The impact on sedimentation in case the Adriatic Sea becomes meromictic due to global climate change

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The role of the Adriatic Sea in the Mediterranean basin

- Oceans, including the marginal seas, are recognized to play a key role in mitigating or accelerating global warming trends, largely because of their ability to rapidly absorb carbon dioxide (CO_2) from the atmosphere or release it from the seawater column to the atmosphere.
- Present-day aeration of the deep Eastern Mediterranean (Emesd) basin results from circulation of oxygen-rich deep water originating mainly in the Adriatic Sea.
- Dense water formation in the EMed is essential in sustaining the Mediterranean overturning circulation.
- Changes in the sources of dense water in the EMed point to changes in the circulation and water properties of the Mediterranean Sea.

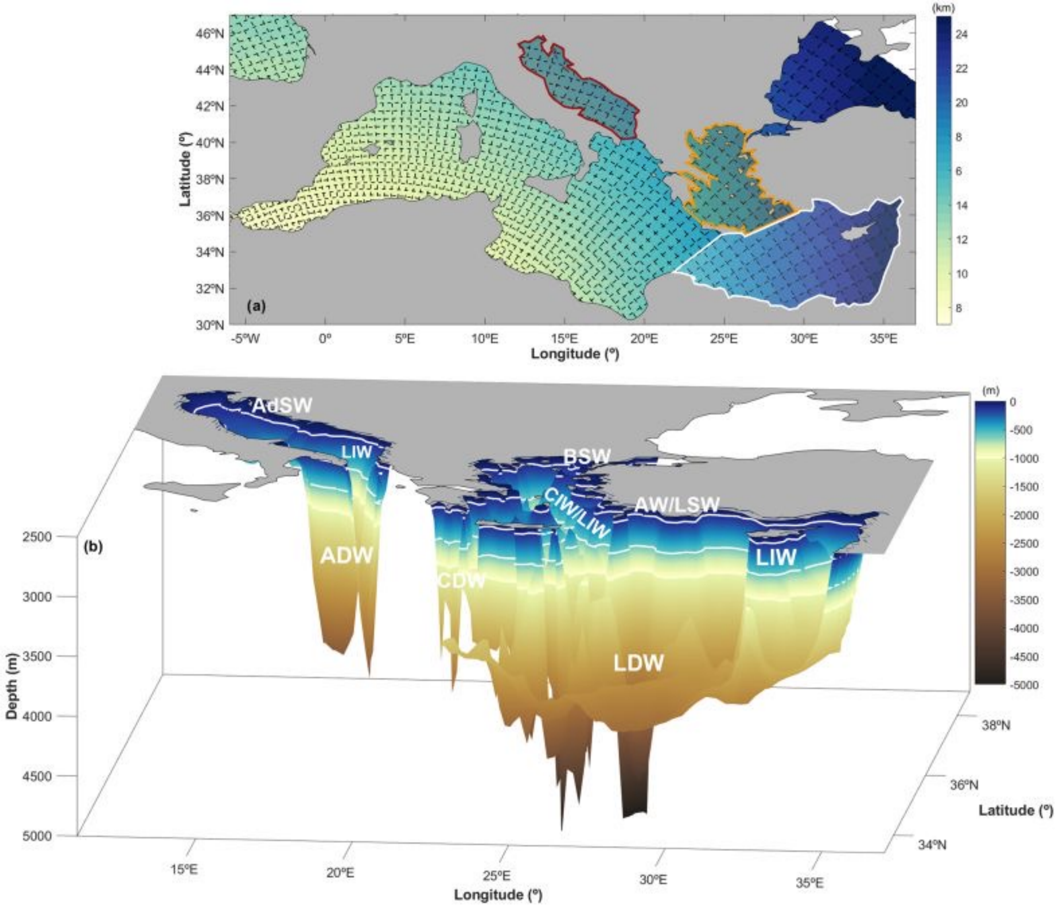


Figure 1: (Up) Easetern Mediterranean sub-basins: Adriatic (red), Aegean (orange), and Levantine (grey). (Down) Bathymetry of the main spots for dense water formation in the EMed:

Impacts of climate change on the overturning circulation

- As surface waters warm, the upper layers of the ocean become more stratified.
- The stratification of the water column requires more energy to break the thermohaline and mix the water layers. This could make it increasingly difficult to ventilate the lower layer.
- Stratification without mixing of sea layers is known as the meromictic state.
- The meromictic condition currently prevails in the Black Sea.
- In meromictic sea, the lower layer becomes increasingly hypoxic, hindering the decomposition of organic matter and causing organic-rich sedimentation.
- According to the sedimentary archives, meromictic conditions often prevailed in the Mediterranean, which is sensitive to the smallest changes in climate changes.

