Modelling changes in the Eastern Mediterranean ocean climate for the early Holocene

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1. Introduction

Fig. 1. Sapropel layer in a marine sediment core from the Eastern Mediterranean

During the early Holocene, the circulation of the Mediterranean Sea has undergone considerable changes which are reflected in the occurrence of sapropels (Fig. 1). Sapropels are dark marine sediment layers with high C_{org} content (> 2%) that indicate the presence of oxygen depleted bottom waters.

Hypothesis for sapropel formation:

Stagnation of the deep water caused by a slowdown or shutdown of the thermohaline circulation leads to oxygen depletion in bottom waters and allows the deposition of preserved organic material on the seafloor.

=> Simulation of plausible scenarios leading to a stagnation of deep water using a regional ocean general circulation model

We focus on early Holocene Eastern Mediterranean sapropel S1 which develops over thousands of years (from 9 to 6.5 ka BP).

Approach:

1- baseline paleosimulation for the 9 ka BP time slice with well-ventilated deep waters
2- perturbation experiments to reach a state with stagnating deep water

2. Model description

MPIOM (physics), Marsland et al. 2003

- Primitive equation ocean general circulation model
- Heat fluxes calculated with bulk formulas
- Freshwater fluxes from precipitation and prescribed river runoff
- Evaporation calculated interactively from latent heat flux
- No restoring to surface salinity
- Sponge zone in the Atlantic (WOA hydrography)

Setups:
- 26 km horizontal resolution
- 29 levels
- 36 min time step

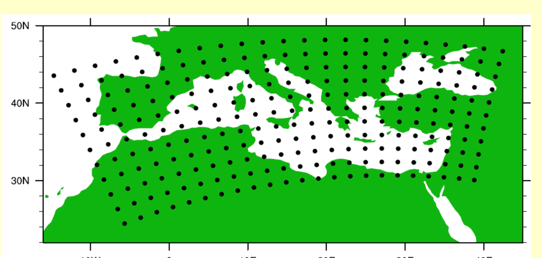

Fig. 2. MPIOM grid, 1 of each 10 grid points represented in each direction.

Atmospheric forcing for MPIOM is derived from Earth System Model (ESM) simulations (see 3. 1).

Time of integration

- MPIOM is run 500 years for the 3 baseline experiments (see 3.3), starting from homogenous water.
- **MPIOM perturbation experiments were started in year 500 of the 9K baseline simulation and run for 400 more years.**

The results shown are averaged over the last 100 years.

3. Baseline simulations description

1- ESM simulations

ESM: ECHAM5(T31L19)-MPIOM-LPJ

- **- CTRL**: control run for the preindustrial climate
- **- 9K**: run for the 9 ka BP time slice (see Fig. 6)
- **- 9Knm**: same as 9K but NO melt water from decaying ice sheets

9K and 9Knm: Bosphorus strait closed, different topography and ice sheet mask, pCO2=260 ppm (vs. 280 ppm for CTRL)

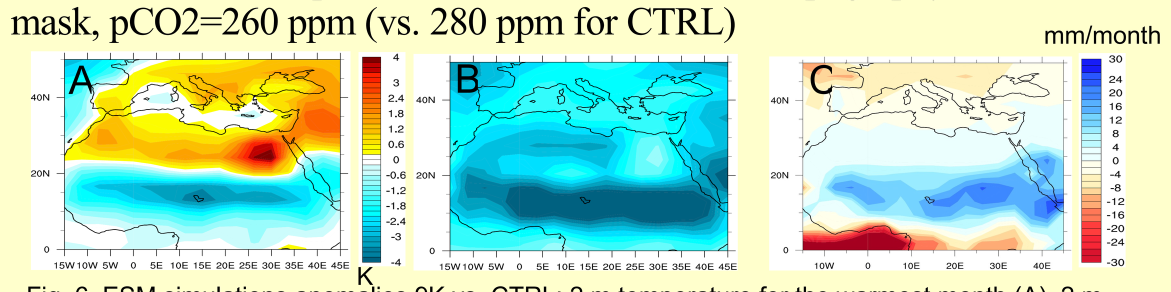

Fig. 6. ESM simulations anomalies 9K vs. CTRL: 2 m temperature for the warmest month (A), 2 m temperature for the coldest month (B) and precipitation (C). Temperature in K, precipitation in mm/month.

2- How do we get the atmospheric forcing for MPIOM?

