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OPTIMIZED ENVIRONMENTAL MONITORING: INNOVATIVE SOLUTIONS TO COMBAT CLIMATE CHANGE

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Abstract

Environmental monitoring has become a crucial component in the fight against climate change, as it allows us to analyze environmental conditions in real time and predict their long-term effects with greater accuracy. In recent years, technological innovation has opened up new avenues for more efficient and precise monitoring, offering essential support for the sustainable management of ecosystems and natural resources. This fusion of modern technology and traditional knowledge is key to effectively addressing the environmental challenges of both the present and the future. From 2014 to 2020, peculiar habitat-formers of the Adriatic Sea showed unequivocal signs of stress, possibly linked to a general warming trend of the basin. Therefore, this study investigates the marine water quality in the last 10 years in the Adriatic Sea with a multidisciplinary approach.

Keywords

Climate change, Environmental monitoring, Adriatic Sea, temperature, salinity, dissolved oxygen

1. *Introduction*

Climate action has been a priority of the EU since the 1970s, with the introduction of the first environmental action program aimed at reducing pollution and raising ecological awareness. In 1987, the Single European Act made environmental protection a goal of the EU, followed by the creation of the European Environment Agency in 1990. The Maastricht Treaty of 1993 fully integrated environmental policy into the EU, strengthening the role of the European Parliament.

In 1999, the Amsterdam Treaty made it mandatory to include environmental protection in all EU policies. In 2015, the EU endorsed the Paris Agreement to limit global warming. In 2019, the EU declared a climate emergency and introduced the Green Deal, aimed at achieving climate neutrality.

Specifically, the EU adopted a long-term strategy for a climate-neutral Europe by 2050, with goals set for 2020, 2030, and 2050, along with tools for monitoring progress.

The monitoring of natural resources requires increasingly advanced tools to address the challenges related to climate change and sustainable environmental management.

The use of automated systems for receiving and querying satellite data, supported by high-performance computing infrastructures and artificial intelligence (AI) algorithms, provides rapid and accurate analysis of the constantly evolving environmental conditions. These innovative techniques allow for timely detection of change indicators and signs of ongoing environmental crises, such as coastal monitoring near rivers, habitat surveillance, and variations in forested areas.

The analysis of satellite data, combined with the expertise and informed judgment of researchers, enables dynamic monitoring, offering crucial information both for the routine management of natural heritage and for the early identification of emergency situations. The prevention of environmental crises, made possible by timely and integrated monitoring, represents an effective strategy to minimize negative impacts and promote proactive resource management.

This work highlights how the interaction between advanced technologies and human interpretation is essential for the success of environmental monitoring that can respond dynamically and swiftly to the needs of the territory and climate change. In particular, this paper explores the impact of climate change on the quality of marine waters in the Adriatic Sea by adopting a multidisciplinary approach

The large-scale circulation and mixing of intermediate water in the Adriatic basin play a vital role in controlling thermocline, freshwater input mixing, salinity distribution, dissolved oxygen (DO) concentration and nutrient availability, supporting lush marine communities. In particular, the seawater temperature increases, and the frequency and intensity of heatwaves are causing extensive mass mortality events all over the Mediterranean Sea, including in the Adriatic basin (Cramer et al., 2018; Ozer et al., 2022; Civitarese et al., 2010). Increases in water temperatures might cause, among others: (i) increased rates of evaporation resulting in higher salinity; (ii) lower levels of dissolved oxygen; (iii) occurrence of alien/invasive species and emerging pathogens for the local fauna; (iv) increase in algal and mucilaginous blooms; (v) biodiversity loss; (vi) habitat degradation and change in species abundance and distribution.

Sea surface temperature (SST) is a key climate variable since it deeply contributes to regulating climate and its variability (Deser et al., 2010).

SST is then essential to monitor and characterise the state of the global climate system (GCOS 2010). Long-term SST variability, from interannual to decadal timescales, provides insight into the slow variations/changes in SST, i.e. the temperature trend (e.g., Pezzulli et al., 2005). In addition, SST anomalies are an essential indicator for extreme events (Hobday et al., 2018).

