Project: **1528**

Project title: **SAPROPEL**

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The first 4 months of the reporting period were dedicated to finalize, analyse and publish the simulations on sapropel formation (Six et al., 2026). Sapropels are thick organic sediment layers in the eastern Mediterranean Sea (eMED) that were deposited under oxygen-free deep-sea conditions over four millennia. As the first research group, we were able to evaluate the drivers of deep-sea anoxia with a comprehensive ocean general circulation model including biogeochemistry of the Mediterranean Sea by using long transient simulations covering the period from 21,0000 years ago to present day. We show that continuous warming of the sea surface during the deglaciation and the steady sea level rise - which intensifies the water exchange with the Atlantic at the Strait of Gibraltar - caused increasing stratification of the water column in the eMED. This stronger stratification inhibited the oxygen transport towards the deep-sea long before sapropels became visible. These changes in the physical ocean alone contributed 47% to the total oxygen depletion. Increased nutrient supply via rivers during the African Humid Period boosted marine biological production and the transport of organic matter towards the sea floor. The combination of reduced oxygen transport into the deep-sea and higher local oxygen demand from organic matter remineralisation eventually leads to anoxic conditions and sapropel formation. The uniqueness of our study is that we investigate not only the formation of sapropels, but also their termination and the transition to the physical and biogeochemical conditions known today in the eastern Mediterranean.

The temporal evolution of oxygen below 2000 m depth is a key factor for sapropel formation, while it is controlled by two contributors: the local oxygen consumption due to remineralization and the oxygen supply by ventilation due mixing or advection. To gain a better understanding of the factors that influence these two contributors, we set up a linear model to reconstruct the oxygen concentrations from our comprehensive simulation. The blue lines in Fig 1 show the oxygen concentrations as simulated (solid) and as reconstructed by the linear model (dashed). The oxygen consumption is tightly linked to the organic matter flux which, in our model, is a function of a constant prescribed settling velocity and a temperature dependent remineralisation rate. We mimic lower (higher) settling fluxes by increasing (decreasing) the temperature in the calculated remineralisation rate of the linear model (Fig 1). The red lines indicate the high sensitivity of the reconstructed oxygen concentration on the temperature dependent remineralisation rate. If remineralization rates in the water column are calculated from warm present-day temperatures only small amounts of organic material reach the deep-sea below 2000 m. The concurrent lower oxygen demand for remineralisation is overcompensated by ventilation and no sapropel is formed (Fig 1a, red line with plus).

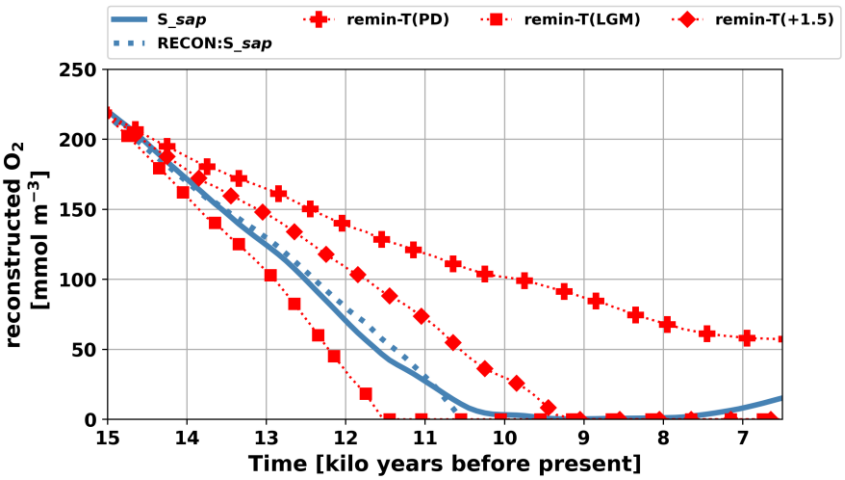


Fig 1: Mean oxygen concentration between 2,000 and 3,000 m as simulated by our model framework (blue solid line) and the reconstructed oxygen concentration from the linear model (blue dotted line). The impact of changed remineralisation temperatures is illustrated by the red lines with present day temperatures (red plus), temperatures from the Last Glacial Maximum (red square), and systematic higher water temperatures (+1.5°C, red diamond)

As already mentioned, the organic matter settling flux in our model is a function of a temperature dependent remineralisation rate and a fixed sinking velocity. This simplified calculation of the settling flux omits the microstructure and composition of marine aggregates including a potential ballasting effect due to aggregation with dust particles from aeolian sources. Temporal and spatial varying settling fluxes will modify the local oxygen demand and can affect the sapropel formation. In particular, ballasting effects might be important in transient simulations as aeolian dust deposition over the Mediterranean Sea was about 2 to 5 times higher at the Last Glacial Maximum (LGM) and during the deglaciation than at present day.

