

**multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate**

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## 1. Technical references

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### 3. ABSTRACT

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The Mediterranean Sea is a semi-enclosed oligotrophic basin located at mid-latitude characterized by a peculiar west-east trophic gradient mainly driven by the distribution of the sources of nutrients in the area (rivers, convective areas and atmospheric deposition) and the exchanges of water masses at the Gibraltar Strait. The basin is widely recognized as a hot-spot for climate change and the assessment of its effects on the marine environment and, in particular, in the coastal areas, is challenging because of the complex land-sea distribution which characterizes the area with the presence of islands, gulfs and peninsulas. Thus, a proper assessment of the current state and future evolution of the marine ecosystems in the basin under different emission scenarios requires the adoption of high-resolution data that considers the complexity of the region under examination.

In this task, state-of-the-art biogeochemical and physical high-resolution datasets, specifically produced for the Mediterranean Sea, have been used to assess current states and future changes of a set of biogeochemical and physical variables (defined as ocean monitoring indicators or OMIs) that have been identified in collaboration with RETURN WP2 Spoke 8. The selected ocean monitoring indicators are: temperature, salinity, dissolved oxygen, dissolved inorganic carbon (DIC), pH, and trophic index (TRIX). The areas where these indicators have been computed are the northern Adriatic Sea (Proof-of-Concept WP2 Spoke 8) and the Ligurian Sea (with a focus on the area of the Gulf of Genoa in collaboration with Return WP2, WP3 and WP5 Spoke 4).

The analysis of the OMIs in the target areas has revealed the existence, in the last 20 years, of significant trends related to warming, deoxygenation and acidification of seawater that, according to climate projections, will continue and intensify throughout the 21st century, in particular under emission scenario RCP8.5. All the projected changes will be stronger than those observed in previous analysis at the basin scale.

The analysis of the OMIs has shown that climate change will dramatically affect the coastal areas of the Mediterranean Sea with likely significant effects on marine ecosystems and, possibly, on related ecosystem services.



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## 5. Space-Time evolution of acidification, de-oxygenation and eutrophication in specific areas of the Mediterranean Sea

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### 5.1 Present and future tendencies of ocean monitoring indicators in the marine environment (OGS)

#### ■ 5.1.1 Introduction

Dramatic processes such as warming, nutrient decline, changes in net primary production, deoxygenation and acidification of the global ocean are currently affecting and will dramatically impact marine ecosystems during the 21st century (IPCC, 2022).

The Mediterranean Sea is a semi-enclosed oligotrophic basin located at mid-latitude and characterized by a peculiar west-east trophic gradient in the marine environment, mainly driven by the distribution of the sources of nutrients in the area (rivers, convective areas and atmospheric deposition) and the exchanges of water at the Gibraltar Strait (e.g. Crise et al., 1999). At the same time, the basin is characterized by a high level of biodiversity, the presence of hot-spots for fisheries, and significant pressures on the marine environment due to human activities. The basin is widely recognized as a hot-spot for climate change (Giorgi, 2006) with observed rates of climate change exceeding global trends for most pelagic variables (Cramer et al., 2018). The assessment of climate change effects on the marine environment and, in particular, on the Mediterranean Sea and its coastal areas, is well known to be challenging due to a complex and highly variable distribution of the atmospheric forcings (such as wind and heat fluxes, e.g. Reale et al., 2022) over the region, but also to a complex land-sea distribution with the presence of islands, gulfs and peninsulas.

A proper assessment of the recent tendencies of the marine environment in response to climate forcing and of future evolution under different emission scenarios requires the analysis of data with a fine spatial resolution (both vertical and horizontal) that considers the complexity of the region under examination.

In this task, state-of-the-art biogeochemical and physical high-resolution datasets (reanalysis and climate projections), specifically produced for the Mediterranean region, have been used to assess present trends and future changes in a set of biogeochemical and physical variables (hereafter ocean monitoring indicators or OMIs) specifically selected for the marine environment (see section 4.1.3). In particular, the impact indicators have been computed (see section 4.1.2) for the northern Adriatic Sea and the Ligurian Sea (with a focus on the area of the Genoa harbour).

