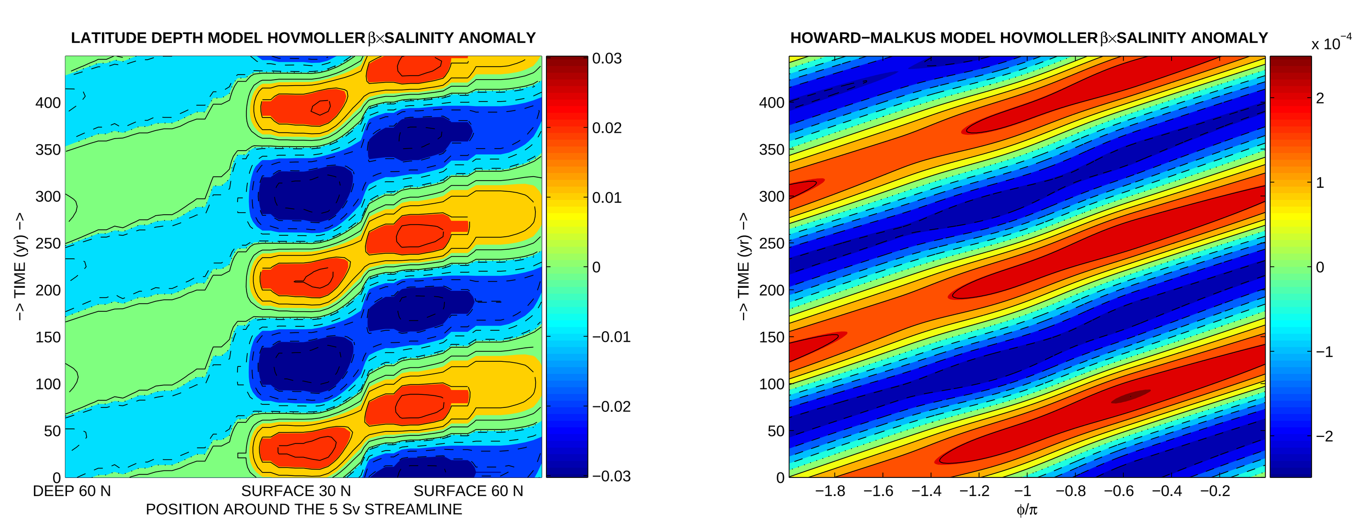
HOWARD-MALKUS LOOP MODEL

The propagation of the anomaly around the overturning cell suggests that a minimal model could be the 1D Howard-Malkus Loop oscillator (Howard, 1971; Malkus, 1972).

$$\partial_t T + \omega \partial_\phi T = r_T \left(T_0 G^T(\phi) - T\right)$$
$$\partial_t S + \omega \partial_\phi S = -\frac{F_0 S_0}{h} G^S(\phi)$$
$$\omega = -\int_0^{2\pi} k\left(-\alpha T + \beta S\right) \sin(\phi)\, d\phi$$



The 1D model reproduces fairly well the 2D model oscillation in terms of period, propagation and surface intensification.



Propagation of centennial anomaly (left) around the 5 Sv streamline in the latitude-depth model and (right) around the Howard-Malkus loop model (direct numerical integration for both).

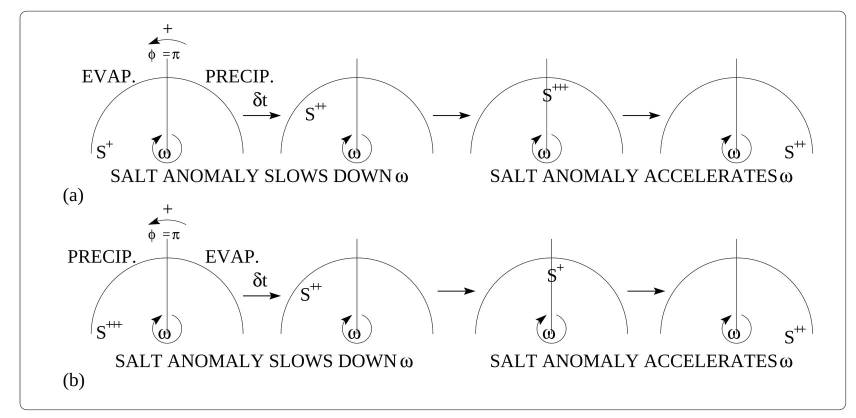
We can compare the impact of temperature and salinity variability on the density variance evolution (Arzel et al., 2004). This density variance budget corresponds to the symmetric part of the evolution equations yielding to growth or damping.