The Mediterranean Sea is a climate change hotspot (Giorgi F., 2006). Indeed, Mediterranean SST are showing a continuous warming trend since the beginning of 1980s (Pastor et al., 2020). Specifically, since the beginning of the 21st century (from 2000 onward), the Mediterranean Sea featured the highest SSTs and this warming trend is expected to continue throughout the 21st century (Kirtman et al., 2013).

Together with seawater temperature, DO is an important parameter in assessing water quality because of its influence on the presence and distribution of marine organisms (Armenio et al; 2018; De Padova et al.; 2023). The amount of dissolved oxygen varies with depth, due to the presence of photosynthetic processes mostly within the euphotic zone, i.e. until the limit of the presence of photophilous algae and seagrass. DO also varies depending on temperature, pressure and salinity (Song et al., 2019).

The Adriatic has recently been found to be an important area for mesophotic and deep coral habitats, including cold-water coral frameworks and coral forests (Chimienti et al. 2020a). All these habitats are mostly created by suspension feeders, such as corals, which are supported by the peculiar seawater circulation and the main physical-chemical features that characterize the basin (Chimienti et al., 2020b). The persistence of appropriate water circulation is essential to maintain these habitats healthy and to guarantee the several ecosystem goods and services they provide (Ponti et al. 2018; Rivetti et al., 2014).

In this study, the spatial and temporal variability of large-scale circulation, mixing of intermediate water, temperature (T), salinity (S) and DO was analyzed to assess the variation trend in the main physico-chemical factors shaping the biota of the Adriatic basin, particularly at mesophotic depths.

2. *Materials and Methods*

2.1 Study area

The Adriatic Sea is generally approximated as a rectangular basin 800 km long and 200 km wide, connected to the rest of the Mediterranean Sea through the Otranto Strait (72 km wide and 780 m deep). The Adriatic is generally divided into three sub-basins: (i) the northern Adriatic, with a maximum depth of about 100 m, influenced by the largest river contribution in the whole basin (Cushman-Roisin et al., 2001); (ii) the central Adriatic, with a maximum depth of about 170 m (mean depth of about 140 m); and (iii) the southern Adriatic which reaches a maximum depth of 1233 m. Because of the significant freshwater river discharge, the Adriatic Sea is considered a dilution basin for the whole Mediterranean Sea (Raicich, 1996), and its general circulation has been widely addressed (Mosetti and Lavenia, 1969; Limic´ and Orlic, 1986). Currents are under the influence of the thermohaline gradients (Orlìc et al., 2006), with the Adriatic thermohaline circulation consisting of a dense water outflow along the western Adriatic coast (Western Adriatic Current, WAC) and a balanced advection of saline water inflow along the eastern Adriatic coast (Eastern Adriatic Current, EAC).

In the shallow northern Adriatic shelf, the air–sea heat and evaporative fluxes are responsible of the formation of the densest water of the whole Mediterranean (North Adriatic Dense Water - NAdDW) (Robinson et al., 1992). NAdDW sinks to the bottom, flows southwards as a bottom density-driven current and eventually spills over the Otranto Strait, contributing to the formation of the deep waters in the eastern Mediterranean (Vilibìc and Supìc, 2005).

In the southern Adriatic, the open-ocean vertical convection processes, facilitated by the quasi-permanent cyclonic gyre, lead to a dense water formation (Adriatic Dense Water – AdDW) contributing to the rising of the intermediate layer saline waters close to the surface. Eastern Adriatic Current (EAC) enters the Adriatic through the Otranto Sill on its eastern side and consists of the Ionian Surface Water (ISW) at the surface layer and of the Levantine Intermediate Water (LIW) at the intermediate layers of the Adriatic. Part of the EAC recirculates along its northward flow, forming several permanent structures (South Adriatic, Middle Adriatic and North Adriatic gyres). However, part of the EAC occasionally reaches the northernmost part of the basin (Poulain 2001).

2.2 Remote sensing data and processing

The data by the Mediterranean Sea Physics Reanalysis (MEDSEA) (Escudier et al.; 2020) provided by Copernicus Marine Environment Monitoring Service (CMEMS) were used to define the spatial variability of environmental parameters (u-v velocities, T, S and DO) on interannual to intraseasonal time scales from 2010 to 2020 in the Adriatic Sea. The modeling system has a horizontal grid resolution of 1/24° and 141 unevenly spaced vertical levels and is forced by ECMWF ERA5 (1/4° horizontal, 1-hour temporal resolution) atmospheric fields (Coppini et al., 2021).