#### ■ 5.1.2 The northern Adriatic Sea and the Gulf of Genoa

As reported in section 4.1.1 and shown in Figure 1, OMIs have been computed for the northern Adriatic and for the Ligurian Sea (with a focus on the area of the Genoa harbour).

The northern Adriatic Sea is a relatively shallow basin located in the eastern Mediterranean. The area is characterized by strong environmental gradients due to the complex orography surrounding the basin, the

presence of strong air-sea interactions, and deep waters formation processes associated with Bora wind episodes. Both physical and biogeochemical dynamics of the coastal areas of the basin are strongly influenced by the presence of the Po river that is one of the major sources of freshwater and nutrients in the Mediterranean Sea. Moreover, the basin is characterized by the presence of coastal lagoons, such as the Venice Lagoon and the Marano-Grado Lagoon, which offer nursery and refuge area for several marine organisms and seabirds, thus supporting lively ecosystems. In the framework of the Return project the northern Adriatic has been identified as Proof-of-Concept by Spoke 8 WP2 (Figure 1 left panel).

The Ligurian Sea is located in the north-western Mediterranean and is characterized by a complex topography of the surrounding area (similar to that observed for the Adriatic Sea). Its dynamics are strongly influenced by the vicinity of the Gulf of Lions, which receives high freshwater input from the Rhone river and represents one of the major deep waters formations areas of the Mediterranean Sea due to the Mistral wind that is associated with significant weather extremes (Morri and Bianchi, 2001). The physical dynamics of the marine environment strongly influence fish and benthic communities in the area (Vietti et al., 2010). Upon the request of the participants of WP2, WP3 and WP5 Spoke 4, OMIs have been calculated for the area of Genoa harbour, one of the most important for the Mediterranean region (Figure 1 right panel).

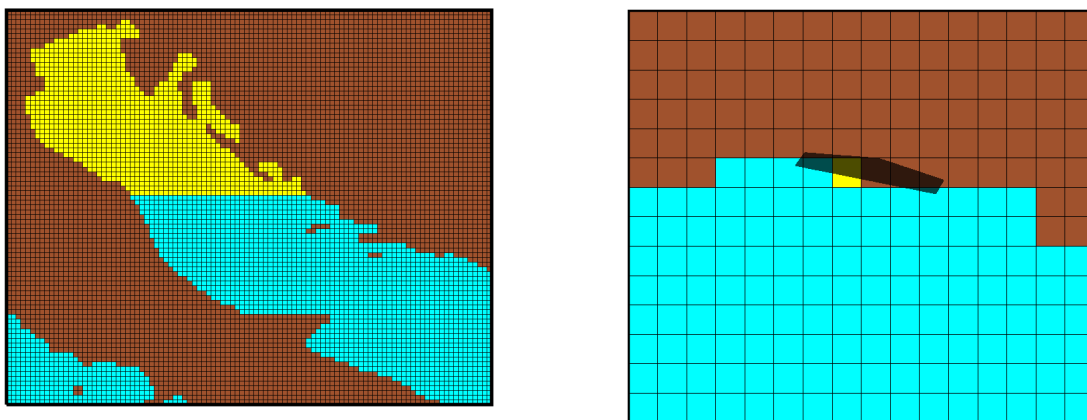


Figure 1 Domain for the analysis (in yellow) for the northern Adriatic Sea (left panel) and Gulf of Genoa (right panel). The grid is based on the reanalysis model.

### ■ 5.1.3 Methodologies

Mean states and temporal trends in key marine ecosystems processes such as net primary production, nutrient cycles, carbon budget and acidification, de-oxygenation and eutrophication are usually assessed by the definition of specific biogeochemical indicators. Recently the EU Copernicus Marine Service (CMS) has developed ocean monitoring indicators (OMIs) for the global ocean and European seas that are defined as

trends and variability indexes of key marine variables (<https://marine.copernicus.eu/access-data/ocean-monitoring-indicators>, Salon et al., 2019). In particular, for ocean biogeochemistry, OMIs are represented by pH, surface chlorophyll-a, CO<sub>2</sub>, nitrate, and oxygen minimum zones.