Variance term	nonlinear	linear	malkus
$-<\overline{\rho' J(\psi', \overline{\rho})}> / <\overline{\rho'^2}>$	**0.000**	**0.001**	**–0.001**
$<\overline{D'_\rho \rho'}> / <\overline{\rho'^2}>$	**–0.070**	**–0.072**	**–0.002**
$\alpha^2\rho_0^2 <\overline{F'_T T'}> / <\overline{\rho'^2}>$	–0.026	–0.029	–0.005
$-\alpha\beta <\overline{F'_T S'}> / <\overline{\rho'^2}>$	0.096	0.094	0.008
$-\alpha\rho_0 <\overline{F'_T \rho'}> / <\overline{\rho'^2}>$	**0.070**	**0.065**	**0.003**
$<\overline{\partial_t \frac{\rho'^2}{2}}> / <\overline{\rho'^2}>$	**0.000**	**–0.006**	**0.000**

This budget focus on the restoring surface term, and specifically on the coupled, for the density, temperature-salinity part, which balance the diffusion term.

After a modal decomposition (around the loop) we can analytically evaluate the period and the growth/damping of the oscillation with the eigenvalue ($\lambda = \lambda_r + i\lambda_i$) of linear stability analysis.

We found analytically that $\lambda_r > 0$ for our parameters. The salt anomaly can be enhanced by its induced circulation. This mechanism is consistent with the variance budget. Indeed, the restoring surface temperature increases the density anomaly as it decreases the temperature anomaly. The overturning circulation is modified accordingly and the salinity anomaly is enhanced.

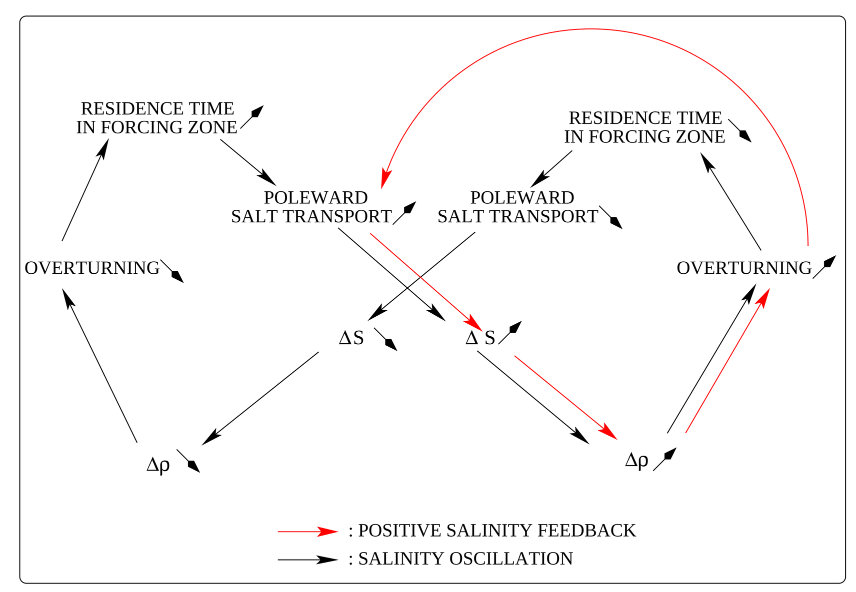


Growth (a) or damping (b) of the salinity anomaly when passing through the freshwater forcing zone and impacting the overturning ω.

The period can be analytically determined: $\lambda_i \simeq \omega$. We can also estimate a criterion of oscillation (Sévellec et al., 2004):

- τ_{SF} corresponding to the freshwater forcing time scale,
- τ_O is the overturning time scale.

If $\tau_{SF} < \tau_O$ there is centennial oscillation.
If $\tau_{SF} > \tau_O$ there is the positive salinity feedback.



Schematic representation of the different mechanism between the salinity oscillation regime (black arrow) and the positive salinity feedback (red arrow).

CONCLUSION

A direct integration of a latitude-depth model produces a centennial oscillation. Linear stability analysis clearly represents the anomaly and its propagation; The budget of density variance reveals the role of the restoring surface boundary condition on temperature as a source term. Since the anomaly is especially advected by the mean flow, we decided to approximate the problem by the simple Howard-Malkus oscillator. This permits us to understand the mechanisms for both growth and oscillation. The latter is strongly related to the positve salinity feedback.

References

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