- Derived from equilibrium simulation with the ESM
- 2 m temperature and dew point temperature anomalies superimposed on NCEP climate
- Wind stress statistically downscaled from the ESM-SLP using NCEP as reference

For paleosimulations: Anomalies (9K - CTRL) are superimposed for both prescribed rivers and hydrography.

3- MPIOM Baseline simulations

CTRL, 9K and 9Knm

4. Present-day ocean climate (CTRL)

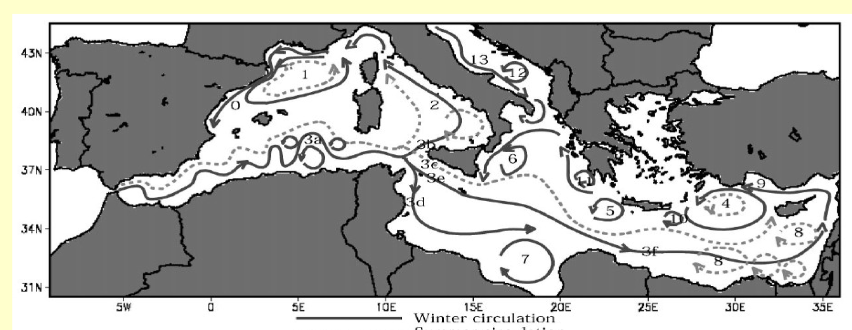

Fig. 3. Observed surface circulation from Pinardi et al. 2000

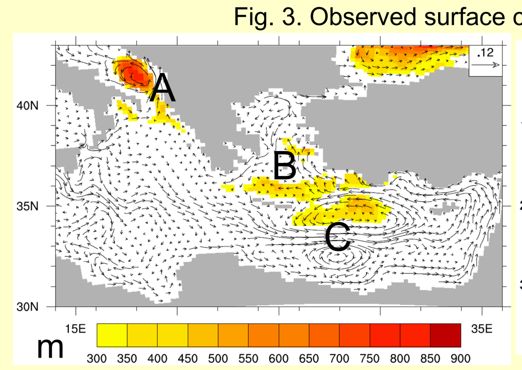

Fig. 4. Sub-surface circulation and mixed layer depth. The arrows represent the yearly mean circulation (m/s) at 27 m of depth; the colour represent the mixed layer depth in March (m).

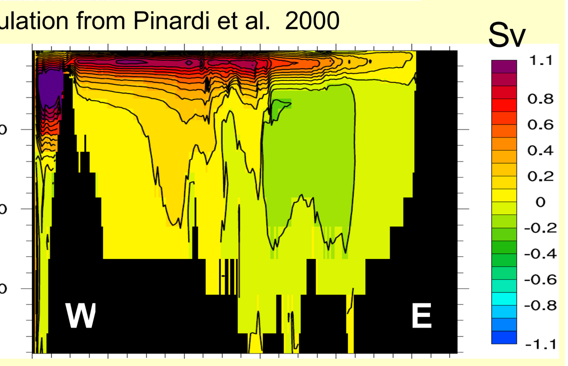

Fig. 5. Zonal overturning stream function (Sv) for the entire Mediterranean. Positive/negative values means clockwise/counterclockwise circulation.

The Fig. 4 shows that the model is able to reproduce the observed surface circulation (Fig. 3) as well as the formation of the Eastern Mediterranean deep water (EMDW) and the Levantine intermediate water (LIW) at the right locations. The EMDW is formed in the Adriatic (A) and in the Aegean (B); the LIW is formed south of Rhodes (C). The EMDW and LIW both contribute to the oxygenation of the eastern basin over the entire water column by driving the thermohaline circulation. The Mediterranean overturning stream function simulated by the model (Fig. 5) shows that the bottom waters are well-ventilated.

5. Results

1- 9K Pre-sapropel well-ventilated state

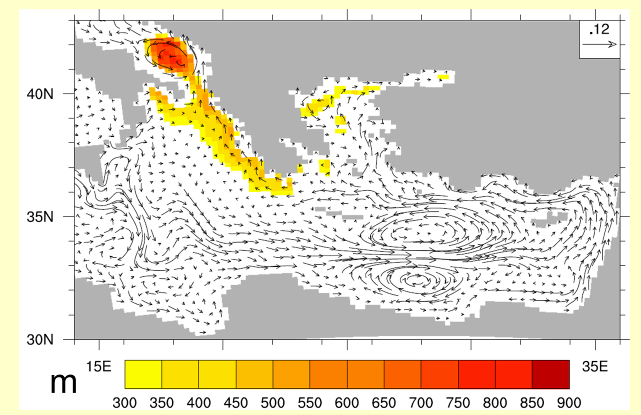

Fig. 7. Sub-surface circulation and mixed layer depth for 9K. The arrows represent the yearly mean circulation (m/s) at 27 m; the color represent the mixed layer depth in March (m).

