Thermohaline overturning circulation in the Mediterranean

The effect of narrow and shallow sea-straits on circulation in box models and an OGCM

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Introduction

The Mediterranean Sea, despite its small size, exhibits thermohaline overturning circulation and deep-water formation (DWF). Periodically, there have been prolonged periods without DWF during which oxygen-depleted, organic-rich sediments, sapropels, have been deposited. True sapropels are only found in the Eastern Mediterranean (EMed) and not in the west (WMed).

Figure 1: Sapropel depositions at Monte Gibliscemi (Sicily)

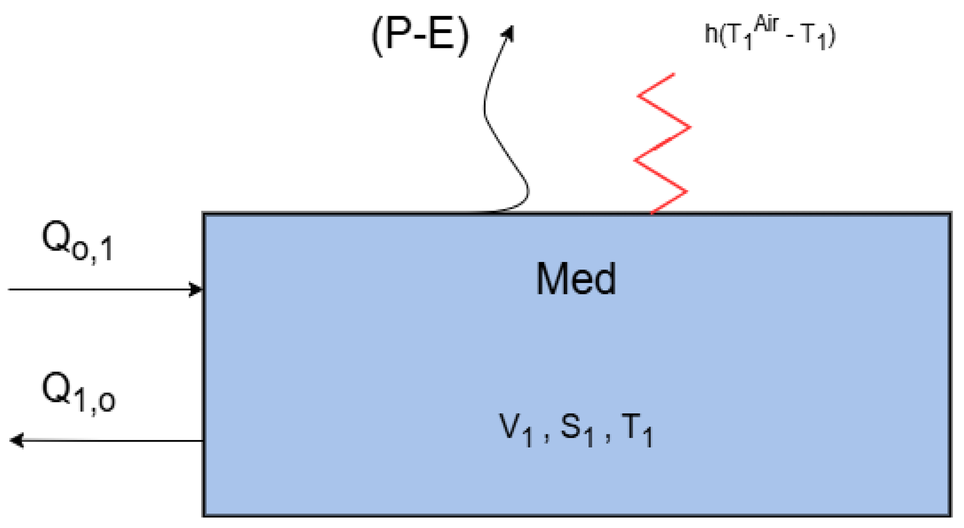
Objectives

In context of sapropel deposition and variations in DWF, our goal is to mechanistically study the transient response to climate variability, using the palaeoceanographic record. As a first step, we will elucidate the role of the Strait of Sicily.

Methods

We will make use of box models to study the transient behaviour of the circulation in the Mediterranean. We continue the work of [1], but here we will make a sub-division.

1-box representation:



2-box representation:

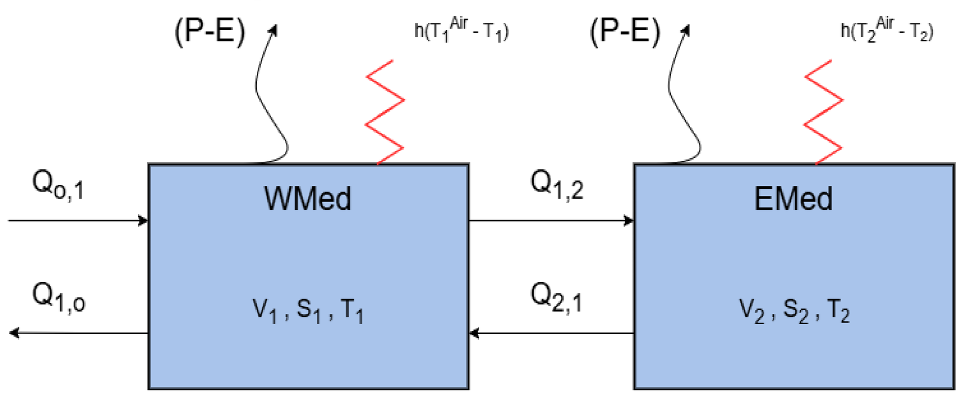


Figure 2: Schematic representation of the model

Equations:

$$V_W \frac{dS_W}{dt} = Q_{o,1}S_o - Q_{1,o}\,S_W - Q_{1,2}S_W + Q_{2,1}S_E$$

$$V_W \frac{dT_W}{dt} = Q_{o,1}T_o - Q_{1,o}\,T_W - Q_{1,2}T_W + Q_{2,1}T_E$$

$$V_W \frac{dS_E}{dt} = Q_{1,2}S_W - Q_{2,1}S_E$$

$$V_W \frac{dT_E}{dt} = Q_{1,2}T_W - Q_{2,1}T_E$$

with the density driven flux:
$Q = \lambda(\rho_1 - \rho_2)\ \ ;\rho_1 \geq \rho_2$

And compensating fluxes:
$Q_{comp} = Q_{out} + eA$

Steady-state solution

When only including salinity and assuming constant evaporation, constant water properties of the Atlantic Ocean and equal, constant hydraulic constants and:

$$\frac{1}{2}A_{Med} = A_{WMed} = A_{EMed}$$

we find that, in steady-state, the following is true for the 2-box representation:

$$S_W^* = S_o + \sqrt{\frac{2eAS_o}{\lambda}}$$

$$S_E^* = S_W^* + \sqrt{\frac{eAS_W^*}{\lambda}}$$

and for the 1-box representation:

$$S_{1B}^* = S_o + \sqrt{\frac{2eAS_o}{\lambda}}$$

In a 2-box model set-up; the western basin will assume the same properties as the entire basin in the 1-box set-up in steady-state. Additionally, the eastern basin will become more saline in the two-box set-up than the western basin. This is a direct consequence of an additional enclosure due to the Strait of Sicily in an already semi-enclosed evaporative basin.

Numerical solution

In a 2-box set-up, we find that the eastern basin becomes much more saline than the western basin and than the entire basin in a 1-box set-up.

The temporal evolution is not the same, the 1-box model reaches steady-state faster than the 2-box model. This is also shown by the fact that the response to perturbations is not the same.

