# Acidification, deoxygenation, nutrient and biomasses decline in a warming Mediterranean Sea

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12 Abstract. The projected warming, nutrient decline, changes in net primary production, deoxygenation and acidification 13 of the global ocean will affect marine ecosystems during the 21st century. Here the climate change-related impacts in the 14 marine ecosystems of the Mediterranean Sea in the middle and at the end of the 21st century are assessed using high-15 resolution projections of the physical and biogeochemical state of the basin under the Representative Concentration 16 Pathways (RCPs) 4.5 and 8.5. The analysis shows in both scenarios changes in the dissolved nutrient content of the 17 euphotic and intermediate layers of the basin, net primary production, phytoplankton respiration and carbon stock 18 (including phytoplankton, zooplankton, bacterial biomass and particulate organic matter). The projections also show an 19 uniform surface and subsurface reduction in the oxygen concentration driven by the warming of the water column and by 20 the increase in ecosystem respiration, and an acidification signal in the upper water column, linked to the increase in the 21 dissolved inorganic carbon content of the water column due to CO<sub>2</sub> absorption from the atmosphere and the increase in 22 respiration. The projected changes are stronger in the RCP8.5 (worst-case) scenario and, in particular, in the Eastern 23 Mediterranean due to the limited influence of the exchanges in the Strait of Gibraltar in that part of the basin. On the other 24 hand, the analysis of the projections under RCP4.5 emission scenario shows a tendency to recover the values observed at 25 the beginning of the 21st century for several biogeochemical variables in the second half of the period. This result supports 26 the idea - possibly based on the existence, in a system like the Mediterranean Sea, of a certain buffer capacity and renewal 27 rate - that the implementation of policies of reducing CO<sub>2</sub> emission could be, indeed, effective and could contribute to 28 the foundation of ocean sustainability science and policies.

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#### 1. Introduction

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The Mediterranean Sea (Fig. 1) is a mid-latitude semi-enclosed basin surrounded by the continental areas of Southern Keurope, Northern Africa and the Middle East. The basin is characterized by a thermohaline circulation composed of three distinctive cells. The first is an open cell associated with the inflow of the Atlantic Water (AW) at the Strait of Gibraltar (which undergoes a progressive increase in salinity due to evaporation becoming Modified Atlantic Water, or MAW) and the formation of Levantine Intermediate Water (LIW) in the Eastern basin (Lascaratos, 1993; Nittis and Lascaratos, 1998;

38 Velaoras et al., 2019; Fach et al., 2021; Fedele et al., 2021). The other two are closed cells associated with deep water

formation processes occurring in the Gulf of Lion (located in the North Western Mediterranean, Fig.1; Somot et al., 2018
 and reference therein) and in the Adriatic Sea (Fig. 1; Mantziafou and Lascaratos 2004, 2008; Schroeder et al., 2012 and
 references therein).

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43 Future climate projections for the Mediterranean region based on different emission scenarios show, at the end of the 21st 44 century, (i) a reduction in precipitation and a general warming of the area (e.g., Giorgi, 2006; Diffenbaugh et al., 2007; 45 Giorgi and Lionello, 2008; Dubois et al., 2012; Lionello et al., 2012; Planton et al., 2012; Gualdi et al., 2013; MedEEC, 46 2020), (ii) a warming of seawater (Somot et al., 2006; Adloff et al., 2015; Soto-Navarro et al., 2020; MedECC, 2020), 47 and (iii) a consistent weakening of the thermohaline circulation and an increase in the stratification index throughout the 48 basin (Somot et al., 2006; Adloff et al., 2015; Soto-Navarro et al., 2020) and a further increase in frequency and severity 49 of atmospheric and marine heat waves and drought (Galli et al., 2017; Darmaraki et al., 2019; Ibrahim et al., 2021; 50 Mathbout et al., 2021). Conversely, the future evolution of sea surface salinity in the Mediterranean Sea and the sign of 51 its change are still uncertain due to the role played by rivers and Strait of Gibraltar exchanges (Adloff et al., 2015; Soto-52 Navarro et al., 2020; MedECC, 2020). In general, the magnitude of the projected changes has been shown to be dependent 53 on the adopted emission scenario (MedECC, 2020).