The aggregation scheme M^{4}AGO (März et al., 2020) calculates the sinking of marine particles based on their microstructure and composition and accounts for ballasting effects from shell material and dust particles. Thus, we implemented M^{4}AGO and performed time slice simulations for the LGM and present day. As a measure for the sinking flux, we calculate the percentage of organic matter surface production that reaches the sediment for the run with fixed sinking velocity (**P_C**) and for M^{4}AGO (**P_M**). In the open ocean and especially in the eMED, **P_M** is higher than **P_C** for both time slices (here shown only for PI in Fig. 2 a,b). During the LGM, deposition fluxes are in general higher than PI fluxes due to colder ocean temperatures. Thus, by subtracting **P_M** for the LGM and **P_M** for PI and dividing the result by the same difference for **P_C,** we can illustrate the amplification factor due to ballasting effects which M^{4}AGO takes into account (Fig 2 c).

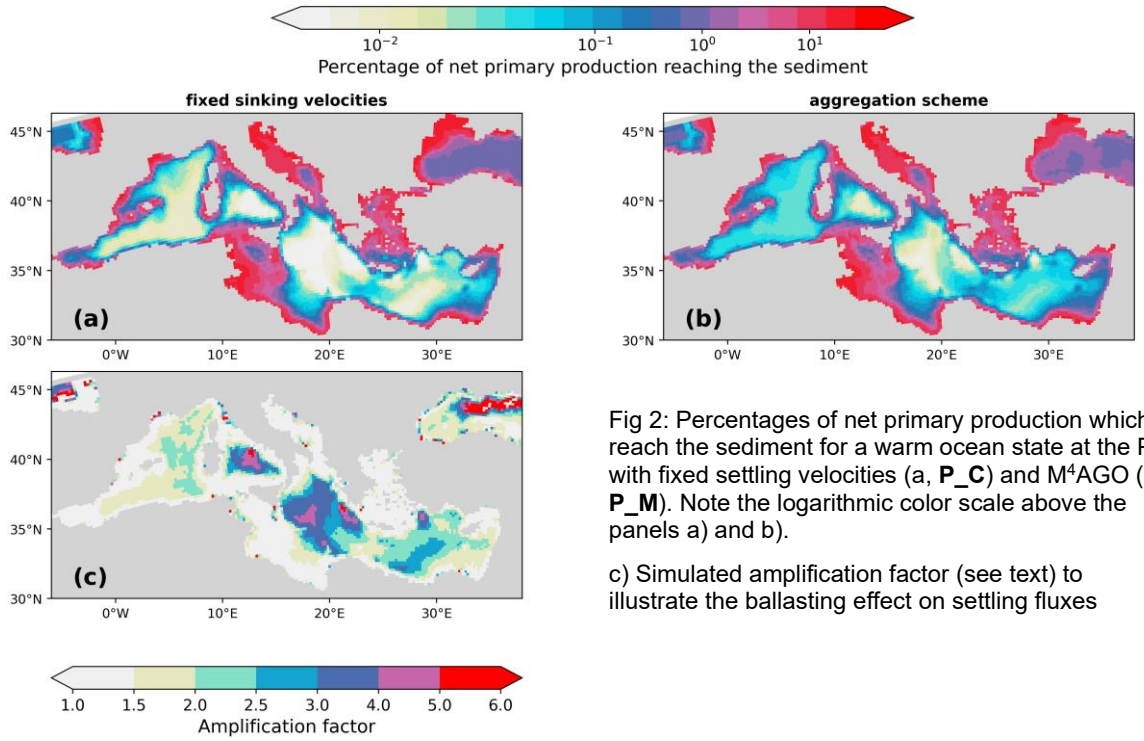


Fig 2: Percentages of net primary production which reach the sediment for a warm ocean state at the PI with fixed settling velocities (a, **P_C**) and M^{4}AGO (b, **P_M**). Note the logarithmic color scale above the panels a) and b).

c) Simulated amplification factor (see text) to illustrate the ballasting effect on settling fluxes

These first results with M^{4}AGO indicate that

- overall larger sedimentation fluxes are simulated, especially in the deep eMED basin,
- the ballasting effects amplify settling fluxes by up to a factor of 5

The simulated differences due to M^{4}AGO imprint on deep-sea oxygen concentrations. Thus, we expect a different temporal behaviour of sapropel formation when including the more realistic particle settling scheme M^{4}AGO. The transient simulation including M^{4}AGO over the deglacial period to present day is planned for 2027.

References:

Six, K.D., Mikolajewicz, U. & Schmiedl, G. (2026). Transient deglacial simulations unravel the causes of Mediterranean sapropel formation, Communications Earth & Environment, 7, 258. doi:10.1038/s43247-026-03290-9

März,,J., Six, K.D., Stemmler, I., Ahmerkamp, S. & Ilyina,T. (2020) Microstructure and composition of marine aggregates as co-determinants for vertical particulate organic carbon transfer in the global ocean, Biogeosciences, https://doi.org/10.5194/bg-17-1765-2020