Simulating the early Holocene eastern Mediterranean sapropel formation using an ocean biogeochemical model

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1. Introduction

The early Holocene eastern Mediterranean sapropel (S1) is an organic rich (>2%) sediment layer, which was deposited under oxygen depleted deep water conditions in a depth below 1800 m between 9.5 to 6.5 kyr BP. We aim to identify plausible scenarios leading to the early Holocene sapropel formation using an ocean general circulation model coupled to a biogeochemical model (MPIOM / HAMOCC).

Hypotheses for sapropel S1 formation

Most studies used the early Holocene enhanced humidity during the African humid period (AHP, 14.8 – 5.5 kyr BP) as a basis to formulate hypotheses (e.g. Rohling et al., 1994):

1) Additional freshwater input adds additional nutrients, inducing an enhanced primary production, and thus enhanced oxygen utilization by remineralization.

2) Increased humidity induces a decrease of the surface salinity, resulting in a shutdown of the thermohaline circulation and thus deep-ventilation.

3) A combination of hypothesis 1 and 2.

Furthermore, it has been proposed that during the last glacial-interglacial transition substantial freshening and warming established a stable density stratification. Therefore, we can formulate new hypotheses:

4) The cool and salty deep water at the end of the Pleistocene in combination with the warming climate did not allow for deep water formation/ventilation resulting in a long persistent stagnation.

5) A combination of hypothesis 4 with an enhanced riverine nutrient input.

2. Methods

Models

MPIOM/HAMOCC ocean (Marsland et al., 2003) biogeochemical (Wetzel et al., 2005) model.

Regional setup

20 km horizontal resolution
46 vertical levels
36 min timestep

Forcing / Boundary conditions

Daily forcing derived from equilibrium simulation with ESM ECHAM5(T31L19) /MPI-OM/LPJ for 9 kyr BP.

- Atmospheric forcing repeated after 100 years of integration.
- Atlantic boundary / rivers: monthly climatological anomalies added onto Atlantic hydrography / rivers.
- Bosphorus closed.

4. Experimental setup

After 1600 years of model spin-up (Baseline) we simulate the hypotheses mentioned in the introduction with the following assumptions:

Baseline (well ventilated, pre-industrial nutrients, simulation time 1600 + 4100 years)
3xNutri (3x nutrient input, simulation time: 2100 years)
Nile (Nile runoff (5358 m^3s^{-1}) +9000 m^3s^{-1}, simulation time: 3100 years)
IniGlac (initialized with -3°C, +1.5 psu, Mikolajewicz, 2011, simulation time: 4100 years)
IniGlac+3xNutri (IniGlac experiment + 3x nutrients, simulation time: 4100 years)

6. Conclusions

- A purely enhanced biological productivity (3xNutri exp) cannot overcome the effect of a continuous ventilation, thus a stagnating deep water circulation is a prerequisite for S1 formation.
- The time frame required for complete oxygen depletion within a stagnating ocean exceeds the time span between the beginning of the AHP and the onset of S1 formation, therefore the AHP climate (Nile experiment) cannot be the cause of S1 formation.
- Our simulations indicate that S1 was triggered by the climatic changes associated with the last glacial-interglacial transition. The time frame for complete oxygen depletion is in accordance with the latest epibenthic d18O records, which indicate that the stagnation started ~6 kyr before S1 deposition. The simulated trend of the strength of the deep water stagnation indicates that a restrengthening of the stagnation, for instance through an additional freshwater input, is required to meet the reconstructed spatial extent and duration of S1 formation.
- The strength and duration of the stagnation depends on the magnitude of the perturbation and the mixing eroding this perturbation With respect to the deep turnovertime we likely underestimate the strength of mixing. However, stronger mixing in the model does not lead to deep oxygen depletion in neither of the rather extreme examples of perturbation presented here.

Grimm, R., 2012. Simulating the early Holocene eastern Mediterranean sapropel formation using an ocean biogeochemical model. *PhD thesis, Reports of Earth system Science No 123.*
Marsland, S.J., et al., 2003. The Max-Planck-Institute global ocean/sea ice model with orthogonal curvilinear coordinates. *Ocean Modelling*, 5, 91-127.
Mikolajewicz, U., 2011. Modeling Mediterranean ocean climate for the last Glacial Maximum. *Climate of the Past*, 7, 161–180.
Rohling, E.J., et al. 1994. Review and new aspects concerning the formation of the eastern Mediterranean sapropels. *Marine Geology*, 122, 1-28.
Wetzel, P.A. et al., 2005. Sea-to-air flux from 1948 to 2003: A model study. *Global Biogeochemical Cycles*, 19, 1-19.