Sapropel sequences in the Eastern Mediterranean

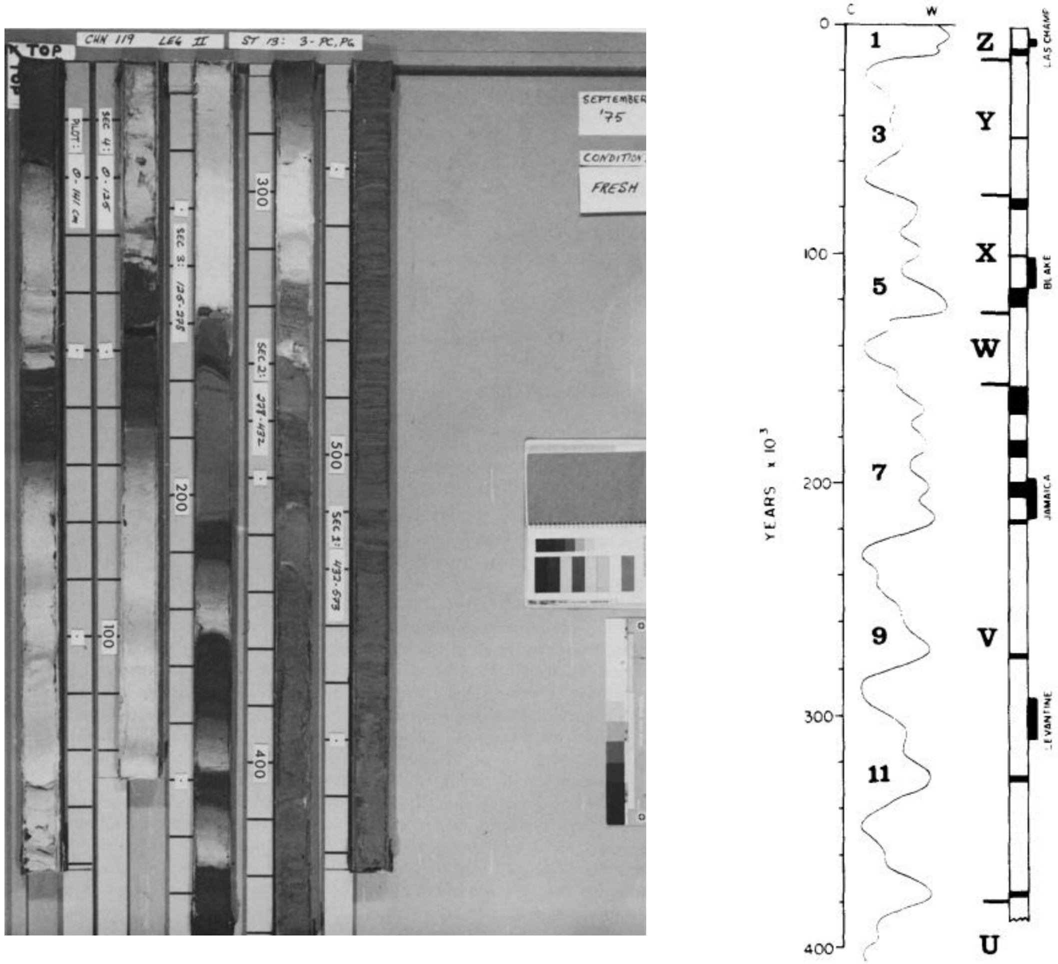


Figure 2: (Right) Photograph of a piston core from the EMed, showing the sapropel sequences. (Left) Relationship of EMed sapropels with the $\delta^{18}0$ climatic curve (Mangini & Schlosser 1986).

- The organic-rich sediments are called sapropel.
- Sapropels are associated with hypoxia due to worm periods in the past.
- The sharp change in color indicates an abrupt change in oxygenation of the deep sea.
- C_{org} concentrations in Mediterranean sapropels are up to 10%, compared to oxidized pelagic sediments with C_{org} content generally less than 0.5%.
- the ^{13}C values for organic matter in sapropels range from -21.0 to -23.7%o, suggesting a predominantly marine origin of organic matter.
- A higher $\delta^{18}0$ value corresponds to a warmer climate.

Climate change in past evident from sediments

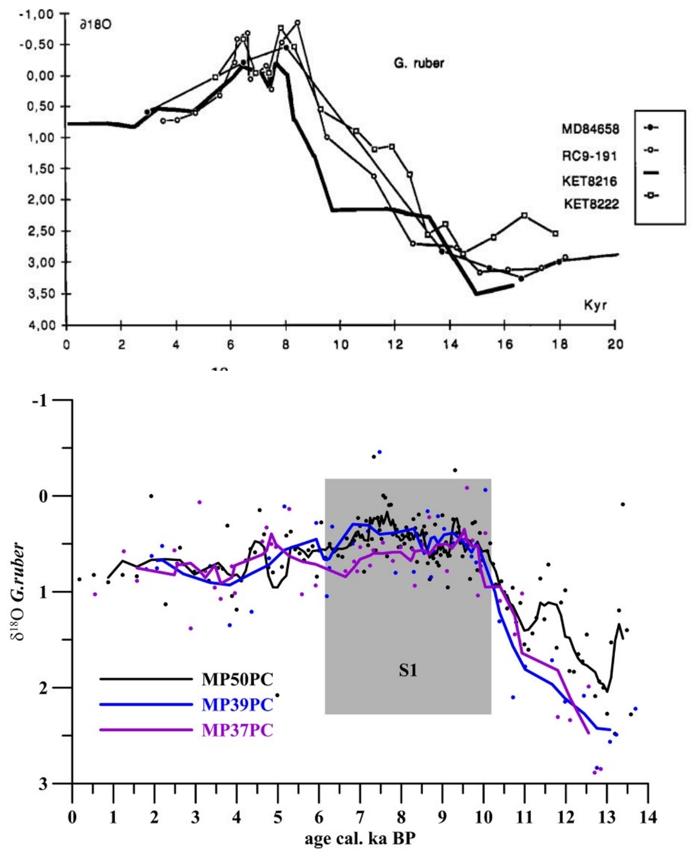


Figure 3: Variations of a δ [18]0 values of *Globigerinoides ruber over* time in the EMed cores by Fontugne et al. (1989) (top) and Filippidi and De Lange (2019) (bottom).