The vertical profiles of T, S and DO have been analyzed at three points in the Adriatic Sea (Fig. 1) representing Northern Adriatic (NA), Central Adriatic (CA) and Southern Adriatic (SA).

SST data were also extracted from Earth Observation satellite data provided by CMEMS in order to estimate the trends in SST from 2010 to 2020. Daily gap-free (L4) maps at ultra-high (0.01°) spatial resolution operationally produced from a collection of the original L2P data from different producers (e.g. NASA, NOAA, ESA) have been used (Buongiorno Nardelli et al., 2013).

Fig. 1: Location of the analysed three points in the Adriatic Sea

To evaluate temporal trends of all the parameters considered in this study, the Seasonal-trend decomposition based on Locally wEighted Scatterplot Smoothing (LOESS), known as STL, was used (Cleveland et al 1990). STL decomposition is a filtering procedure for decomposing a seasonal times series (Y_t) into three components: trend (T_t), seasonal (S_t) and residual (I_t):

$$Y_t = T_t + S_t + I_t \qquad (1)$$

T_t represents an upward or downward movement over the time horizon; St is the repetitive pattern over time; and It is the stochastic residual after the other components have been removed.

3. Results

3.1 Water temperature

Daily water-column temperature data from MEDSEA showed the overall increase of water temperature from the surface down to 50 m depth during late spring and summer with a marked warming trend from 2015 up to date (Fig. 2a÷2c).

The surface temperatures exhibit a strong positive trend in the first 20 m (up to 3°C), which is most probably a result of increased heat uptake by the sea (Somot et al. 2006).

Seawater temperature below 30 m depth broadly increased by ~ 2 °C from 2016 to 2020, particularly in the CA and SA, from late spring to early autumn. A general warming trend is also evident considering STL analysis for all the sites considered (Fig. 3).

Trend in water temperatures show different intensities for the three sites, with the highest in the northern area, showing that the NA is warming up faster than the rest of the basin.