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Fig.1 Mediterranean Sea bathymetry (in m) and relative sub-basins considered in the analysis: Alboran Sea (ALB), North
 Western Mediterranean (NWM), South Western Mediterranean (SWM), Tyrrhenian (TYR), Adriatic Sea (ADR), Ionian Sea
 (ION), Aegean Sea (AEG), Levantine basin (LEV). The dark orange line marks the 200m isobath in the model domain. The
 domain boundary is set at longitude 8.8°W, westward of the Strait of Gibraltar.

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From a biogeochemical point of view, the Mediterranean Sea is considered as an oligotrophic (ultraoligotrophic in its
Eastern part) basin (Bethoux et al., 1998; Moutin and Raimbault, 2002; Siokou-Frangou et al., 2010; Lazzari et al., 2012).
It is characterized by low productivity levels and an east-west trophic gradient (Crise et al., 1999; D'Ortenzio and Ribera

d'Alcala 2009; Lazzari et al., 2012) which results from the superposition of different mechanisms such as the biological

pump, the estuarine inverse circulation, and the position of nitrate (NO<sub>3</sub>) and phosphate (PO<sub>4</sub>) sources (Crise et al., 1999;

66 Crispi et al., 2001). The only exceptions to the oligotrophy of the basin are some areas (Gulf of Lion, Strait of Sicily, 67 Algerian coastlines, Southern Adriatic Sea, Ionian Sea, Aegean Sea and Rhodes Gyre) where strong vertical mixing and 68 upwelling phenomena associated with air-sea interactions and wind stress forcing enrich the surface in nutrients, so 69 favouring phytoplankton rapid growth (or bloom) mostly in the late winter-early spring period (D'Ortenzio and Ribera 70 d'Alcala, 2009; Reale et al., 2020b). A proxy widely adopted to detect phytoplankton blooms is the surface concentration 71 of chlorophyll-a that is characterized by relative high values in specific open sea/coastal areas, where it is linked to the 72 physical forcing and river inflow (D'Ortenzio and Ribera d'Alcala, 2009; Lazzari et al., 2012; Herrmann et al., 2013; 73 Auger et al., 2014; Richon et al., 2018; Di Biagio et al., 2019; Reale et al., 2020a). The open sea chlorophyll-a vertical 74 dynamics follows a seasonal cycle with winter-early spring surface blooms, and summer onset of a deep chlorophyll-a 75 maximum (DCM) which deepens from approximately 50 m in the Western areas to 100 m in the Eastern areas (e.g. 76 Lazzari et al., 2012; Macias et al., 2014; Lavigne et al., 2015; Cossarini et al., 2021).

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Due to the strong links between ocean/atmosphere dynamics and biogeochemical patterns, it has to be expected that future climate change will have relevant impacts on the biogeochemistry and, in turn, on the marine ecosystem dynamics of the Mediterranean Sea. In fact, all the projected changes for the region will likely affect the vertical mixing and reduce the nutrient supply into the euphotic layer of the Mediterranean Sea (e.g. Richon et al., 2019), which is essential for phytoplankton dynamics and productivity, with possible impacts on the biogeochemical carbon cycle and CO<sub>2</sub> exchange with the atmosphere (e.g., Lazzari et al., 2012; Cossarini et al., 2015; Canu et al., 2015; Solidoro et al., 2022).