- By using sediment dating, carbon analysis, stable isotopes, and other analyses of Holocene sediments and foraminifera, it has been possible to estimate the changes in oxygen levels in the Mediterranean over the past 20,000 years and to determine that the entire Mediterranean region was prone to hypoxia in the past.

Global temperature reconstruction from proxy data

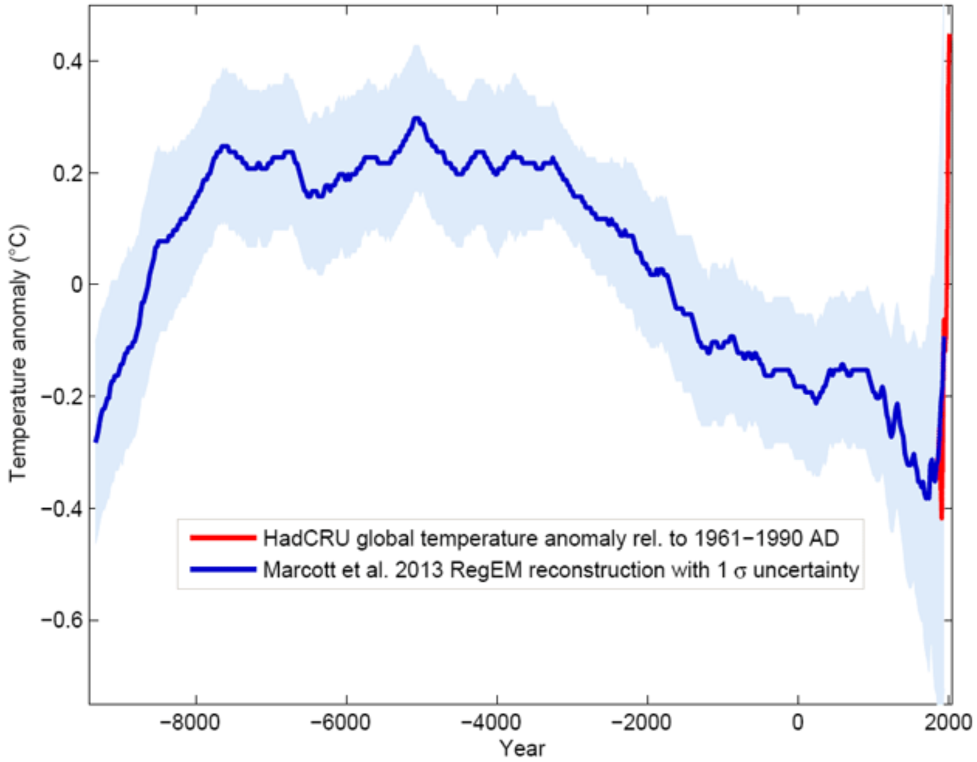


Figure 4: The blue line represents the reconstruction of the temperature anomaly in the last 10000 years until 2013. The red line shows the temperature anomaly from 1961 to 1990 (Marcott et al. Science 2013).

Adriatic Sea

- The Adriatic Sea are very sensitive to any small climatic amelioration.
- This is evident from the periodically increased organic carbon content in Holocene sediments.
- The Adriatic Sea exhibited many periods of benthic anoxic/hypoxic conditions.
- The last one occurred only 1650 ±100 years B.P. as determined by ^{14}C AMS dating of sediment core
- How can we predict cessation of the overturning circulation?