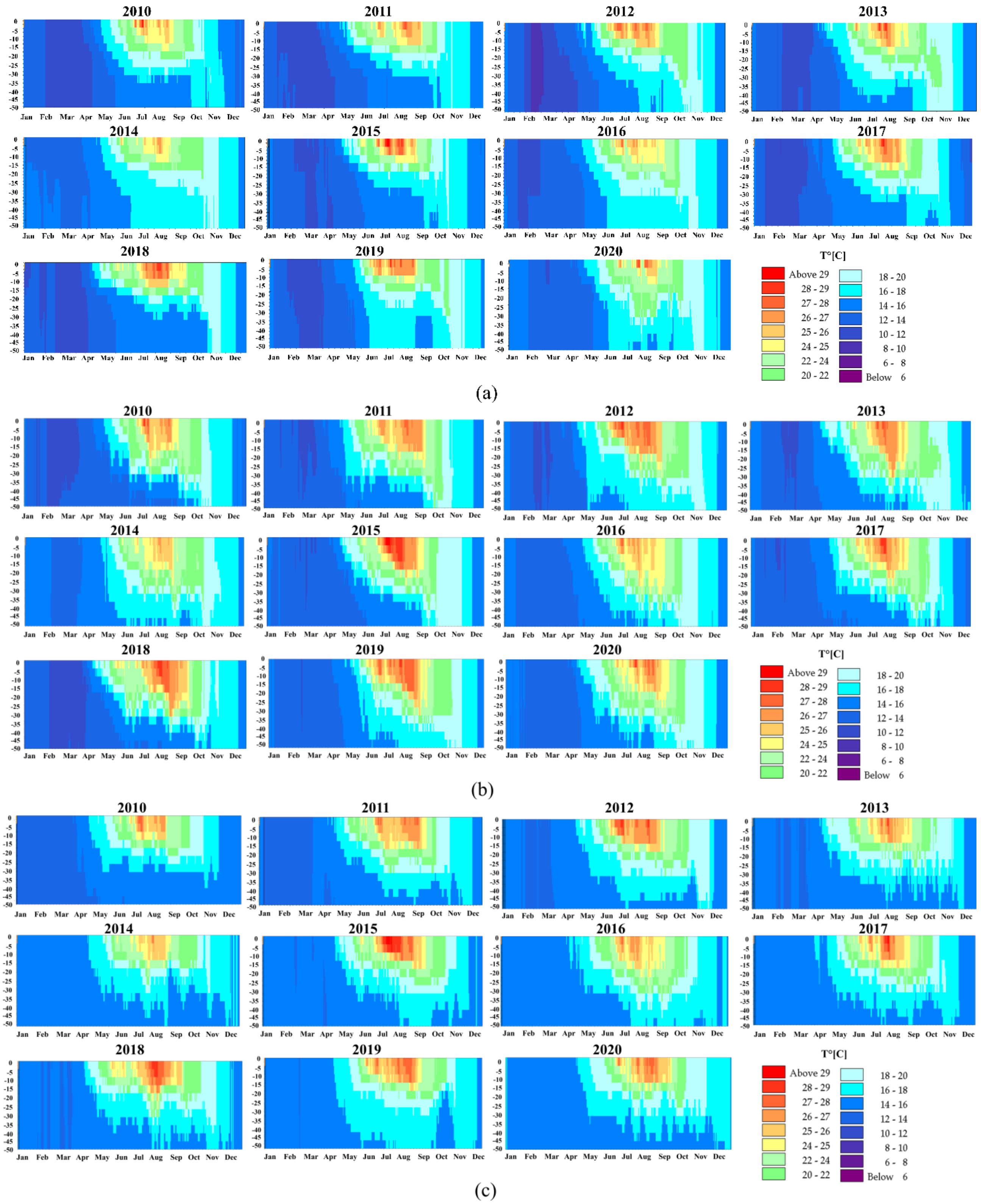


Fig. 2: Vertical profiles of water temperature at (a) northern (NA), central (CA) and southern (SA) Adriatic Sea.

The trend in water temperature in NA seems also to be progressively more marked with the depth

The trend analysis on SST data acquired by satellite sensors (Fig. 4) confirmed the trends observed for MEDSEA data.

3.2 Water temperature, Salinity and Dissolved Oxygen

In Figure 5 the temporal profiles of the trend component of Salinity for NA (a), CA (b) and SA (c) at different depths are shown.