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85 An assessment of the effects of climate change on the biogeochemistry and marine ecosystem dynamics of the 86 Mediterranean Sea has been considered in a number of previous studies based on different emission scenarios. Hermann 87 et al. (2014) assessed the response of the pelagic planktonic ecosystem of the North Western Mediterranean to different 88 emission scenarios and showed that, at end of the 21st century, the biogeochemical processes and marine ecosystem 89 components should be very similar to those observed at the end of the 20th century, although quantitative differences 90 might be observed, such as an increase in the bacteria growth, gross primary production and biomass of small-size 91 phytoplankton group. Lazzari et al. (2014) found a negative change in the plankton biomass in response to the A1B 92 emission scenario, resulting from an increase of productivity and community respiration. Benedetti et al. (2018), using 93 environmental niche models and considering six physical simulations based on different emission scenarios (A2, A2-F, 94 A2-RF, A2-ARF, A1B-ARF, B1-ARF; Adloff et al., 2015), projected, in response to climate change, a loss of copepods 95 diversity throughout most of the surface layer of the Mediterranean Sea. On the other hand, Moullec et al. (2019) under 96 RCP8.5 emission scenario found an increase/decrease in both phytoplankton biomass and net primary production by the 97 end of the 21st century in the Eastern/Western Mediterranean Sea. Macias et al. (2015) showed that, under emission 98 scenarios RCP4.5 and RCP8.5 and despite a significant observed warming trend, the mean integrated primary production 99 rate in the entire basin will remain almost unchanged in the 21st century. However, they pointed out some peculiar spatial 100 differences in the basin such as an increase in the oligotrophy of the Western basin due to a surface density decrease and 101 an increase in net primary production in the Eastern basin due to the increased density. Richon et al. (2019) observed, 102 under the A2 emission scenario (which is similar to the RCP8.5 emission scenario in terms of magnitude of the projected 103 changes in the global mean temperature), an accumulation of nitrate in the basin and a reduction of 10% in net primary 104 productivity by 2090, with a peak of 50% in specific areas (including the Aegean Sea). On the other hand, no tendencies 105 in the phosphorus were observed. Pagès et al. (2020) showed, under emission scenario RCP8.5, a decline in the nutrient

106 concentration (stronger in NO<sub>3</sub> than PO<sub>4</sub>) at the surface of the basin due to the increase in the vertical stratification and 107 pointed out that the Mediterranean Sea will become less productive (14% decrease in integrated primary production in 108 both Western and Eastern basins) and will be characterized by a reduction (22% in the Western basin and 38% in the 109 Eastern basin) in large phytoplankton species abundance in favor of small organisms. All these changes will mainly affect 110 the Western basin, while the Eastern basin will be less impacted (Pagès et al., 2020). Solidoro et al. (2022) discussed the 111 evolution of the carbon cycling, budgets and fluxes of the basin under the A2 scenario, highlighting an increase in the 112 trophodynamic carbon fluxes and showing, at the same time, that the increment in the plankton primary production will 113 be more than compensated by the increase in the ecosystem total respiration, which corresponds to a decrease of the total 114 living carbon and oxygen in the epipelagic layer. Moreover, Solidoro et al., (2022) also projected an increase of dissolved 115 inorganic carbon (DIC) pool and quantified for the first time the related acidification of the basin, a process that might 116 significantly alter the Mediterranean ecosystems (Zunino et al., 2017; 2019) and their capability to sustain ecosystem 117 services (Zunino et al., 2021).

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All the above-mentioned works demonstrate that the dynamics of the marine ecosystem may be affected directly and indirectly by climate change and the magnitude of their response is dependent on the emission scenario adopted. Different levels of warming, acidification and changes in the vertical distribution of the oxygen, nutrient concentration and net primary production related to water column stratification are all potential marine stressors affecting marine organisms and ecosystem dynamics (see Kwiatkowski et al., 2020 for a review about the synergistic effects among potential marine stressors).

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A proper simulation of these marine stressors and related impacts require the adoption of suitable horizontal and vertical resolutions. In fact, it has been shown that meso and submesoscale structures of the Mediterranean circulation influence indeed the biogeochemical dynamics of many areas of the basin (Moutin and Prieur, 2012; Richon et al., 2019), while the vertical resolution affects the features of the simulated stratification and subsurface ventilation pathways (see Kwiatkowski et al., 2020 and reference therein for a review).

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132 These considerations emphasize the importance of providing eddy-resolving future projections of the Mediterranean Sea 133 biogeochemistry under different emission scenarios. In fact, although observational and modeling studies have been 134 already carried out in the recent period to assess the importance of the mesoscale dynamics on the physical and 135 biogeochemical state of limited areas of the Mediterranean Sea (e.g. Hermann et al., 2008; Moutin and Prieur, 2012; 136 Guyennon et al., 2015; Ramirez-Romero et al., 2020), long-term eddy-resolving biogeochemical projections under 137 different emission scenarios, to the best of the authors' knowledge, have not been analyzed so far in the region. Such 138 projections might be used in future studies specifically focused on the analysis of climate change impact on specific 139 organisms, habitats and/or local areas.