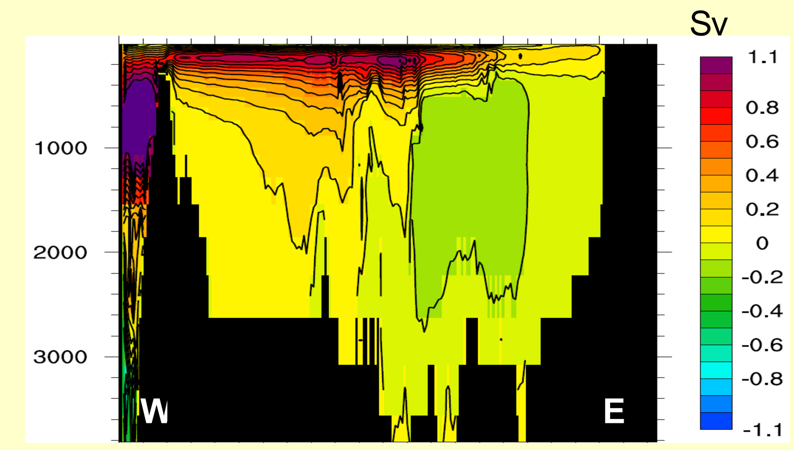

Fig. 8. Zonal overturning stream function (Sv) for the entire Mediterranean for 9K. Positive/negative values means clockwise/counterclockwise circulation.

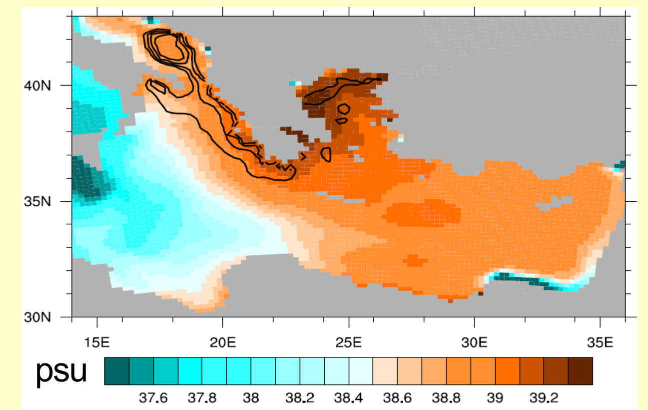

Fig. 9. Sea surface salinity (color, in psu) and mixed layer depth in March (isolines) for 9K.

During the early Holocene, the main location for the EMDW formation remains the Adriatic (Fig. 7) where well-oxygenated dense water sinks down and flows to the Ionian Sea to fill the bottom of the entire eastern basin. The second main location for the EMDW formation in the Aegean is shifted northwestward (Fig. 7). Since the connection with the Black Sea is closed, the Aegean basin contains water with high salinity (Fig. 9) which is cooled by the Etesians winds. Water of high density is then formed and flows through the Antikithira Strait and spreads into the Ionian basin at intermediate depth. The overturning stream function (Fig. 8) shows that the basin is in a well-ventilated state for 9K.

2- Perturbation experiments

- Perturbation **A**: Bosphorus inflow of 5000 m^3/s
- Perturbation **B**: Freshening of the Atlantic water of 0.04 psu/century
- Perturbation **C**: Surface warming caused by an enhanced AMOC, due to the absence of melt water in the ESM simulation (9Knm) from which we derived the atmospheric forcing
- Perturbation **D**: Perturbations B + C