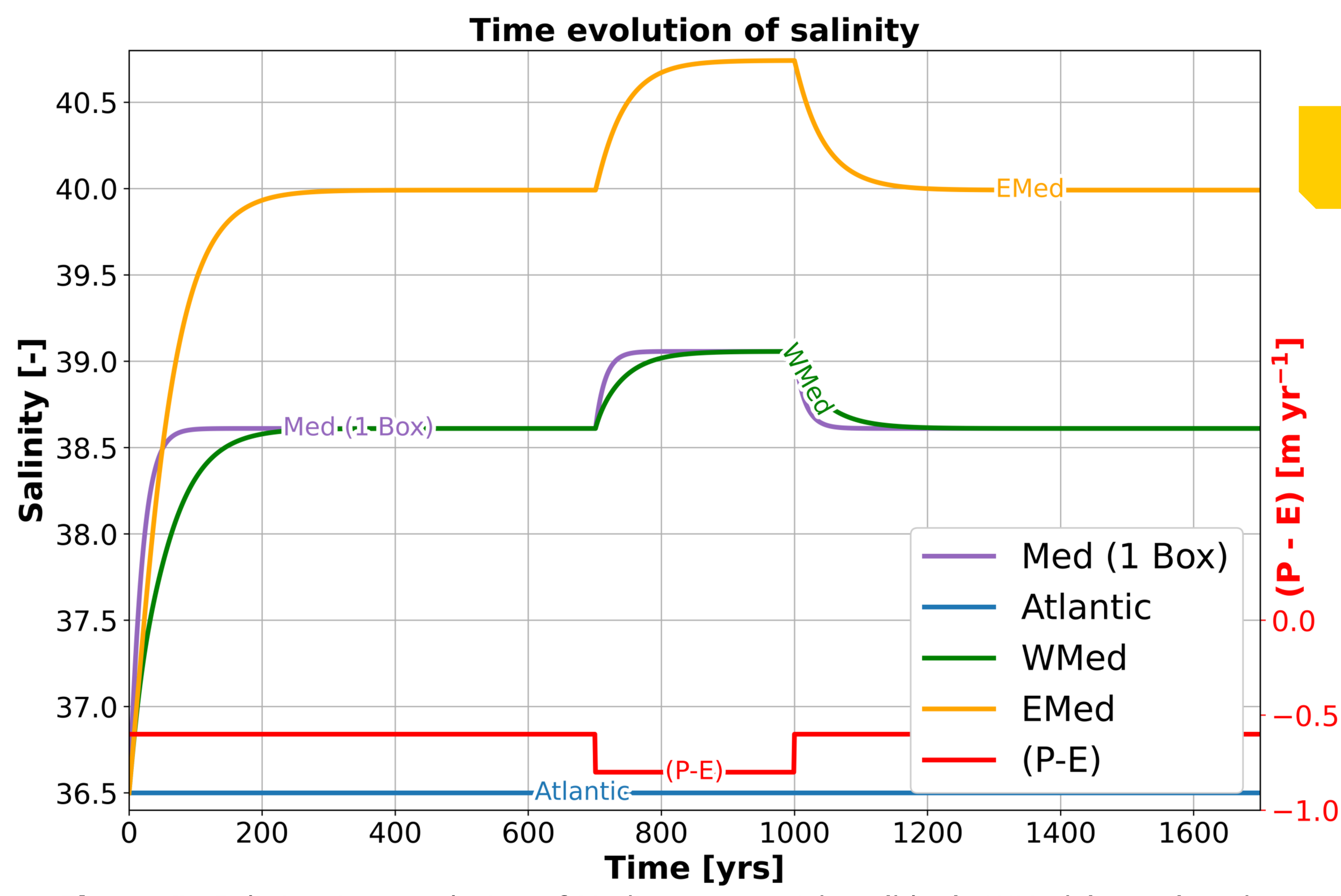


Figure 3: Salinity time evolution of Mediterranean 1 box (blue), WMed (green) and EMed (orange) with constant evaporation (red). At t = 1000 years, a perturbation in evaporation is imposed.