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141 Therefore, here climate change-related impacts in the marine ecosystems of the Mediterranean Sea in the middle and at

142 the end of the 21st century are assessed using eddy-resolving projections of the physical and biogeochemical state of the

basin under emission scenarios RCP4.5 and RCP8.5. These projections are derived from the offline coupling between the

144 physical model MFS16 (Mediterranean Forecasting System at 1/16°; Oddo et al., 2009) and the transport-reaction model

145 OGSTM-BFM (OGS Transport Model-Biogeochemical Flux Model; Lazzari et al., 2012). The analysis focuses on 21st

146 century projected changes of dissolved nutrients and oxygen, net primary production, respiration, living/non-living 147 organic matter, plankton and bacterial biomass, and particulate organic matter (POC). Moreover, the response of the basin 148 to the increasing atmospheric CO<sub>2</sub> concentrations is thoroughly investigated. The projected changes are also correlated 149 with changes in the physical forcing in the region.

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151 The article is organized as follows: the MFS16-OGSTM-BFM system along with the physical forcing used to drive the 152 biogeochemical scenarios, initial and boundary conditions and numerical experiments are described in Section 2. Section 153 3 discusses the projected changes in climate change-related impacts in the marine ecosystems of the Mediterranean basin. 154 Finally, Section 4 summarizes and discusses the results of this work, together with their uncertainties, paving the way for 155 possible future research avenues.

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#### 1. Data and Methods

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159 The biogeochemical projections of the Mediterranean Sea state during the 21st century have been produced by driving 160 the transport-reaction model OGSTM-BFM (Lazzari et al., 2012) with the 3D outputs of the physical model MFS16 161 (Oddo et al., 2009) through an off-line coupling. In fact, the physical model MFS16 supplies to the OGSTM-BFM the 162 temporal evolution of daily horizontal and vertical current velocities, vertical eddy diffusivity, potential temperature, 163 salinity, and surface data for solar shortwave irradiance and wind stress. The resulting transport processes affecting the 164 concentration of biogeochemical tracers (advection, vertical diffusion and sinking) are computed by OGSTM, which is a 165 modified version of the OPA tracer model (Océan PArallélisé, Foujols et al., 2000). The temporal evolution of 166 biogeochemical processes is computed by the Biogeochemical Flux Model (BFM; Vichi et al., 2015).

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#### 168 2.1. The MFS16 physical model

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170 MFS16 is the Mediterranean configuration of the NEMO modelling system (Nucleus for European Modelling of the 171 Ocean; Madec, 2008; see also http://www.nemo-ocean.eu, version 3.4) and constitutes the climate implementation of the 172 Mediterranean Ocean Forecasting System (Oddo et al., 2009; Lovato et al., 2013).

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174 The original MFS16 domain covers the whole Mediterranean Sea and part of the neighboring Atlantic Ocean region with 175 a horizontal grid resolution of 1/16° (~6.5 km) and 72 unevenly spaced vertical levels (ranging from 3 m at the surface 176 down to 600 m in the deeper layers, see Lovato et al., 2013). The model computes the air-sea fluxes of water, momentum 177 and heat using specific bulk formulae tuned for the Mediterranean Sea (Oddo et al., 2009) applied to the atmospheric 178 fields obtained from the atmosphere-ocean general circulation model CMCC-CM (CMCC-Coupled model; Scoccimarro 179 et al., 2011).

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181 The open boundary conditions in the Atlantic region for the physical variables (zonal/meridional component of current 182 velocity, sea surface height, temperature and salinity) were derived from the ocean component of the CMCC-CM coupled 183 model, while the riverine freshwater discharges and fluxes in the Dardanelles Strait were provided by the hydrological 184 component of the same coupled model (Gualdi et al., 2013). The initial conditions of the Mediterranean Sea were obtained 185 from the gridded temperature and salinity data produced by the SeaDataNet infrastructure (http://www.seadatanet.org/).

186 The model was initially spun-up for 25 years under present climate conditions and then scenario simulations were 187 performed over the 2005-2100 period.

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#### 189 2.2. The OGSTM-BFM transport-reaction model

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The OGSTM-BFM transport-reaction model is based on the coupling of a transport model (OGSTM) based on the OPA system (Foujols et al., 2000) and the BFM biogeochemical reactor. OGSTM-BFM is fully described in Lazzari et al. (2012, 2016), where it was used to simulate chlorophyll-*a*, primary production and nutrient dynamics of the Mediterranean Sea for the 1998-2004 period.

