Sensitivity of Oceanic Fronts to Nonlinearities of Equation of State Investigated Using Numerical Experiments

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Context

Transition zones between saline warm subtropical water and cold fresh subpolar water arise abruptly. These boundaries are called oceanic fronts and have similar structures in the North Atlantic Ocean, the North Pacific Ocean and the Southern Ocean, suggesting that the same processes lead to these frontal structures. The nonlinearities of the equation of state for seawater – the relation that gives density as a function of pressure, salinity, and temperature – are expected to constraint these fronts. To test this hypothesis, we are developing an idealized triple-gyre configuration with the ocean global circulation model NEMO (Nucleus for European Modelling of the Ocean). This configuration includes a continental slope along the coastline with a terrain following coordinate, except at the equator where an open boundary with a no meridional flow condition is imposed.

Objectives

- We analyzed the sensitivity of transition zones to perturbations of the nonlinear equation of state.
- We ran 5 experiments, varying the cabbeling parameter λ_1 from $3.952 \cdot 10^{-2}$ to $7.952 \cdot 10^{-2}$ $(°C)^{-1}$, and analyzing the resulting stratification and circulation.
- We are building a reference NEMO triple gyre configuration.

The basin configuration

Description of the grid

- Mercator grid
- Continental slopes (2 km deep at the coast, 4 km deep at the bottom)
- Coarse resolution (for the moment)
- 36 vertical levels
- Terrain following vertical coordinates
- Symmetry condition at the equator (no meridional flux)

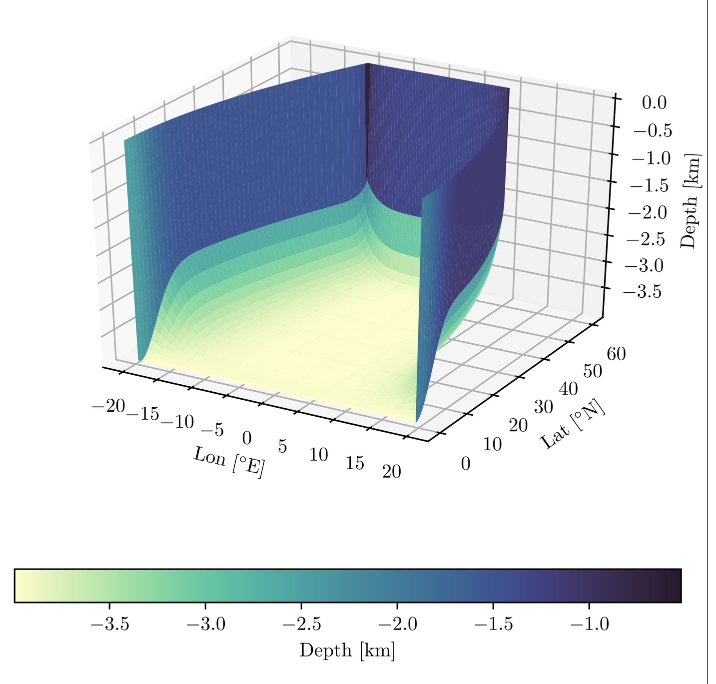

Figure 1. Bathymetry of the basin.

Description of the forcing fields

- Restoring temperature
- Penetrative solar radiation
- Restoring salinity (used here) or E-P flux
- Zonal wind stress