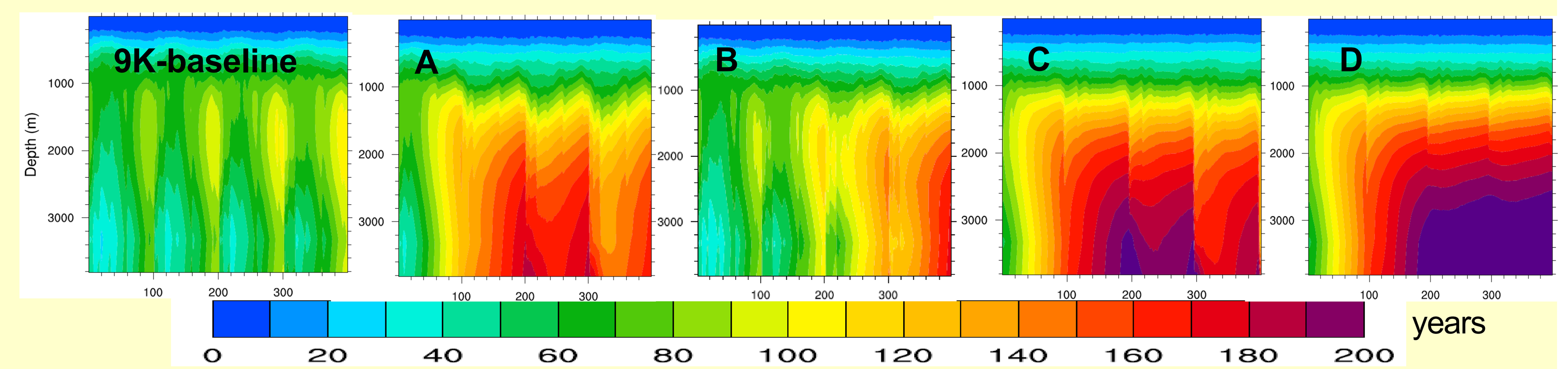

Fig. 10. Time evolution of the age of the water (yrs) averaged over the eastern basin at different depths for the 9K Baseline experiment and the perturbation experiments A, B, C and D.

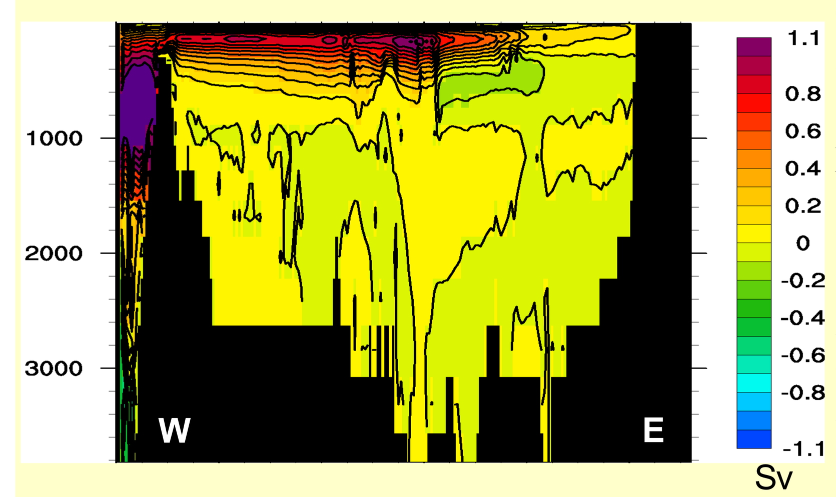

Fig. 11. Zonal overturning stream function (Sv) for the entire Mediterranean for perturbation D. Positive/negative values means clockwise/counterclockwise circulation.

The Fig. 10 shows that both a sudden Bosphorus outflow (A) or a surface warming (C) can lead to a stagnation of the deep water, as we can infer from the presence of old water at greater depths. Nevertheless, this stratification is slowly eroded by the vertical mixing and becomes fragile allowing some cold event to restore a temporary deeper convection. Perturbations A or C need to be combined with a continuous source of decrease in surface density (e.g. freshening of the Atlantic water from the melting ice sheets, Fig. 10. case D) to maintain the state with stagnating deep water over thousands of years, as found in the sapropels. The Fig. 11 shows that the circulation cell is restricted to the upper 700 m with the perturbation D.