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196 The OGSTM transport model resolves the advection, vertical diffusion and the sinking terms of the biogeochemical 197 tracers. The temporal scheme of OGSTM is an explicit forward temporal scheme for the advection and horizontal 198 diffusion terms, whereas an implicit time scheme is adopted for the vertical diffusion. The BFM biogeochemical reactor 199 considers co-occurring effects of multi-nutrient interactions and energy/material fluxes through the classical food chain 200 and the microbial food web which are both very important in the Mediterranean Sea (Bethoux et al., 1998). BFM has 201 been extensively applied to the studies of the dynamics of dissolved nutrients, chlorophyll-a and net primary production 202 in the Mediterranean Sea (Lazzari et al., 2012; 2016; Di Biagio et al., 2019; Reale et al., 2020a), marine carbon 203 sequestration and alkalinity (Canu et al., 2015; Cossarini et al., 2015; Butenschön et al., 2021), impacts of climate change 204 on the biogeochemical dynamics of marine ecosystems (Lazzari et al., 2014; Lamon et al., 2014; Solidoro et al., 2022), 205 influence of large-scale atmospheric circulation patterns on nutrient dynamics (Reale et al., 2020b) and operational short-206 term forecasts for the Mediterranean Sea biogeochemistry (Teruzzi et al. 2018; 2019; Salon et al., 2019). The version 207 adopted here is the v5.

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209 The model simulates the biogeochemical cycles of carbon, nitrogen, phosphorus and silicon through dissolved forms and 210 living organic and non-living organic compartments (labile, semi-labile and semi-refractory organic matter). Moreover, 211 it presently includes nine plankton functional types (PFTs), meant to be representative of diatoms, flagellates, 212 picophytoplankton, dinoflagellates, carnivorous and omnivorous mesozooplankton, bacteria, heterotrophic 213 nanoflagellates and microzooplankton. It also simulates the carbonate system dynamics, by solving the set of physico-214 chemical equilibria related to total alkalinity (ALK) and dissolved inorganic carbon (DIC) chemical reactions (Cossarini 215 et al., 2015). Total alkalinity variability is driven by processes that alter the ion concentration in seawater (nitrification, 216 denitrification, uptake and release of nitrate, ammonia and phosphate by plankton cells, and precipitation and dissolution 217 of carbonate calcium-CaCO<sub>3</sub>, see Wolf-Gladrow et al., 2007). DIC dynamics are driven by biological processes 218 (photosynthesis and respiration, precipitation and dissolution of CaCO<sub>3</sub>) and physical processes (CO<sub>2</sub> exchanges at the 219 air-sea interface and, as for all the other biogeochemical tracers, dilution-concentration due to evaporation minus 220 precipitation processes).

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#### 222 2.3. Initial and boundary conditions for the biogeochemistry

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Boundary conditions are adopted to represent the external supply of biogeochemical tracers and properties from the Strait of Gibraltar and the rivers into the Mediterranean basin. The exchanges of nutrients and other biogeochemical tracers in 226 the Strait of Gibraltar are achieved by relaxing the 3D fields in the Atlantic zone (Fig. 1) to average vertical profiles 227 which, for dissolved oxygen, phosphate, nitrate and silicate, refer to Salon et al. (2019), while total alkalinity is based on 228 what was described in Cossarini et al. (2015). These profiles do not consider a seasonal cycle or a future temporal 229 evolution, with DIC as the only exception, which is prescribed from a global ocean-climate simulation under RCP8.5 230 emission scenario performed within the framework of the CMIP5 project (Coupled Model Intercomparison Project Phase 231 5; Taylor et al., 2012) and based on the CMCC-CESM modeling system (CMCC-Coupled Earth System Model; Vichi et 232 al., 2011). The reasons for these choices rely on: (i) anomalous values observed in N:P ratio under the RCP8.5 emission 233 scenario, (ii) negligible variation, under emission scenario RCP8.5, of the total alkalinity along the 21st century, (iii) lack 234 of a consistent RCP4.5 scenario, (iv) the possibility, using the same conditions at the Atlantic boundary, to test the impacts 235 of the different atmospheric and ocean forcings. Riverine inputs of phosphate, nitrate, dissolved oxygen, total alkalinity 236 and DIC are based on the PERSEUS FP7-287600 project dataset (Policy-oriented marine environmental research in the 237 Southern European seas; Van Apeldoorn and Bouwman, 2014) and, also in this case, do not include temporal evolution 238 in the future scenarios.