Resulting fields

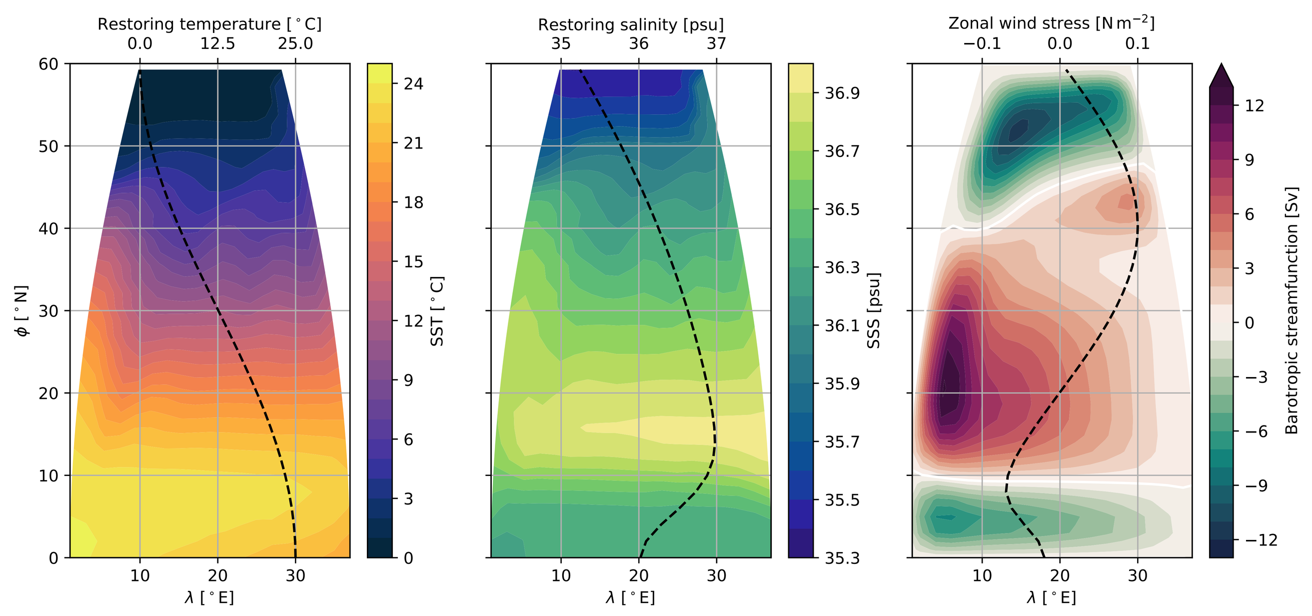

Figure 2. Sea Surface Temperature, Sea Surface Salinity, Barotropic Streamfunction. The forcing fields are represented in dashed lines.

Results

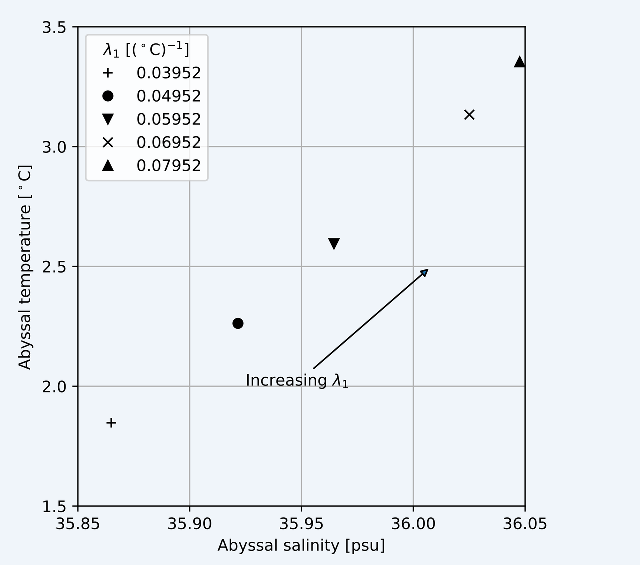

Figure 3. T-S diagram for the abyssal water for the fives values of λ_1. Both the temperature and the salinity increase with λ_1: the convective region is displaced to the south.