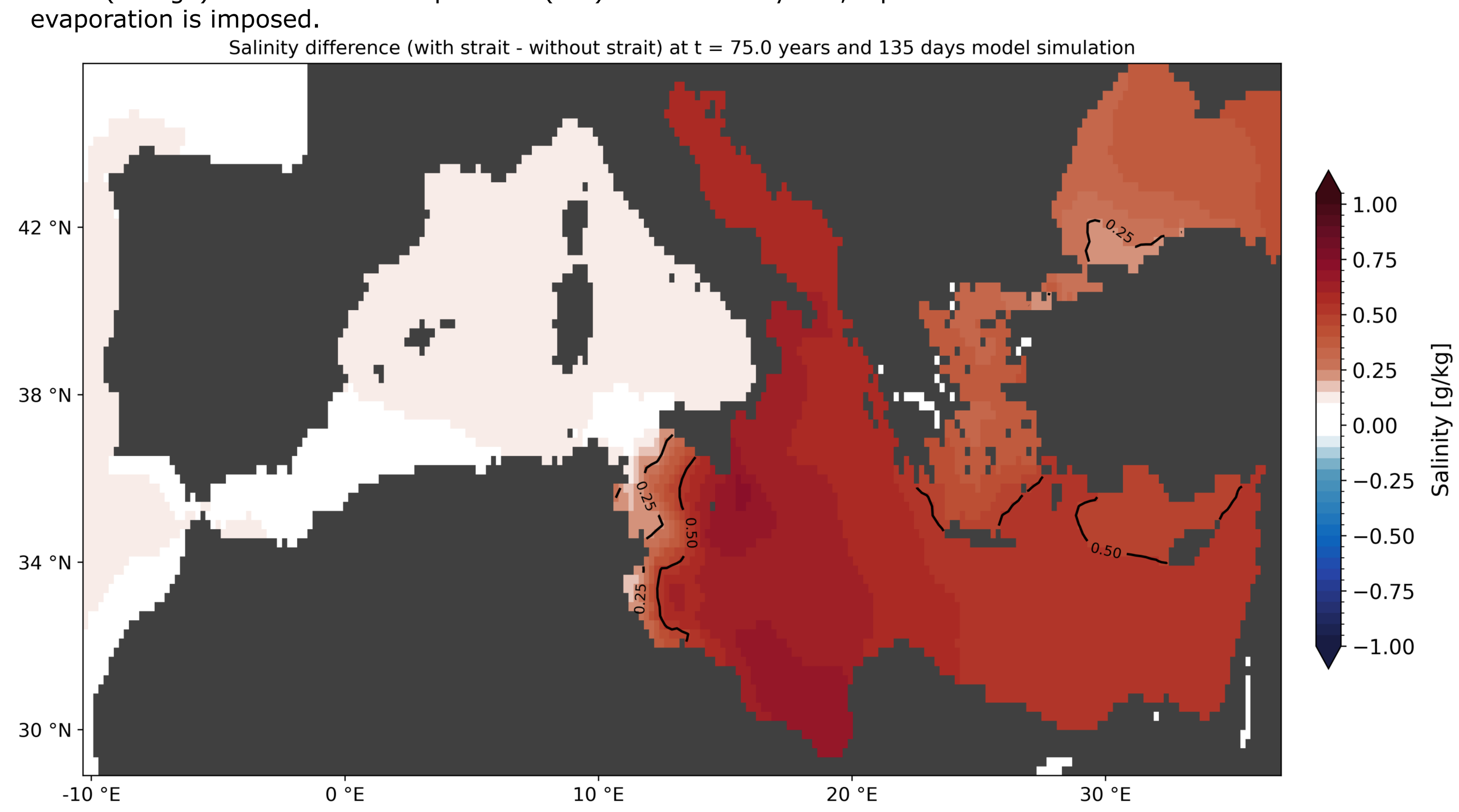


Figure 4: Salinity difference in an OGCM[2] between a simulation with strait and simulation without strait (strong deepening of the Strait of Sicily).

Additionally, in an OGCM[2] (Figure 4), we performed 2 two simulations: 1 with the current topography and 1 with a strong deepening of the Strait of Sicily. Here, we also find that the eastern basin becomes more saline in case with strait than without strait. Also, we see almost no differences in the western basin. Note that the simulation only ran for 75 model years, which could explain the smaller difference in terms of magnitude.

Sensitivity analysis

The 2-box system proves to be stable because there is no feedback with the Atlantic Ocean. However, changes in forcing or incoming Atlantic water do have a linear effect on the Mediterranean Sea.