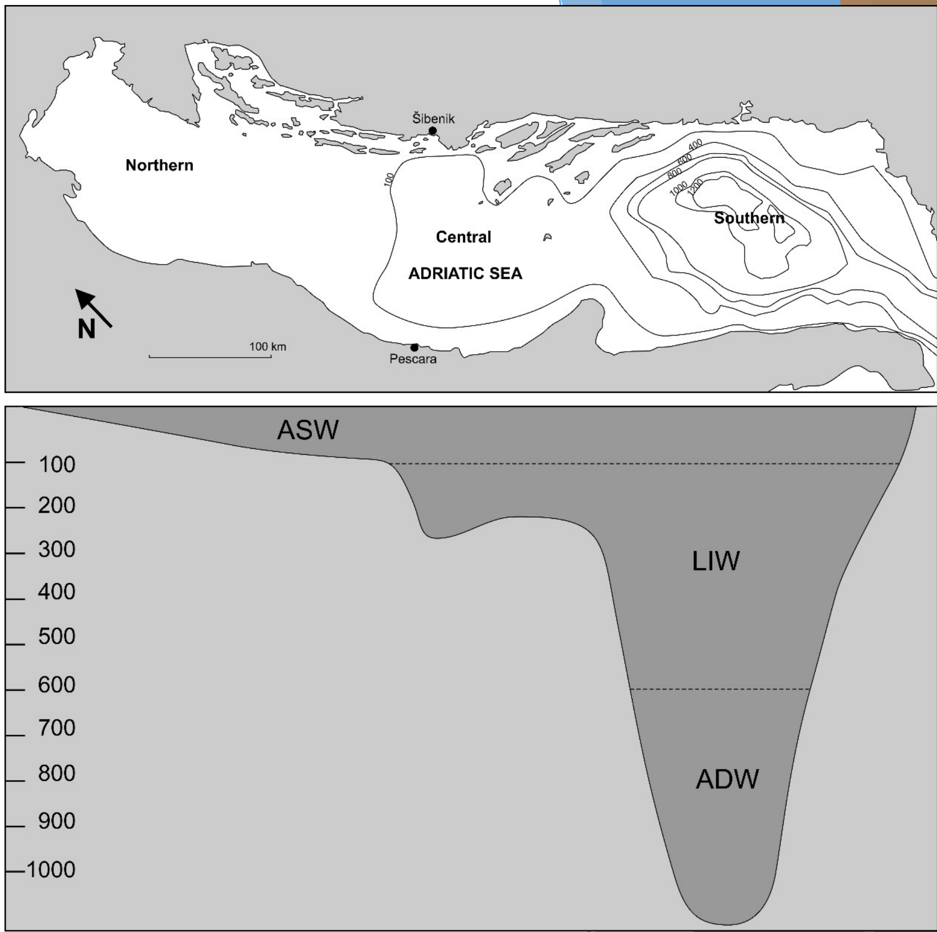
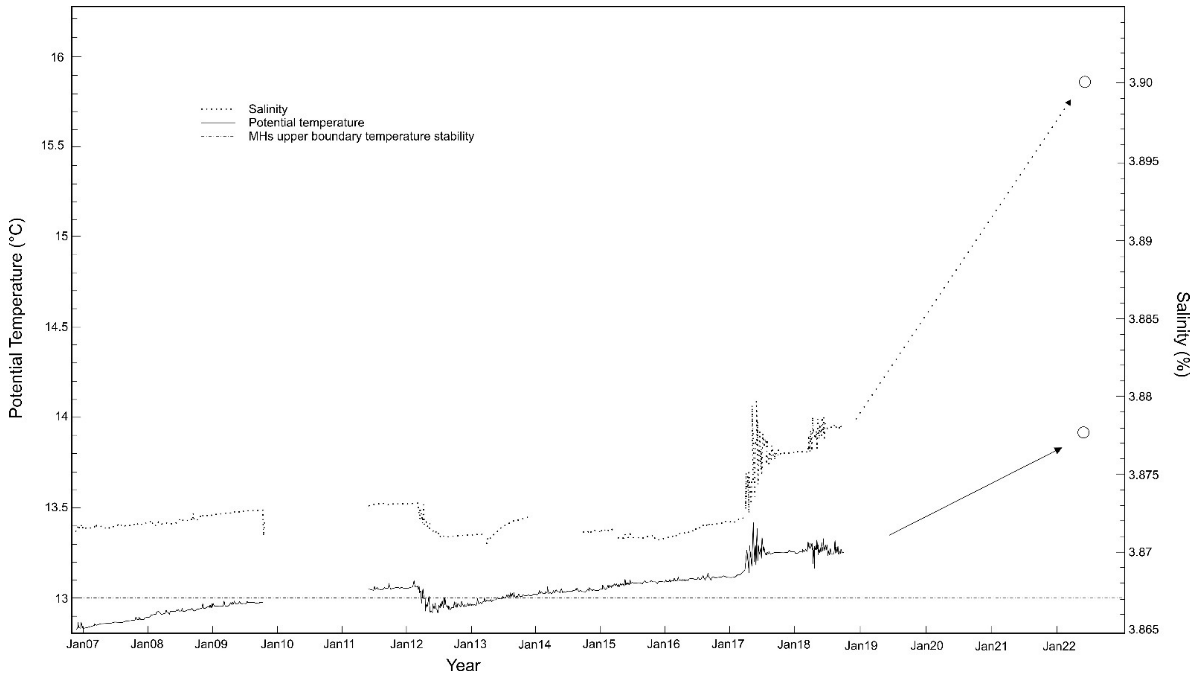


Figure 5: a) Three distinct portions of the Adriatic Sea basin: Northern (shallow), Middle (deep) and Southern (very deep); b) Three water types: ASW - Adriatic Surface Water (>100 m), LIW - Levantine Intermediate Water (100 – 600 m), ADW - Adriatic Deep Water (< 600 m) (Obhodas *et al.* 2020).