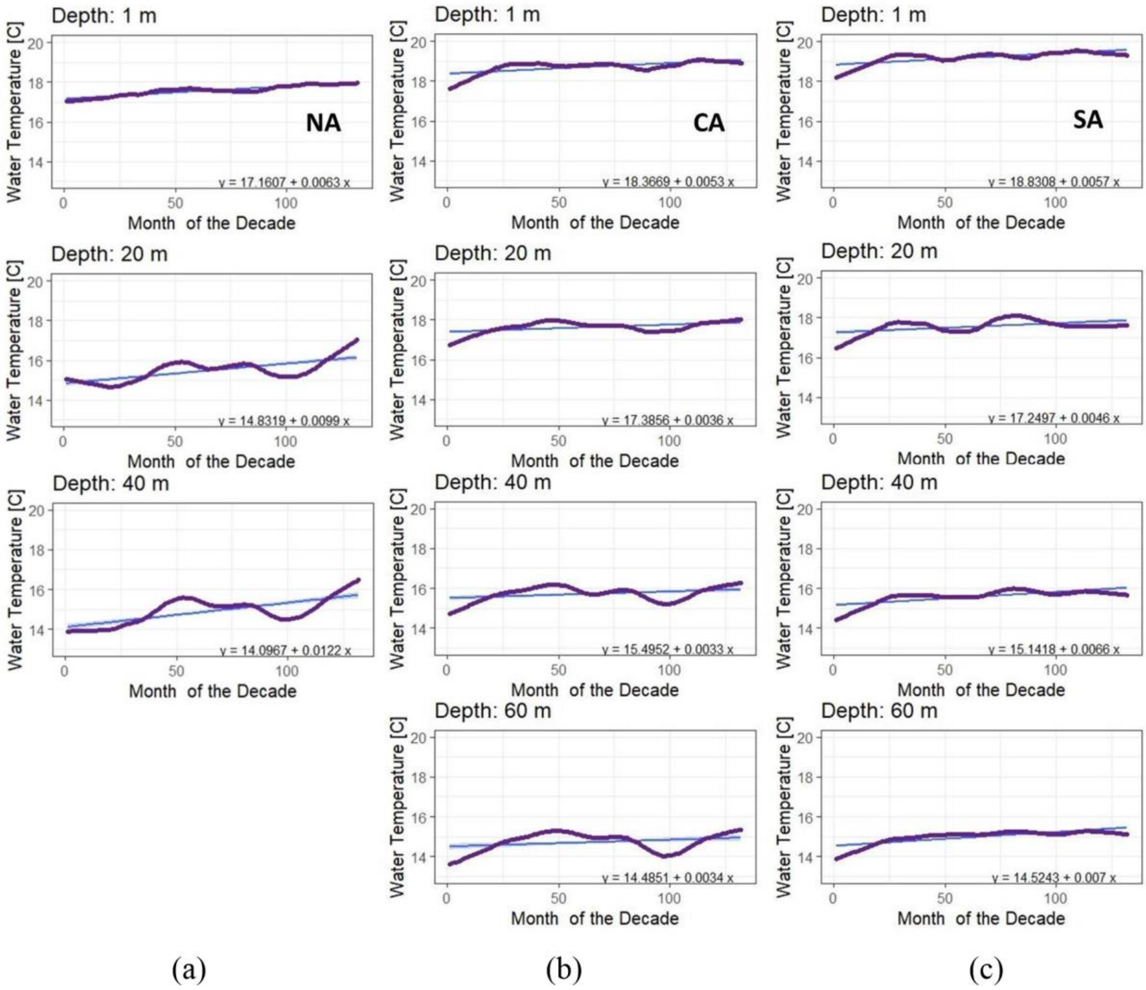


Fig. 3: STL trend component and linear regression of MEDSEA water temperatures at NA (a), CA (b) and SA (c) between 2010 and 2020 at different vertical levels