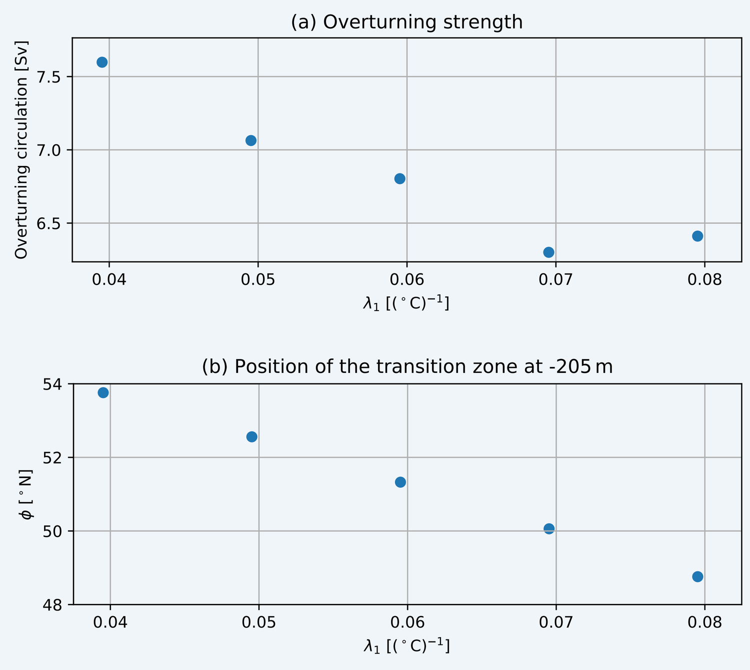

Figure 4. (a) Overturning strength function of the cabbeling term λ_1. The overturning circulation decreases when cabbeling is more important. (b) Position of the transition zone at a depth of 205 m and a longitude of 23 °E. The transition zone corresponds to the northern part of the convective region, and its latitude decreases when λ_1 increases, leading to the change of abyssal water properties.