In this task and in collaboration with the Return WP2 Spoke DS, a series of OMIs were defined and then selected for the analysis. The selected OMIs are: temperature, salinity, dissolved oxygen, dissolved inorganic carbon (DIC), pH, and trophic index (TRIX, Vollenweider et al. 1998).

All the OMIs have been computed at different depths. In the present deliverable only the results related to the sea temperature, dissolved oxygen, DIC and pH in the surface layer will be shown.

#### ■ 5.1.4 Modelling approaches

For each OMI, the monthly time series of the mean values computed at different pre-selected depths have been considered. The datasets used for producing the time series are the following:

3. Copernicus Marine Service (CMS) Mediterranean Physical Reanalysis (Escudier et al., 2021), with a horizontal resolution of 1/24° and 125 vertical levels. The dataset covers the period 1987-2020. The CMS reanalysis features ERA5 as atmospheric forcing, climatological run-off and nutrient discharges for 39 major Mediterranean rivers (including Po, Rhone, Ebro and Nile), and the assimilation of physical variables such as sea surface height (SLA), and vertical profiles of temperature and salinity.
4. Copernicus Marine Service (CMS) Biogeochemical Reanalysis (Teruzzi et al., 2021), with a horizontal resolution of 1/24° and 125 vertical levels. The dataset covers the period 1999-2020. The CMS reanalysis features ERA5 as atmospheric forcing, climatological run-off and nutrient discharges for 39 major Mediterranean rivers (including Po, Rhone, Ebro and Nile), and the assimilation of biogeochemical variables (i.e, satellite chlorophyll-a).
5. High-resolution model outputs of the MITgcm-BFM coupled system for the northern Adriatic Sea (Cossarini et al., 2017; Silvestri et al., 2020) with a horizontal resolution of 1/128° (approximately 700 m) and 27 vertical levels. The physical-biogeochemical dataset covers the period 2006-2017. The modeling system uses as meteorological forcing the outputs from the Regional Climate Modelling system RegCM4 (Giorgi et al., 2012) and from the COSMO-I2 model (IdroMeteoClima Service from ARPAE) and run-off and nutrient discharges from observational data for the major Adriatic rivers (i.e., the Po river and the other 18 minor rivers).
6. High resolution model outputs from two climate/biogeochemical simulations covering the period 2005-2100 under Representative Concentration Pathways (RCP) 4.5 and 8.5 (Reale et al., 2022). The datasets cover the period 2005-2100 with a horizontal resolution of 1/16° (approximately 6 km) and 70 vertical levels. Atmospheric forcing and river run-off come from the CMCC-CM CMIP5 model (Scoccimarro et al., 2011). The nutrient discharges are derived from the Perseus dataset (Van Apeldoorn and Bouwman, 2014).

#### ■ 5.1.4 Results

Figure 2 shows the temporal evolution of the monthly sea surface temperature, dissolved oxygen, DIC and pH in the present climate (1999-2020) and in the future climate (2005-2100) in the selected datasets for the northern Adriatic. A straightforward comparison of the trends estimated from the different datasets in the present climate is not possible due to their different time length.

On the other hand, it is clear that a continuous warming (almost 1°C in the Copernicus Marine Service Reanalysis) of the northern Adriatic Sea surface is recorded in all the datasets starting from 2000 (Figure 2A). The observed warming is timely in phase with the decrease of the dissolved oxygen content of the upper layer (Figure 2C). This is because, together with an increase in ecosystem respiration, an increase in water temperature reduces the solubility of the oxygen (Reale et al., 2022). Moreover, all the datasets agree on the decrease of pH and thus the beginning of the acidification process in the basin (Figure 2E). This process is clearly driven by the increase in DIC (which represents the sum of inorganic carbon species in the marine environment) in the surface layer (Figure 2G) driven, in turn, by the increase of the CO<sub>2</sub> in the atmosphere.