Temperature and salinity in the Adriatic Sea



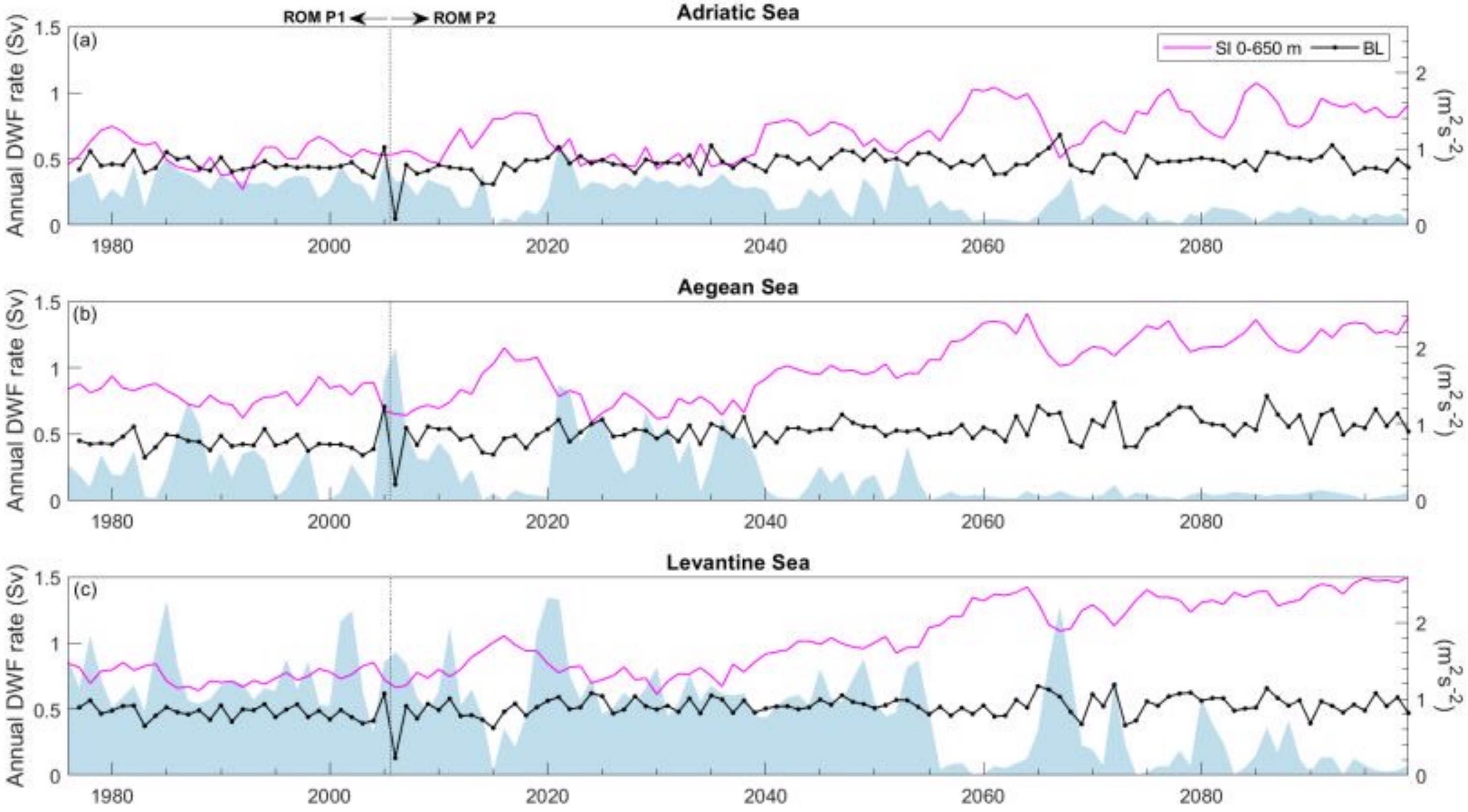
- The water masses in the ocean are stratified according to their density. This depends on temperature and salinity.
- A water mass can become heavier either by an increase in salinity or by cooling, and vice versa.

Figure 6: Deep sea Adriatic time-series for potential temperature (°C) and salinity (%) at 1200 m in the period November 2006 – November 2018 measured at E2-M3A observatory (OGS-SAILOR 2019 modified)

Temperature and salinity in the Levantine Sea

Figure 7: Analysis of in-situ temperature and salinity data in the Levantine Sea. Serimozu (2021).

Predictions



- The predictions are based on slightly underestimated values for temperature and salinity (Parras-Berrocal et al. 2023).

Figure 8: Time series (1976–2099 simulations of the yearly deep water formulation (DWF) rate (Sv) (filled area), winter integrated buoyancy loss (BL, m2 s −2) (dotted black), and stratification index (SI, m2 s −2) for 0–650 m (magenta) averaged over the (a) Adriatic Sea, (b) Aegean Sea, and (c) Levantine Sea. All time series correspond to winter months (December–January–February–March), whereas SI was computed in December of the preceding year.

Temperature-salinity diagram up to the 2000s and at present

- In temperature-salinity diagrams (T-S), isopycnals denote water masses of equal density.
- An increase in water temperature of only 0.7 °C or a slight decrease in salinity of 0.2 could lead to stratification of Adriatic waters and cessation of formation of oxygen-rich Adriatic deep waters (Mangini and Schlosser, 1986).
- In the last two decades we have observed an abrupt increase in the average temperature and salinity of the AdDW, from 12.6 °C to 13.9 °C for temperature and from 38.6 to 38.9 for salinity.
- This needs to be confirmed with the latest data from the M3A network of ocean observatories.

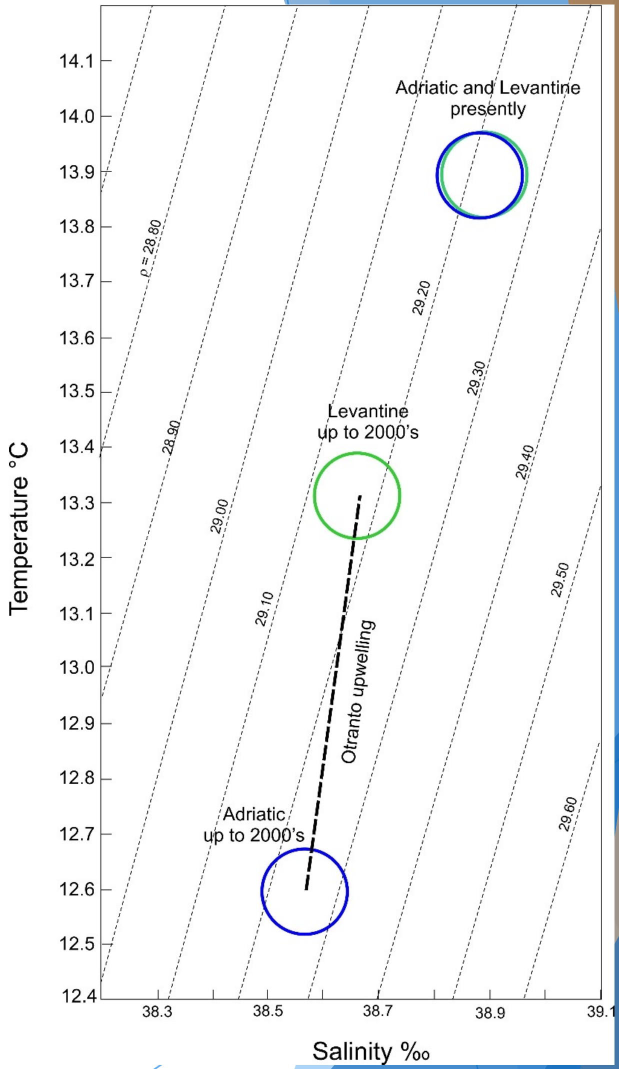


Figure 9: Temperature-salinity diagram for the Emed.