5. Results

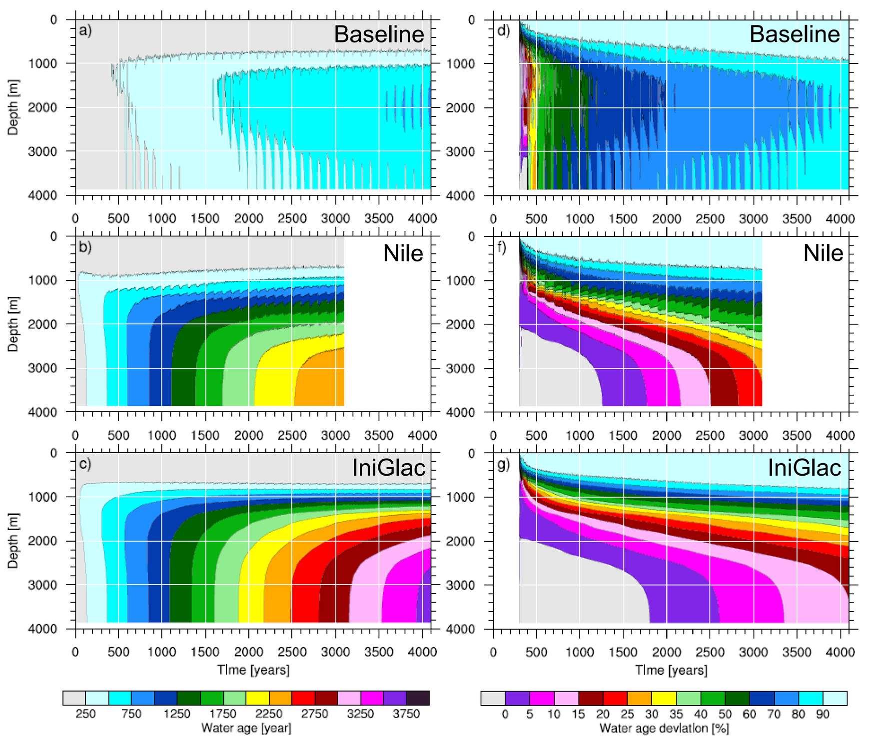

Fig. 1. Hoffmöller diagram of the annual mean apparent water age (a, b, c) and the annual mean apparent water age deviation (ageD) (d, f, g) averaged over the Ionian Sea.

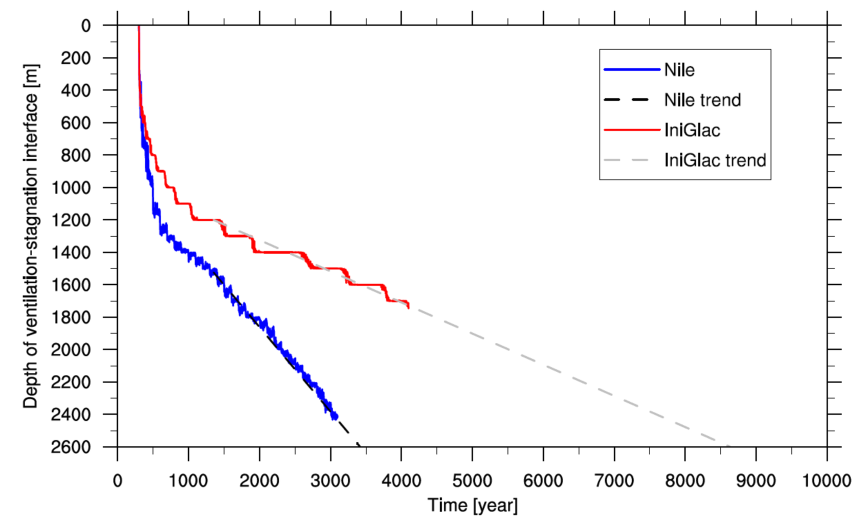

Fig. 2. Time series of the ventilation stagnation interface depth (derived as ageD=35%). Dashed lines show the linear trend calculated between the years 1351-3050 for the Nile, and the years 1351-3950 for the IniGlac experiment, and extrapolated until the ventilation-stagnation interface depth reaches 2600 m.