Both climate simulations show that the warming of the sea surface will continue along the 21st century, stronger under RCP8.5 that represents the worst-case scenario. In particular, under this scenario the warming in the northern Adriatic will exceed 5°C, higher than the increase expected for the Mediterranean Sea (4°C, e.g., Reale et al., 2022). Likewise, seawater deoxygenation and acidification will continue along the 21st century, with stronger signals projected under RCP8.5 scenario. In particular, the projected pH decrease will be around 0.30, higher than the value predicted on the basin scale (i.e., -0.20, Reale et al., 2022).

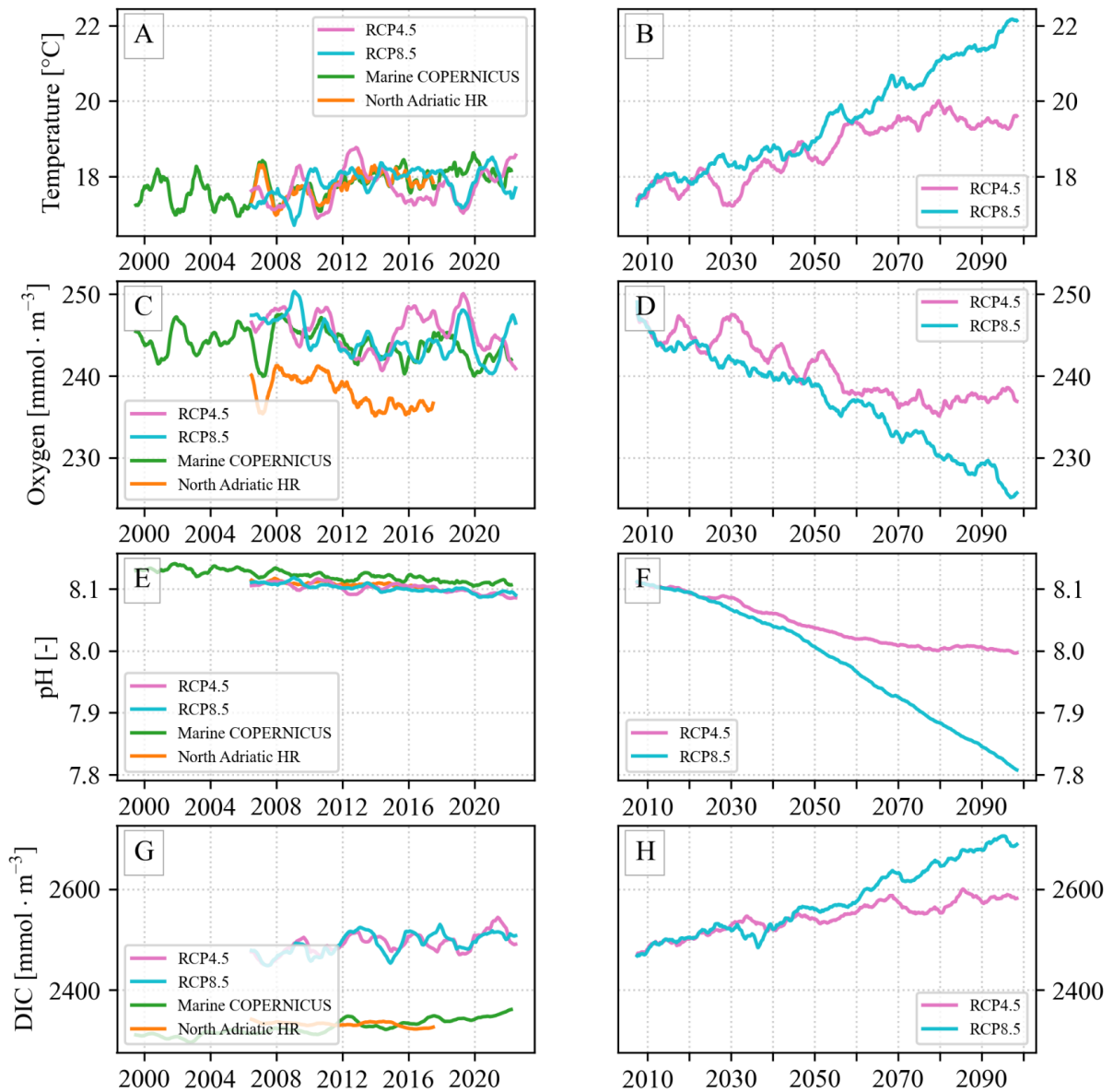


Figure 2 Monthly time series of surface temperature (A, B; in °C), dissolved oxygen (C, D; in  $\text{mmol m}^{-3}$ ), pH (E, F) and DIC (G, H; in  $\text{mmol m}^{-3}$ ) in the present climate 1987-2020 (A, C, E, G) and 2005-2100 under emission scenario RCP8.5 and RCP4.5 (B, D, F, H) in the northern Adriatic Sea. All the time series have been filtered with a moving average with a 120 months window.