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As observed in previous works (e.g. Richon et al., 2019), a transient scenario for the evolution of the atmospheric deposition of nitrogen and phosphorus over the Mediterranean Sea is presently not available. Following Di Biagio et al. (2019) and Reale et al. (2020a), the atmospheric deposition of phosphate and nitrate is parametrized as a mass flux at the surface and is set for the entire basin equal to 4780 Mmol year<sup>-1</sup> for phosphate and 81275 Mmol year<sup>-1</sup> for nitrate. Additional boundary conditions consider the sequestration of inorganic compounds in the marine sediment at the seabed.

- 246 The Representative Common Pathway (RCP) 4.5 and 8.5 emission scenarios (Moss et al., 2010) were used to force the 247 coupled physical-biogeochemical MFS16-OGSTM-BFM system. RCP4.5 represents an intermediate scenario in which 248 CO<sub>2</sub> emissions peak around 2040 (causing the maximum increase in CO<sub>2</sub> concentration), and then decline (with a resulting 249 CO<sub>2</sub> concentration plateau) while the RCP8.5 represents the worst-case scenario, in which CO<sub>2</sub> emissions (eventually 250 driven by feedback effects such as the release of greenhouse gasses from the permafrost) will continue to increase 251 throughout the 21st century, and the pCO<sub>2</sub> concentration will rise to more than 1200 ppm at the end of the 21st century 252 (IPCC, 2014). Recently some authors have begun to consider the RCP8.5 scenario as "implausible", being based, for 253 example, on a large use of coal, larger than its effective availability at the end of 21st century (e.g. Hausfather and Peters, 254 2020). On the other hand, it is still widely used to assess in the Mediterranean region the potential risks (also in the marine 255 ecosystems) emerging in an extreme warm world climate (5 °C) with respect to the pre-industrial era (IPCC, 2014). 256 Because of that the projections under this emission scenario are still discussed here.
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The initial conditions for the dissolved oxygen, nutrient, silicate and carbonate system variables are based on Medar Medatlas dataset (Mediterranean Data Archeology and Rescue-Mediterranean Atlas), as described in Cossarini et al.
 (2015) and Salon et al. (2019).

Finally, all the simulations discussed in the next sections, use as initial conditions the resulting final fields from a run that started in January, 1st 2005 following a spin-up of 100 years made with a loop over the 2005–2014 period for the physical forcing, the river nutrient discharge and atmospheric forcing (nutrient deposition and CO<sub>2</sub> air value).

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#### 266 2.4. Simulations protocol and set-up

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268 Long-term simulations can be affected by drifts in state variables due to the imbalance among boundary conditions, 269 transport processes and internal element cycle formulations of the biogeochemical model. Therefore, a specific simulation 270 protocol, based on the use of a control/scenario pair of simulation, has been implemented in order to disentangle the 271 climate change signal from spurious signals (Solidoro et al., 2022). The protocol consists of a control simulation (CTRL) 272 of 95 years and two 95-year biogeochemical scenario simulations, RCP4.5 and RCP8.5 (Fig.S1). All the simulations 273 adopt as initial conditions the resulting final fields from the spin-up simulation (section 2.3). The CTRL is performed by 274 repeating the 2005–2014 physical forcing and river discharge over the remaining 2015-2100 period (Fig. S1). The 275 difference between each biogeochemical scenario and the CTRL provides the future evolution of a biogeochemical 276 variable due to climate forcing.

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278 Under each specific emission scenario and in the CTRL, our simulation protocol computes the time series of the mean 279 annual 3D fields of the following variables: dissolved nutrients and oxygen, chlorophyll-a, net primary production, 280 phytoplankton respiration, organic matter, plankton and bacterial biomass, POC, DIC and pH.