Open ocean observatories M3A in the EMed

Measured parameters

1. Meteorological parameters: atmospheric pressure, wind speed and direction, air temperature, relative humidity, solar radiation, infrared radiation, precipitation

2. Oceanographic parameters: Temperature and salinity, Pressure, Chlorophyll-a (E1), Turbidity, Dissolved oxygen (E1 up to 100 m, E2 up to 765 m), pH and pCO2(E2 up to 15 m) wave (E1), Currents (E1 up to 1 m, E2 up to 1186 m).

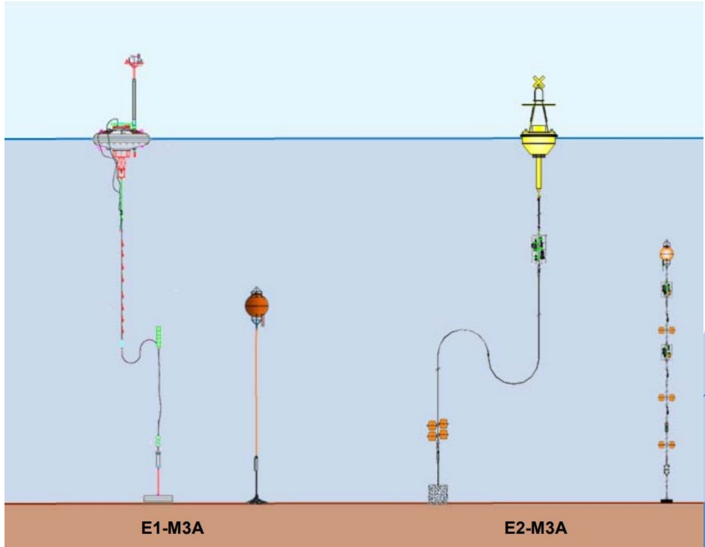
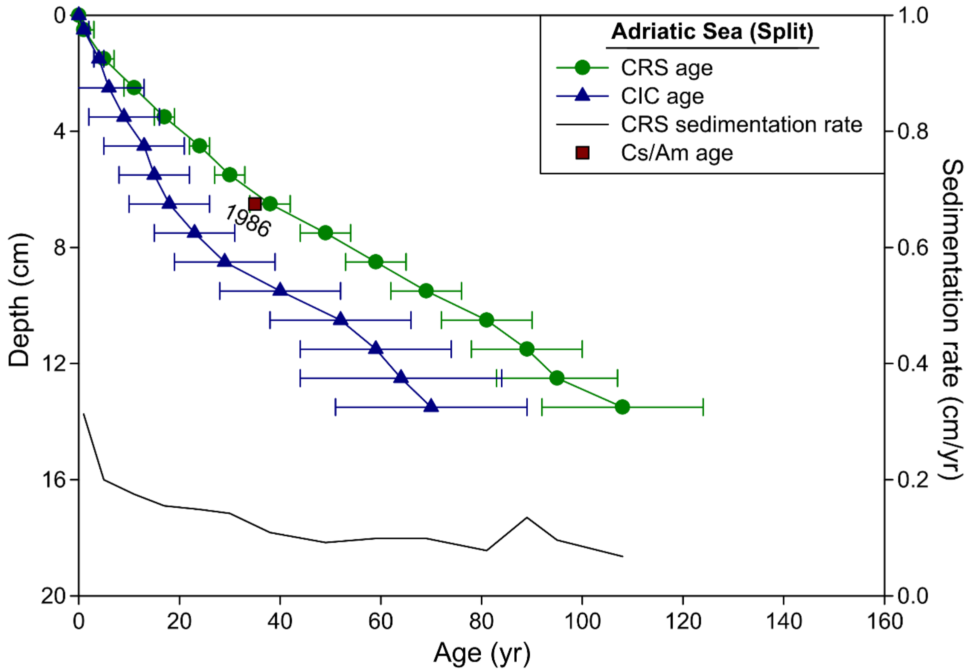


Figure 10: Geographic location (left) and scheme of the major components of the EMed M3A observatories (right).