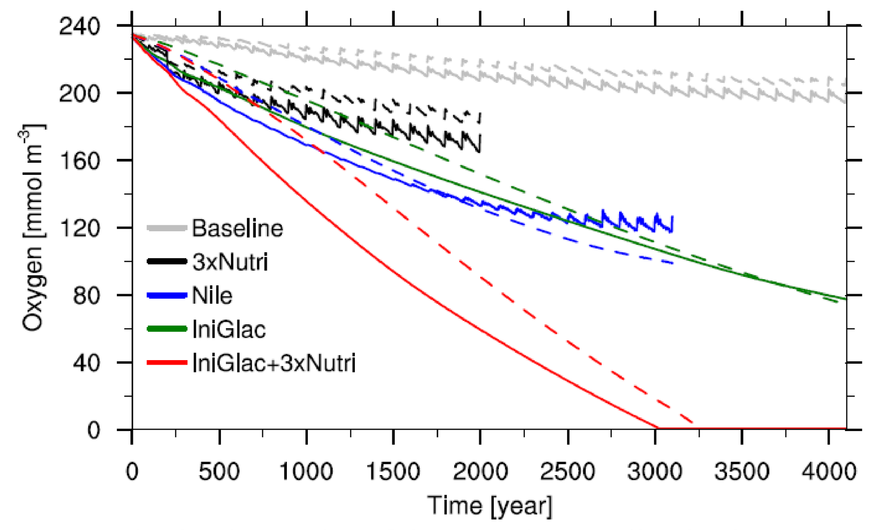

Fig. 3. Time series of the annual mean dissolved oxygen concentration in 1800 m (solid line) and 2660 m (dashed line) averaged over the Ionian Sea.

The strength of the stagnation as indicated by the apparent water age is weakened with time in both the Nile and IniGlac simulation (Fig. 1). The apparent age deviation (ageD) describes the deviation from the perfect stagnation (linear aging of water with time) (Fig. 1). ageD indicates that the deep water renewal is < 30% in the stagnation experiments. Assuming that ageD < 35% indicates a complete stagnation with only little diffusive imprint of younger upper ocean water, we can use ageD=35% as a measure to illustrated the depth of the ventilation-stagnation interface (Fig. 2). A linear extrapolation of the ventilation-stagnation interface depth shows that the deep ocean of the Nile experiment will be reventilated after ~3.5 kyr, and the IniGlac after ~8.5 kyr.

Both the 3xNutri and the Nile experiment show no potential to develop deep water anoxia, since either continuous ventilation or the progressive deepening of the ventilation front leads to a deep oxygenation (Fig. 3). Only the IniGlac+3xNutri experiment develops basin-wide deep water anoxia after 3 kyr of simulation. The nearly linear trend of the oxygen utilization in the IniGlac experiment indicates at least 6.5 kyr until deep water anoxia will be developed. After this time, however, the ventilation stagnation interface will be at ~2200 m depth. Therefore, deep water anoxia could only be established below this depth until deep water reventilation will be established after 8.5 kyr. This indicates that a restrengthening of the stagnation, for instance through an additional freshwater input, is required to meet the reconstructed spatial extent (> 1800 m water depth) and duration (3.5 kyr) of S1 formation.