6. Comparison Model vs. Reconstruction

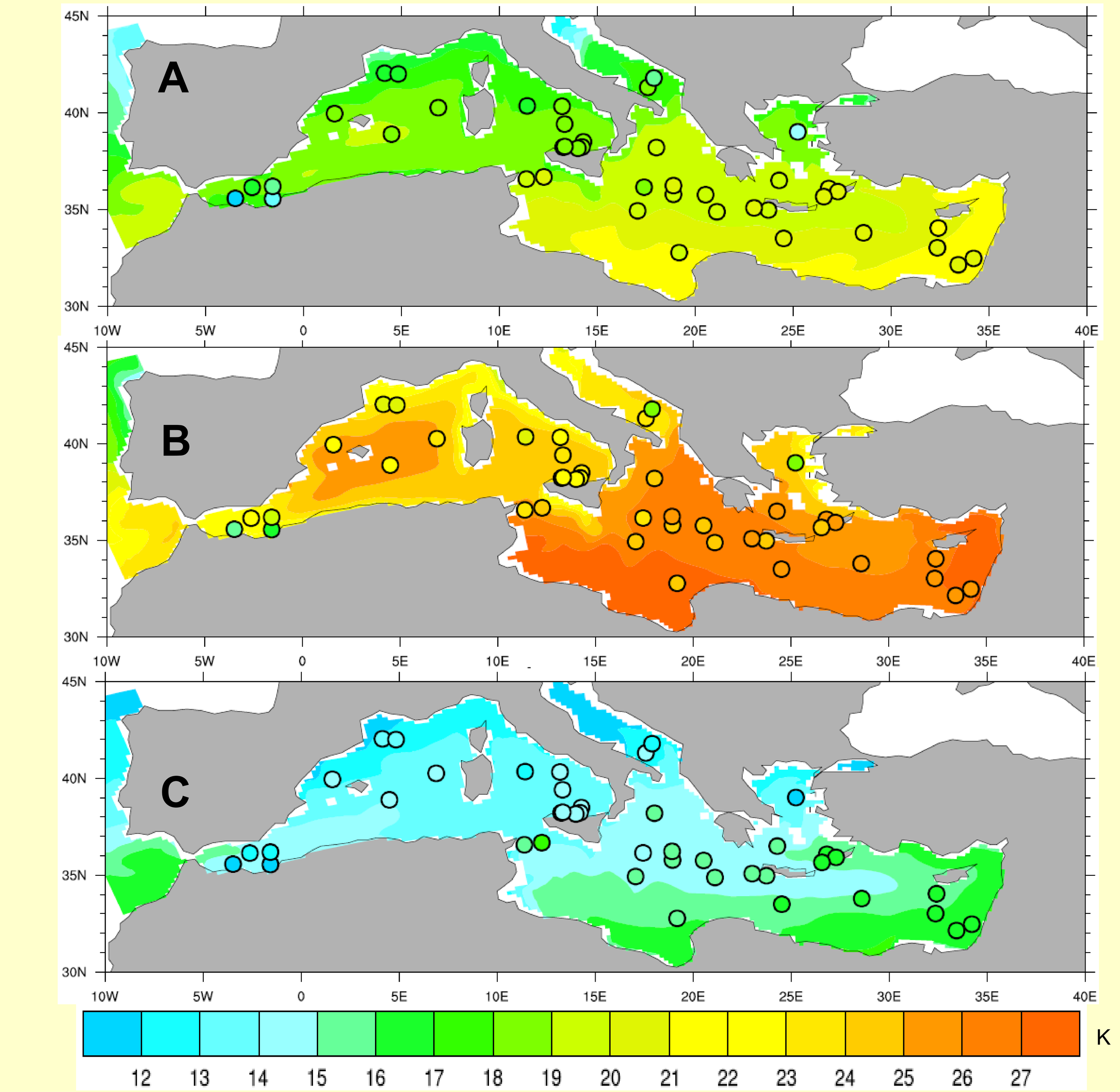

Fig. 11. Comparison of the simulated SST for 9K (background colour) and reconstructed SST from artificial networks based on planktic formalinifera (dots). Annual mean SST (A), summer SST (B) and winter SST (C) are shown in K.

The comparison between modelled and reconstructed SST (Fig. 11) shows a general agreement of the spatial patterns. Major deviations occur in the Alboran, Adriatic and Aegean seas, areas with particularly variable oceanographic conditions. Some of the model-reconstruction discrepancies may be due to ecological and seasonal effects in the planktic foraminiferal signals.

7. Conclusion and outlook

- The approach to force a regional OGCM with forcing from a global ESM yields reasonable results for the present-day as well as for the early Holocene
- The results from the perturbations experiments tell that:
  - a gradual freshening of the Atlantic by 0.04 psu/century (case B) leads only to a weak reduction in deep ventilation
  - a sudden onset of an outflow of fresh water from the Black Sea (case A) as well as a surface warming (e.g. by an amplification of the Atlantic overturning, case C) yield stagnant deep water in the Eastern Mediterranean Sea
  - vertical mixing gradually reduces density differences between well-ventilated intermediate water and stagnant deep water
  - in order to maintain a stagnant deep water over thousands of years, a permanent source for the decrease in surface density is required, e.g. fresh water from ice sheet melt (case D)
- The comparison model/reconstruction for the early Holocene SST remains non-trivial

References:
- Marsland et al., 2003. *Ocean Modelling*
- Pinardi, N. and E. Masetti, 2000. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*

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