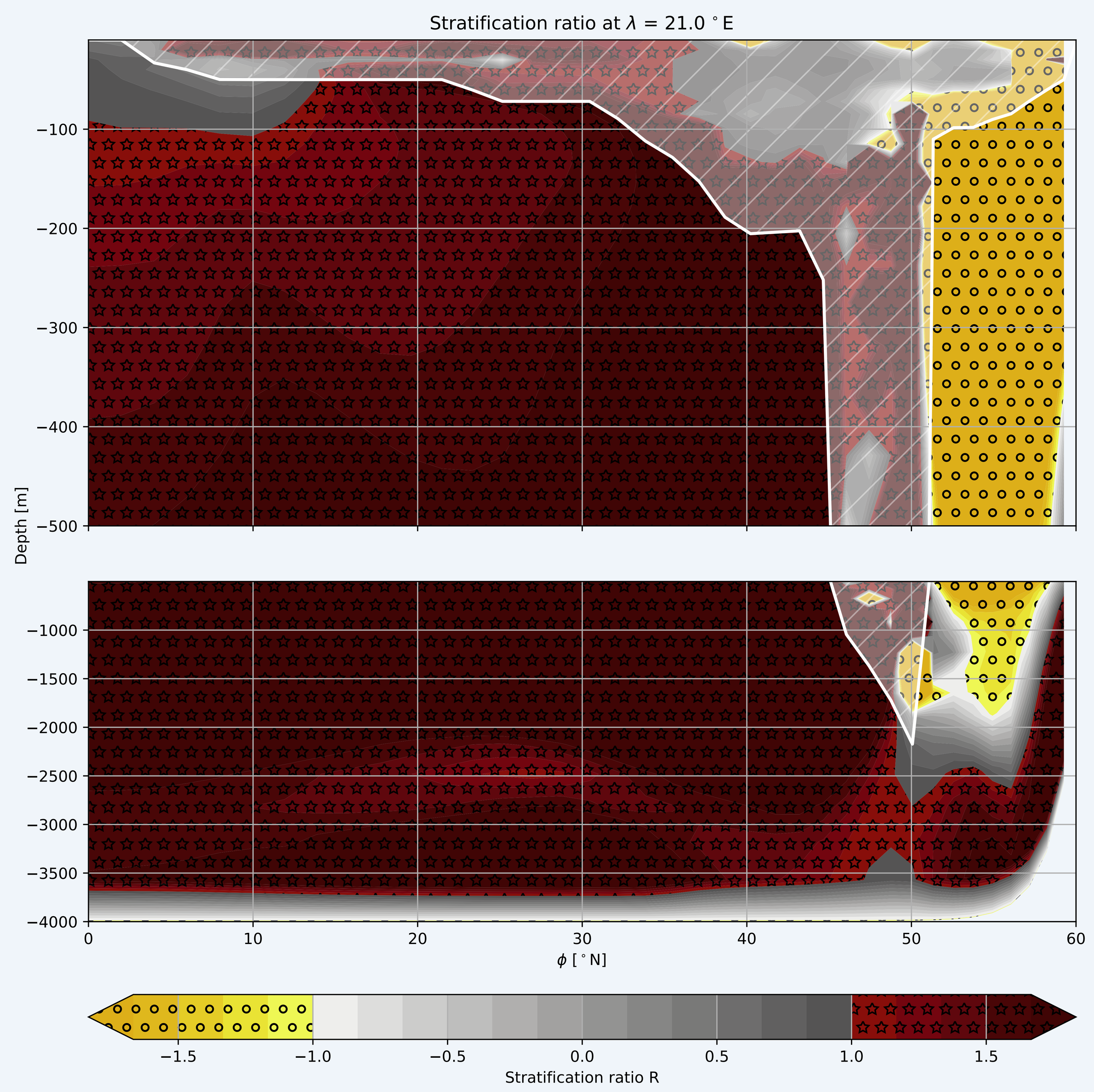

Figure 5. Section of the stratification ratio. The red colors (star background) represent alpha-ocean stratified by the temperature only, the yellow areas (round background) are the beta-ocean stratified by the salinity only and the gray zones are doubly stratified. The white line represents the diagnostic mixed layer depth and the white dashed area is the mixed layer.

Conclusion

With the increase of the cabbeling parameter λ_1, the stratification becomes less sensitive to the temperature more south in the basin. As the northern area is stabilized by a strong halocline due to fresh surface water, the salinity control of the stratification pushes the transition zone to the south. This is accompanied by a more southern convection zone and thus a creation of warmer and saltier deep water. An unexpected effect is the reduction of the overturning strength with cabbeling.

Thermodynamic properties

The nonlinear equation of state

We use the simplified nonlinear equation of state proposed by *Roquet et al.* (2015).

$$\rho(\Theta, S_A, Z) = \overline{\rho}(Z) - \frac{C_b}{2}(\Theta - \Theta_0)^2 - T_h Z \Theta + b_0 S_A \quad (1)$$

The term $\overline{\rho}(Z)$ does not play a role in the ocean dynamics.

$$\alpha = \frac{1}{\rho_0}[C_b(\Theta - \Theta_0) + T_h Z] \quad \text{and} \quad \beta = \frac{b_0}{\rho_0} \quad (2)$$

The stratification ratio

The stratification ratio R determines if the water column is stratified by the temperature only ($R > 1$), by the salinity only ($R < -1$) or doubly stabilized ($-1 \leq R \leq 1$).

$$R = \frac{N_\Theta^2 - N_{S_A}^2}{N^2} = \frac{\alpha \frac{\partial \Theta}{\partial z} + \beta \frac{\partial S_A}{\partial z}}{\alpha \frac{\partial \Theta}{\partial z} - \beta \frac{\partial S_A}{\partial z}} \quad (3)$$

The thermal expansion α is proportional to the temperature (cabbeling effect) while the haline contraction is constant. Thus on warm and tempered regions, the stratification is mainly controlled by the temperature (alpha-ocean (*Carmack*, 2007)). But at high latitude, the lower value of α associated with the halocline lead to a salinity controlled stratification (beta-ocean).