Recent measurements of carbon in sediments



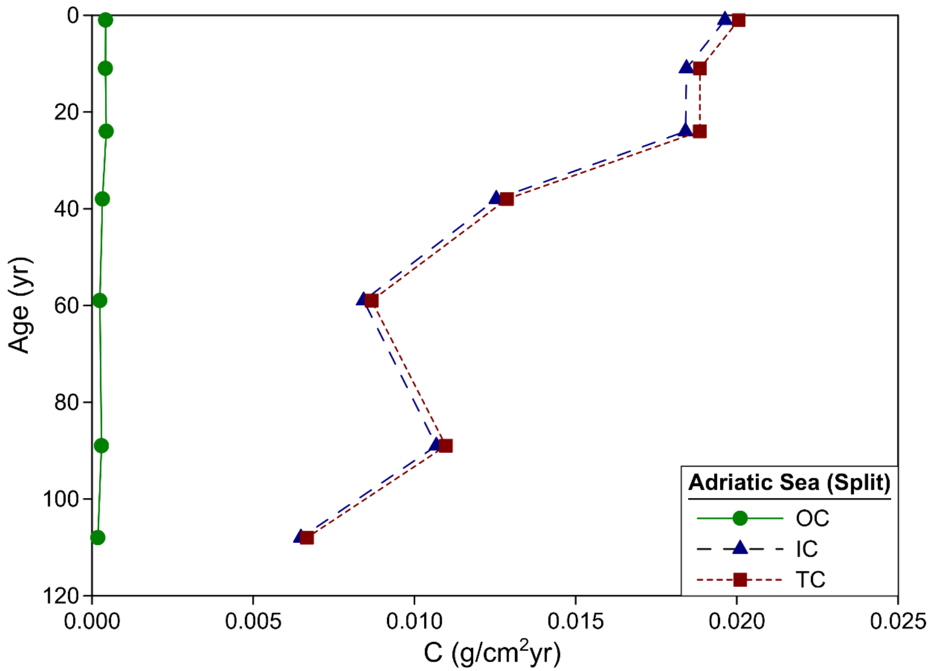


Figure 11: (Right) Depth and sedimentation rates versus age for the Adriatic Sea core sampled near Split. (Left) Organic carbon (OC), inorganic carbon (IC), and total carbon (TC) flux measured in the Adriatic Sea core sampled near Split (Vinković *et al*. 2022).

Are the identified trends driven by climate change?

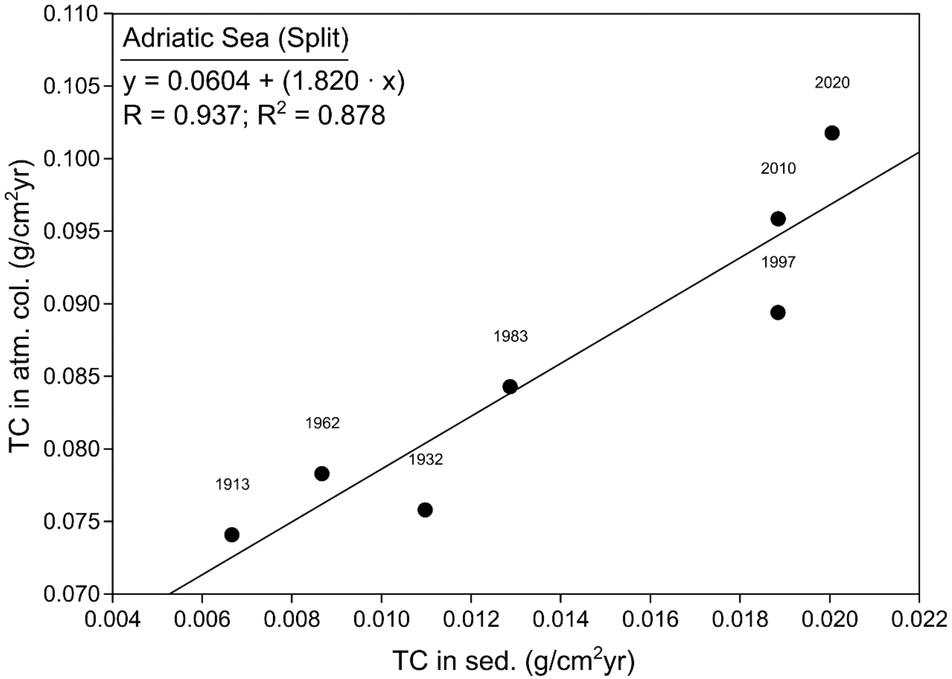


Figure 12: Atmospheric carbon (C) and C stored in sediments of the Adriatic Sea core sampled near Split (Vinkovic *et al.* 2022).

Oceans are greener due to climate change

- NASA data (MODIS Aqua Satellite): Intensity of purple colour indicates Signal-to-noise ratio (SNR). Black stippling indicates regions where there are also significant trends in Chl (12% of the ocean). More than half of the world's oceans have become greener in the last 20 years, likely due to global warming (Cael et al. 2023).
- ESA data (Sentinel 2 Satellite): The average global trend for the period 1997-2021 was 0.51% per year, with a maximum value of 25% per year and a minimum value of -6.1% per year (ESA Copernicus Programme).
- Phytoplankton is an important player in the carbon cycle.