A similar warming (Figure 3 A) is observed in the area of the Gulf of Genoa where an increase of almost  $1^{\circ}\text{C}$  has been observed in the last 30 years. The positive trend is present in the CMS reanalysis since the beginning of 2000's. Also oxygen, pH and DIC are characterized by a similar temporal evolution to that observed in the northern Adriatic: a slight decrease in oxygen and a significant decrease (increase) in the pH (DIC) (Figure 3 C, E, G). Also for the Gulf of Genoa the warming, deoxygenation and acidification of the sea surface will continue along the 21st century and will be stronger under RCP8.5 (Figure 3, B, D, F, H) .

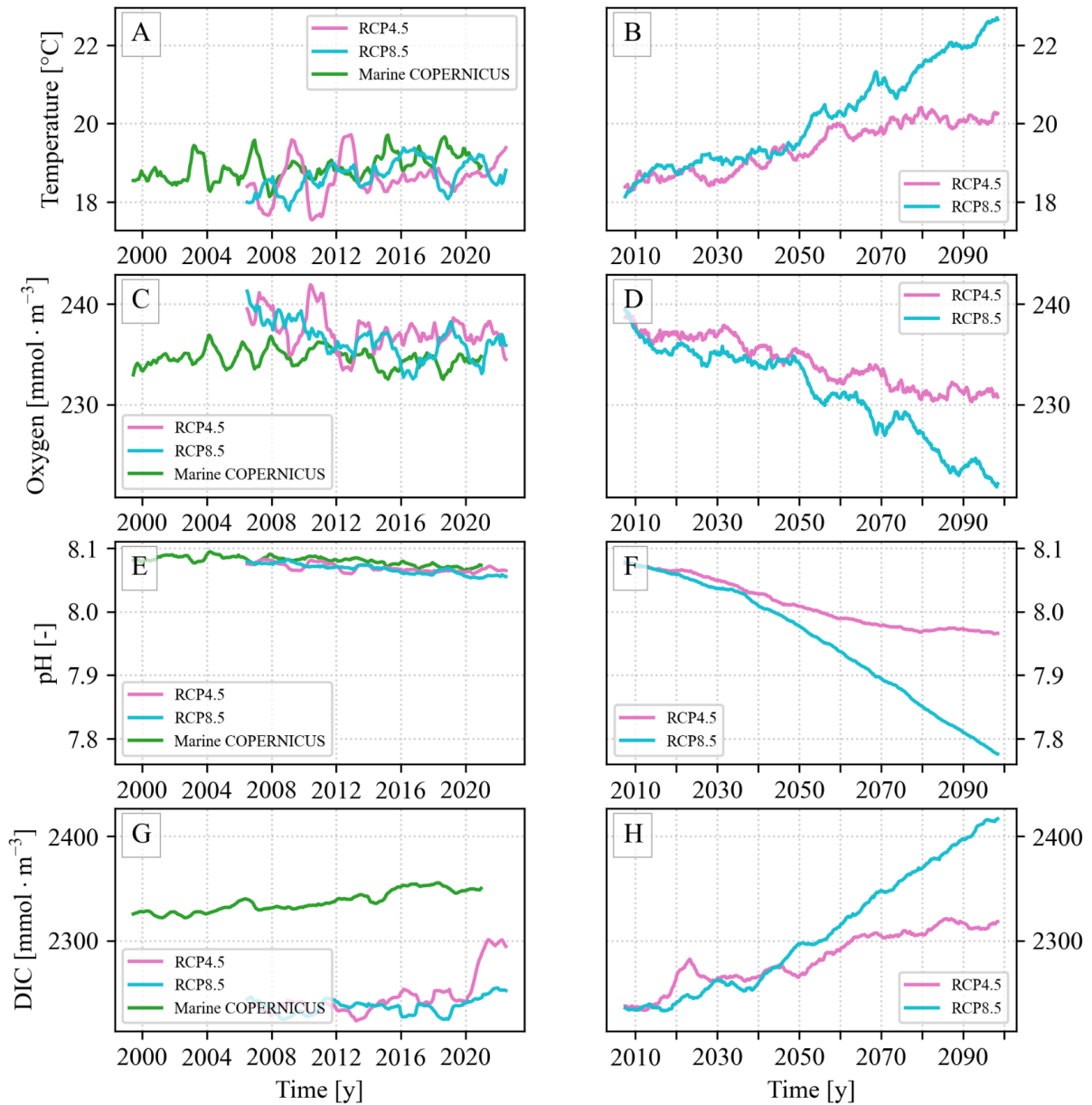


Figure 3 As Figure 2 but for Gulf of Genoa.

### ■ 5.1.5 Scientific products and dissemination

Piani et al.,2024 Biogeochemical indicators for marine ecosystems. Dissemination Workshop, Torino (Italy), 1-2 February 2024. DOI: 10.5281/zenodo.1059800

## 5.2 Conclusions

A series of Oceans Monitoring Indicators (OMIs) has been defined and employed to assess present and future tendencies for a series of key physical and biogeochemical variables characterizing the marine ecosystems within selected sub-basins of the Mediterranean Sea. In this task the selected OMIs (computed at different depths) are represented by temperature, salinity, dissolved oxygen, dissolved inorganic carbon (DIC), pH, and trophic index (TRIX, Vollenweider et al., 1998).

The time series of the OMIs have been computed using start-of-the-art datasets available for the basin: (i) Copernicus Marine Service (CMS) Mediterranean Physical and Biogeochemical Reanalysis (Escudier et al., 2021; Teruzzi et al., 2021), (ii) MITgcm-BFM coupled system for the northern Adriatic Sea (Cossarini et al., 2017; Silvestri et al., 2020) and (iii) climate/biogeochemical simulations covering the period 2005-2100 under Representative Concentration Pathways (RCP) 4.5 and 8.5 (Reale et al., 2022). All these datasets, based on advanced modeling tools, are characterized by a relatively high temporal and spatial