A T-S profile with a stratification ratio $R < -1$ can become unstable when the cabbeling term is perturbed, leading to a different polar stratification: the nonlinearities of the equation of state are an essential parameter.

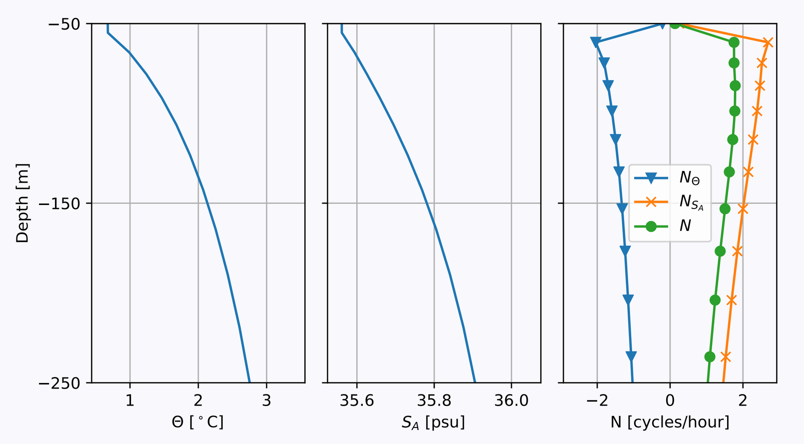

Figure 6. Temperature, salinity and buoyancy frequencies profiles in a beta-ocean (19 °E, 55 °N).

Reference numerical values of the parameters

$$C_b = 9.851 \cdot 10^{-3}\,\mathrm{kg\,m^{-3}\,K^{-2}}$$
$$\Theta_0 = -6.801\,°\mathrm{C}$$
$$T_h = 2.478 \cdot 10^{-5}\,\mathrm{kg\,m^{-4}\,K^{-1}}$$
$$b_0 = 7.6554 \cdot 10^{-1}\,\mathrm{kg\,m^{-3}\,(g\,kg^{-1})^{-1}}$$
$$\rho_0 = 1026\,\mathrm{kg\,m^{-3}}$$

NEMO simplified EOS equivalence

Implemented equation of state:

$$\rho(\Theta, S_A, z) = \rho_0 - a_0\left(1 + 0.5\lambda_1 \Delta\Theta + \mu_1 z\right) \cdot \Delta\Theta + b_0 \cdot \Delta S \quad (4)$$

$$\Delta\Theta = \Theta - 10 \quad \text{and} \quad \Delta S = S_A - 35$$
$$C_b = a_0 \cdot \lambda_1 \quad \text{and} \quad T_h = a_0 \cdot \mu_1$$
$$\Theta_0 = 10 - 1/\lambda_1 \quad \text{and} \quad a_0 = 1.655 \cdot 10^{-1}\,\mathrm{kg\,m^{-3}\,K^{-1}}$$

xbasin and xnemogcm python packages

xnemogcm

https://github.com/rcaneill/xnemogcm

- Python package interfacing NEMO outputs to xgcm

xbasin

https://github.com/rcaneill/xbasin

- Python package used to deal with terrain-following coordinates on idealized configurations
- Based on NumPy, xarray, xgcm, f2py

Open source projects!

Please feel free to use, fork, and help on these new projects!

References

Carmack, E. C. (2007), The alpha/beta ocean distinction: A perspective on freshwater fluxes, convection, nutrients and productivity in high-latitude seas, *Deep Sea Research Part II: Topical Studies in Oceanography*, *54*(23-26), 2578–2598.

Roquet, F., G. Madec, L. Brodeau, and J. Nycander (2015), Defining a Simplified Yet "Realistic" Equation of State for Seawater, *Journal of Physical Oceanography*, *45*(10), 2564–2579, doi: 10.1175/JPO-D-15-0080.1.