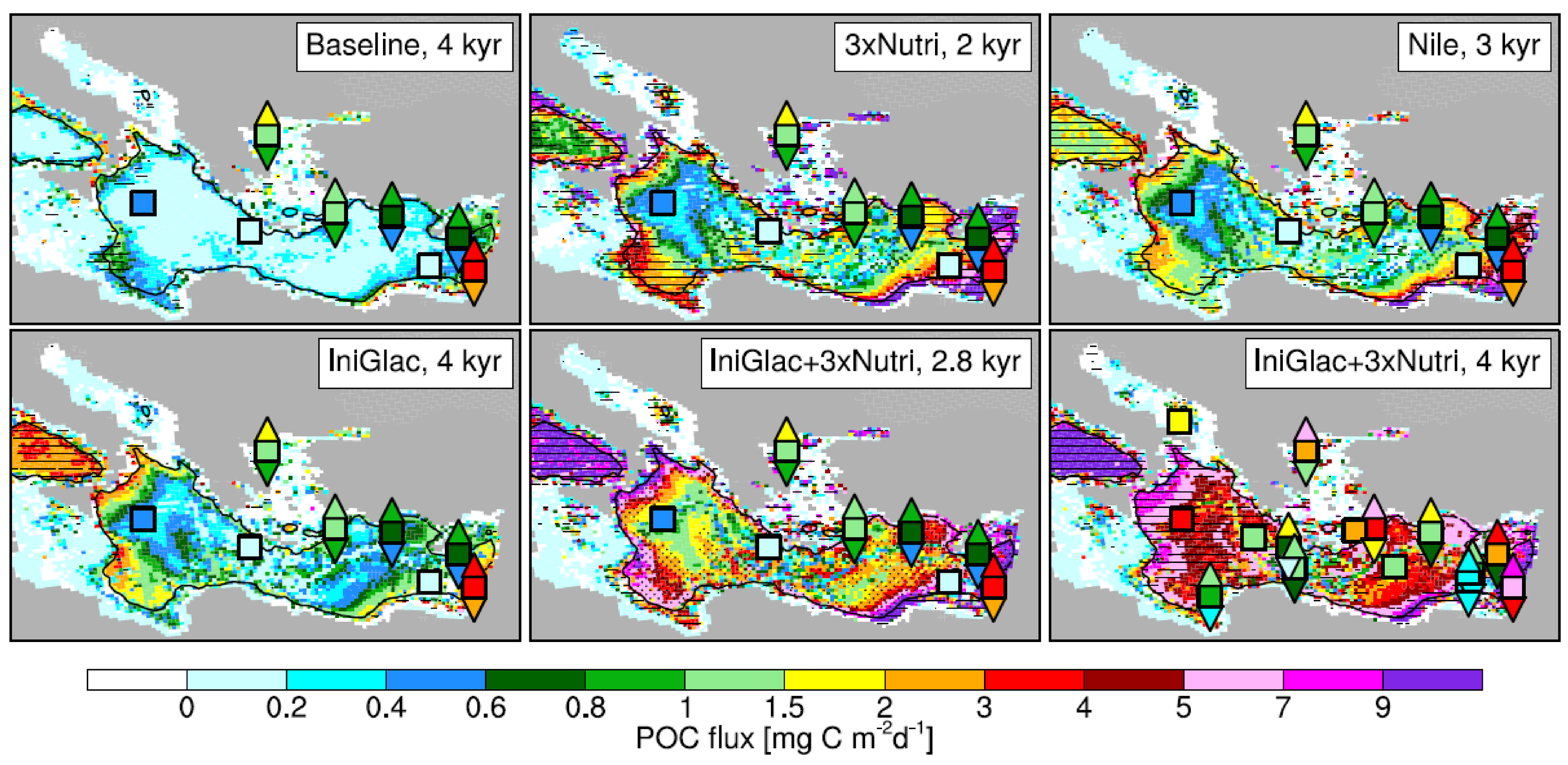

Fig. 4 Sediment particulate organic carbon (POC) burial-flux of indicated model experiment time slices (e.g. 4 kyr averaged between the simulation years 4000 to 4100) superimposed with organic carbon burial-fluxes derived from sediment cores for the pre-sapropel period between 10.5 to 11.5 kyr BP, and the sapropel period between 6.5-9.5 kyr BP, (sapropel only shown in IniGlac+3xNutri, 4kyr). Squares show mean values, triangle pointing upward maximum and triangle pointing downward minimum values. Line shaded regions show areas where the trend of the simulated POC burial flux is on average lower than -0.05 mgC $m^{-2}d^{-1}$ over the last 500 years of simulation, and point shades areas where this trend is higher than 0.05 mgC $m^{-2}d^{-1}$. The black line represents the 1500 m contour line. Note the nonlinear scale.

Figure 4 shows the sediment POC burial flux. For the pre-sapropel time, the Baseline underestimates, and the IniGlac +3xNutri strongly overestimates the POC burial flux. The 3xNutri and Nile experiment show reasonable POC burial fluxes over large areas, however, the simulated fluxes are too high in the eastern and northern Levantine Sea, indicating that the additional nutrient load by the Nile river is too high. In contrast, the IniGlac experiment shows a very good basin wide representation of the burial flux, indicting that S1 formation involved no particularly strong eutrophication through the Nile river. In addition, this shows that the POC sediment burial flux is rather sensitive to the deep water temperature, modulating the strength of the POC remineralization.

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