resolution and thus they are suitable to provide a better representation of tendencies and variability of the physical and biogeochemical processes in the shallow/coastal areas of the Mediterranean Sea. The areas where these indicators have been computed are represented by the northern Adriatic Sea (Proof-of-Concept WP2 Spoke 8) and by the Ligurian Sea (with a focus on the area of the Gulf of Genoa, upon request of the Return WP2, WP3 and WP5 Spoke 4).

All the datasets show a clear continuous warming, deoxygenation and acidification of the seawater at the surface in two target areas starting from the beginning of 2000's. Moreover, the analysis of climate projections under two different emission scenarios shows that the present trends will intensify along the 21st century, in particular under the RCP8.5 emission scenario, where the projected changes are almost double with respect to the RCP4.5. It is worth mentioning that the projected changes in the target areas will be significantly higher with respect to those observed on the basin scale: for example, the projected temperature and pH changes for future scenarios in the northern Adriatic Sea exceed 5°C and -0.30, respectively. Both values are higher than those observed on basin scale (4°C and -0.20 respectively; e.g., Reale et al., 2022).

The analysis of the OMIs has shown that climate change will strongly affect the shallow coastal areas of the Mediterranean Sea where local factors will likely amplify the effects of global warming. Adverse impacts of climate change on shallow water ecosystems of the Mediterranean Sea have already been reported (e.g., Bertolini et al., 2023), and are expected to exacerbate under likely scenarios of climate change evolution threatening sea life, particularly organisms with reduced motility that are unable to move toward more suitable habitats (Galli et al., 2017). The degradation of marine ecosystems and biodiversity loss will in turn likely hamper the capability to provide essential ecosystem services.

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