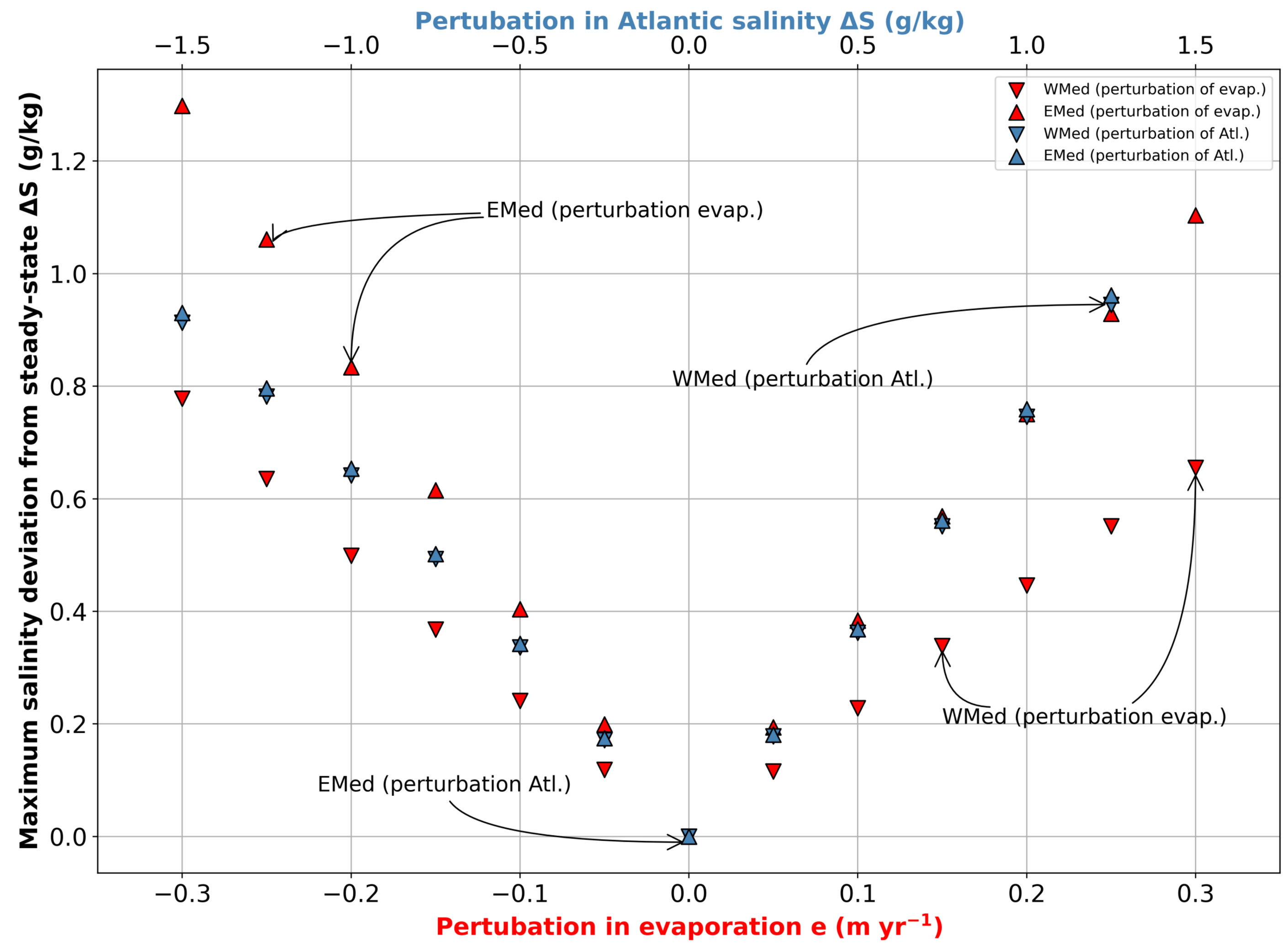


Figure 5: Response of the system to a perturbation (like Figure 3). Here, either the rate of evaporation is changed (red) or the properties of the Atlantic waters are changed (blue) and the response of the WMed (down-pointing triangle) and EMed (up-pointing triangle) is shown.

The larger the perturbation, the larger the deviation from the steady-state is, for both basins. However, there is only a small difference in deviation between the WMed a EMed for Atlantic perturbations (blue triangles). There is a much larger effect on the response to a perturbation for the EMed than for the WMed. Thus, EMed is more sensitive to changes in forcing than WMed.

Next steps

Using a box model approach allows us to:

- Extend the model with more vertical layers to represent characteristic intermediate- and deepwater masses and DWF
- Perform long-duration simulations, with timescales in $t = \mathcal{O}(10^4\text{–}10^5)\ y$ to simulate response to orbital related climate variability
- Study the transient response to changes in the atmosphere, using palaeoceanographic data

[1] Dirksen, J. P., & Meijer, P. (2020). The mechanism of sapropel formation in the Mediterranean Sea: insight from longduration box model experiments. Climate of the Past, 16(3), 933–952. https://doi.org/10.5194/cp-16-933- 2020

[2] Häfner, D., Jacobsen, R. L., Eden, C., Kristensen, M. R. B., Jochum, M., Nuterman, R., and Vinter, B.: Veros v0.1 – a fast and versatile ocean simulator in pure Python, Geosci. Model Dev., 11, 3299–3312, https://doi.org/10.5194/gmd-11-3299-2018, 2018

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