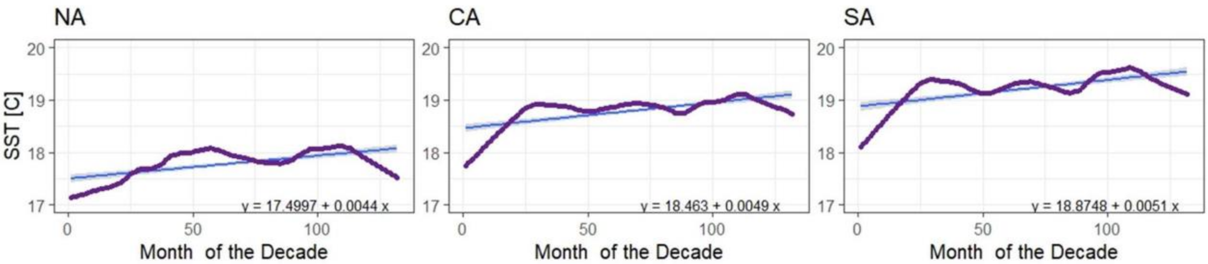
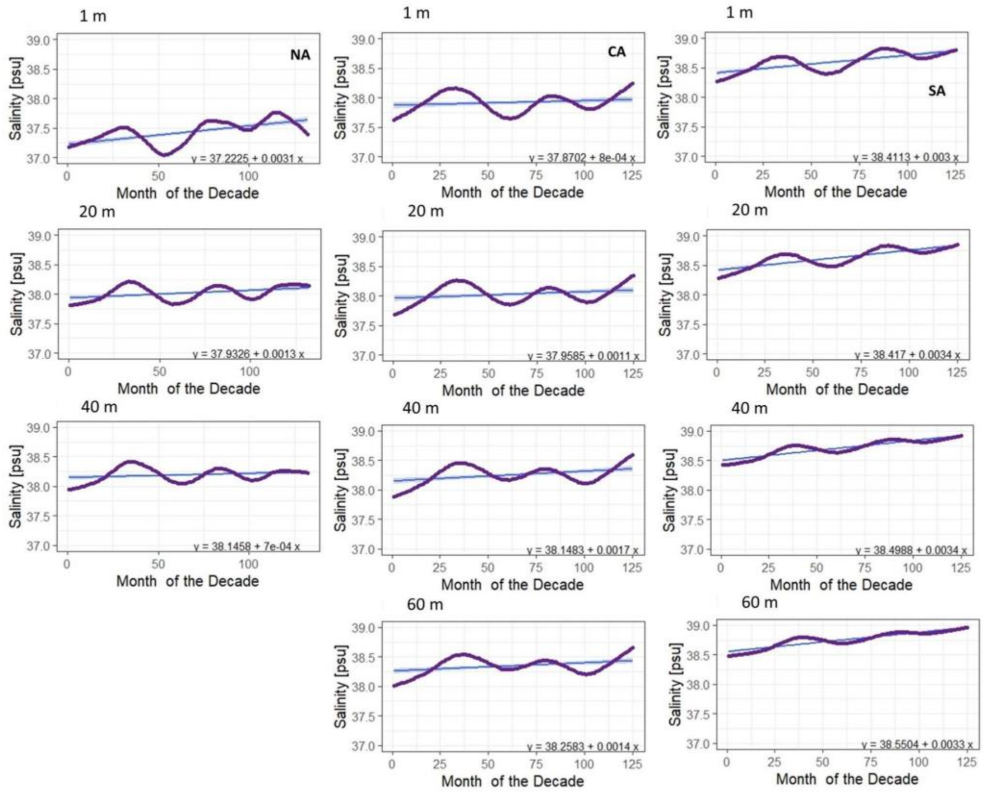
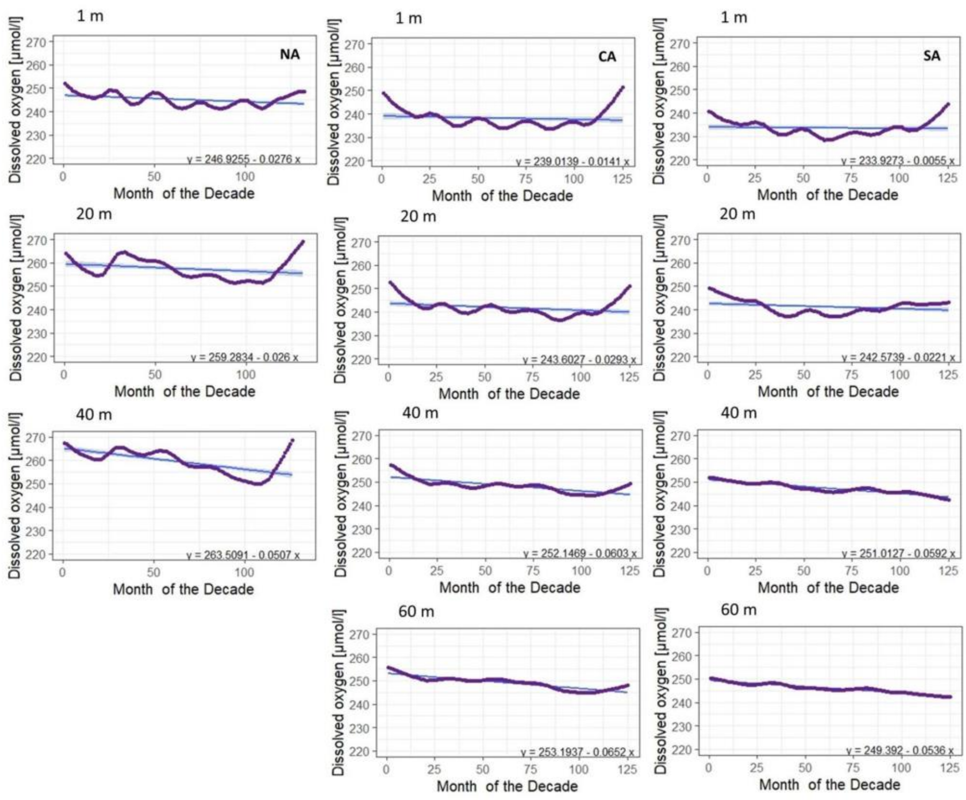


Fig. 4: STL trend component and linear regression of satellite-derived SST between 2010 and 2020.



(a) (b) (c)

Fig. 5: STL trend component and linear regression of MEDSEA Salinity for NA (a), CA (b) and SA (c) between 2010 and 2020, at different vertical levels.



(a) (b) (c)

Fig. 6: STL trend component and linear regression of MEDSEA Dissolved Oxygen for NA (a), CA (b) and SA (c) between 2010 and 2020, at different vertical levels.

The salinity trends confirm a general increase over time following the observed changes in the thermohaline circulation.