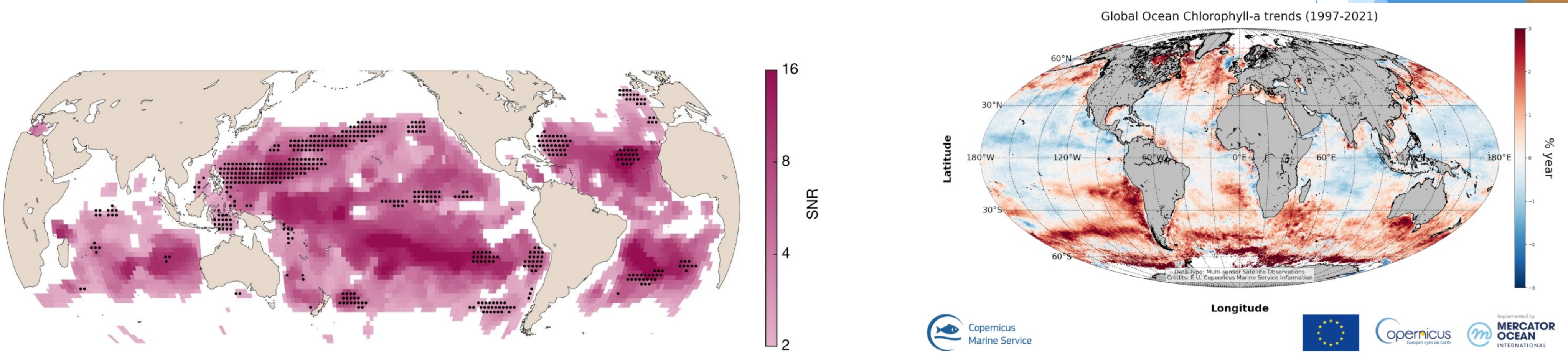


Figure 13: Map of chlorophyll-a trend in the ocean according to NASA MODIS -Aqua data from July 2002 to June 2022 (left) and ESA Sentinel 2 Observations Reprocessing from 1997 to 2021 (ESA Copernicus Programme) (right).

When will the oxygen in the bottom layer of the Mediterranean Sea be depleted?

- If the oxygen content is below a minimum value of ~10 μmol/L, the proportion of organic matter incorporated into the sediment increases (Mangini & Schlosser 1986).
- ^{14}C and ^{3}H studies indicate that EMed water is replaced approximately every 150 years (Mangini & Schlosser 1986).
- The O_2 content of the Adriatic water was about 225 mmol/L until 2000. 75 mol/m^2 and 150 years are required for the oxidation of organic matter in the deep sea. In a 1200 m thick water column, 340 mol of 0_2 is added every 150 years over 1 m^2 of bottom surface. Thus, by the 2000s, at least 4.5 times more oxygen was present in the water column than is required for organic matter decomposition (Mangini & Schlosser 1986).
- About 90% of organic matter is oxidized in the uppermost 1000 m of the ocean, which explains why less than 1%o of the organic matter produced is incorporated into sediments.

Conclusions

- Responses of the marine environment to increasing atmospheric CO_2 concentrations are evident in changes in sea temperature, salinity, acidity, and sea level at an alarming rate, especially in recent decades.
- Less obvious responses of the marine environment are changes in water mass fluxes between the upper and lower seawater layers, affecting the oxygen content of deep seawater, and the acceleration of sedimentation rates.
- The Mediterranean region will become warmer and drier, while the North Sea region will become colder. This will lead to more extreme weather events.
- We can expect changes in phytoplankton communities, keeping in mind that new species may be toxic to aquaculture.
- Bentic species at certain depths will disappear , affecting the fishing industry.
- The changes in the overturning circulations are first seen in an increase in the variance of the measured parameters. It is critical to continue observations to feed climate models with the latest data for more accurate predictions.
- While the older model calculations predict a collapse of the Atlantic and Mediterranean currents by the end of the 21st century, the new models suggest that it more likely that this will occur in the 2050s (Ditlevsen & Ditlevsen 2023).

For more information

Thank you for your attention!

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SEDIMENT CHALLENGES AND OPPORTUNITIES

Could atmospheric carbon be driving sedimentation?

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Abstract

Purpose The objective of this study was to provide insights into the most recent responses of sediments to climate change and their capability to sequester atmospheric carbon (C).

Methods Three sediment cores were collected, one from the western Black Sea, and two from the southern Adriatic Sea. Cores were extruded and sectioned into 1 cm or 0.5 cm intervals. Sections were frozen, weighed, freeze-dried, and then weighed again to obtain dry weights. Freeze-dried samples were dated by using lead 210 (^{210}Pb) and cesium 137/ americium 241 (^{137}Cs/^{241}Am). Organic and inorganic C were determined by combustion. Particle size distribution was determined using a Beckman Coulter particle size analyzer (LS 13,320; Beckman Coulter Inc.). Mineralogical analyses were carried out by a Philips X'Pert powder diffractometer.

Results Sedimentation and organic and inorganic C accumulation rates increased with time in both the Black Sea and the Adriatic Sea. The increase in accumulation rates continued after the global introduction in the early 1970s of controls on the release of phosphorus (P) into the environment and despite the reduced sediment yield of major rivers (Po and Danube). Therefore, the increased accumulation of organic and inorganic C in the sediments cannot be assigned only to nutrient availability. Instead, we suggest that the increase in organic C is the consequence of the increase in atmospheric C, which has made more carbon dioxide (CO_2) available to phytoplankton, thus enabling more efficient photosynthesis. This process known as CO_2 fertilization may increase the organic C accumulation in sediments. Simultaneously, the increase of sea temperatures decreases the calcite solubility resulting in increases of the inorganic C accumulation.

Conclusion Our results suggest that long-term, general increases in accumulation rates of organic and inorganic C in sediments are the consequence of increases in atmospheric C. This shows that coastal sediments play an important role in C uptake and thus in regulating the Earth's climate.

Keywords Climate change · Pb-210 and Cs-137 dating · Carbon · Particle size distribution · X-ray powder diffraction · The Adriatic Sea · The Black Sea · Sediment · Sedimentation rate

1 Introduction

1.1 Carbon dynamics

Organic carbon (OC, from primary production) and inorganic carbon (IC, mainly calcite) measured in intact sediment cores in combination with dating provide signals of changes in sea productivity and sea temperature which are

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