The strongest increase is found over the areas influenced by the rivers, indicating a significant decrease in the river runoff. The decrease of river runoff, along with the enhancement of evaporation, is a major mechanism for projected salinity increase in the Mediterranean.

In particular, it can be noted that:

1) in NA the greater increase of S at the surface (compared to deeper layers) may be caused by a decrease of river runoff along with the enhancement of evaporation (Fig. 5a).

2) in CA the lowest positive salinity trend is found where the NAdDW occurs (Fig. 5b).

3) in SA the trend intensity remains stable as the depth changes. This can be explained by the joint effect of the increase in SST and by the inflow of saline Levantine waters along the eastern Adriatic coast (SA), indicating a significant increase of the same current (below 20 m) (Fig. 5c).

In Figure 6 the temporal profiles of the trend component of Dissolved Oxygen for NA (a), CA (b) and SA (c) at different depths are shown.

From the temporal analysis carried out on the MEDSEA, DO results in a decreasing trend for all considered areas, which is consistent with the increasing trends observed for T and S. The rate of decrease becomes higher as depth increases.

4. Discussion

In general, the Adriatic water is characterized by a rapid decrease in DO content, a weak salinity increases and a slight temperature increase. High salinity in the northern, middle and southern Adriatic coastal area may be caused by (1) extremely low precipitation and river runoff (Grbec et al.; 2007), accompanied by strong evaporation, which increased the salt content in the surface layer, and (2) enhanced inflow of saline Levantine Intermediate Water (LIW) in the Adriatic (below 20 m).

The largest negative values of DO occurring in the deepest waters may be a result of the increased downward flux of organic matter caused by higher primary production, as well as by the decomposition of the abundant organic matter from mass mortality events.

NA shows highest DO values, probably as a main result of enhanced primary production fuelled by nutrient-rich waters south of the Po River (Penna et al., 2004; Mauri et al., 2007).

Therefore, the results highlight that the ongoing climate processes are altering also the role of Adriatic Sea as a dilution basin for the whole Mediterranean Sea, because of the significant weakening freshwater river discharge (Raicich, 1996).

Our results are in agreement with recent evidences showing that the increased intensity and frequency of marine heat waves and other changes occurring at global scale could be reshaping key coastal marine ecosystems (Garrabou et al. 2022). For instance, the observed trends support the several mass mortality events observed in the Mediterranean Sea, particularly involving corals and sponges (Chimienti el al., 2021). In particular, an unprecedented mortality of the red gorgonian *Paramuricea clavata* has been recently observed at Tremiti Archipelago, in the CA, at 30-35 m depth, potentially due to the overall increasing of water temperate and the lowering of the thermocline, which stresses the gorgonians and triggers massive algal epibiosis (Chimienti el al., 2021).

Despite the rising of water temperatures and the increasing frequency of heatwaves represent the main causes of present and future mass mortality events throughout the Mediterranean (Garrabou et al., 2022), other important parameters such as salinity and dissolved oxygen can provide useful information to better understand these processes and identify them.

5. Conclusion

Environmental monitoring has always been a key element in understanding and managing natural dynamics, but with the evolution of global challenges such as climate change, it is necessary to integrate traditional knowledge with innovative techniques.

The global warming is altering patterns of large-scale circulation, which affects the mixing of oxygen-rich surface waters with deeper oxygen-poor water. It also changes how quickly organisms metabolise and respire, which affects consumption of marine oxygen.

At the sea surface, oxygen is supplied through air-sea gas exchange and from photosynthesising marine plants. The distribution of oxygen is, therefore, governed by a delicate balance of supply from the surface via circulation and mixing and consumption by marine life through respiration.

Earlier studies suggest that these low-oxygen regions are expanding, which could have "dramatic" biological, ecological, economic and climatic consequences. Humans also play an additional role through the input of nutrients to the oceans in coastal regions. Warming affects the sea and its dissolved oxygen content in several ways. In fact, the warmer the water, the less gas can dissolve in it.

The results of this work highlighted that the dramatic oxygen decrease, associated with significant salinity increase from 2010 to date, is a clear sign of the significant weakening freshwater river discharge, of extremely low precipitation and of enhanced inflow of saline Levantine Intermediate Water (LIW) in the Adriatic.

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