281 First, the annual 3D fields are vertically averaged over two separate key vertical levels: the surface zone and the 282 intermediate zone. The first one spans the upper 100 m of the water column, which represents the location of MAW and 283 the euphotic layer of the basin where most biological activities are concentrated. The second one covers the 200-600 m 284 level, which includes the location of LIW. Only for the net primary production and phytoplankton respiration, a vertical 285 integral over the 0-200 m layer is considered (Lazzari et al., 2012).

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287 Second, the temporal evolution of the unbiased scenario starting from the present state,  $U(k)_{SCEN}$  (with k = 2005, ..., 2099), 288 is defined as:

$$U(k)_{SCEN} = X'_{SCEN} + X(k)_{SCEN} - X(k)_{CTRL}$$
(1)

290 where X'<sub>SCEN</sub> is the average of X(k)<sub>SCEN</sub> over the 2005-2020 period (hereafter the PRESENT, Fig.S1), and X(k)<sub>SCEN</sub> and 291 X(k)CTRL are the yearly average in the scenario and CTRL simulations, respectively. We introduce the concept of 292 "unbiased scenario" because equation (1) removes the effect of potential model drifts due to unbalanced boundary 293 conditions and model errors. The time series of CTRL are filtered with a linear regression to keep the long-term drift and 294 remove spurious variability. The period 2005-2020 has been chosen as reference (also in the forthcoming validation) due 295 to: (i) the availability, after year 2000, of more advanced satellite and assimilated datasets to evaluate the biogeochemistry 296 of the basin, (ii) to avoid the overlapping between historical and scenario part of the simulations (with the latter starting 297 in 2005). It is important to stress here that the choice of the period should not significantly affect the results of the study 298 as the observed differences during this period between the two scenarios for temperature, salinity and current speed fields 299 have been found to be not statistically significant over most of the basin (not shown). 300

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 $CCS(k)_{SCEN} = U(k)_{SCEN} - U_{SCEN-PRESENT} (2)$ 

Finally, the temporal evolution of the climate change signal (CCS) with respect to the present is given by:

304 where USCEN-PRESENT is the average of U(k)SCEN in the PRESENT. Hereafter, if not differently specified, all the shown time 305 series will be represented by CCS<sub>SCEN</sub>.

307	Horizontal spatial averages are computed considering the sub-basins defined in Fig. 1, the whole Mediterranean basin					
308	scale, and two macro-areas: the Western Mediterranean (WMED which includes ALB, SWM, NWM, TYR) and the					
309	Eastern Mediterranean (EMED which includes ION and LEV). The Adriatic and Aegean Seas are usually not considered					
310	part of the Eastern Mediterranean due to the importance of local forcing, such as riverine loads, in shaping the variability					
311	of the biogeochemical dynamics in those two sub-basins. Because of that, following the approach already adopted in					
312	previous works (Lazzari et al., 2012; 2016; Di Biagio et al., 2019; Reale et al., 2020 a,b) they are not considered in the					
313	spatial averages related to WMED and EMED.					
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315	Temporal averages of the climate change signals are computed over two 20-year periods: 2040-2059, hereafter referred					
316	to as "MID-FUTURE" and 2080-2099, hereafter referred to as "FAR-FUTURE" (Fig.S1). The relative climate change					
317	signals (in %, except for pH which will be measured in units of pH) in the MID-FUTURE or FAR-FUTURE periods with					
318	respect to the PRESENT are computed as:					
319	$U_{MID-FUTURE}=100*(U_{SCEN-MID-FUTURE}-U_{SCEN-PRESENT})/U_{SCEN-PRESENT}(3)$					
320	UFAR-FUTURE=100*(USCEN-FAR-FUTURE- USCEN-PRESENT)/USCEN-PRESENT(4)					
321	where Uscen-mid-future, Uscen-far-future and Uscen-present are the averages of U(k)scen for the MID-FUTURE, FAR-					
322	FUTURE and PRESENT periods, respectively. Hereafter, if not differently specified, all the percentages shown in the					
323	maps are represented by UMID-FUTURE and UFAR-FUTURE. The statistical significance of the relative climate change signals					
324	in each point of the basin is assessed by means of Mann-Whitney test with p<0.05.					
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328	3. Results					
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330	3.1 Evaluation of the MFS16-OGSTM-BFM control simulation for the present climate					
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332	MFS16 modelling system performances under present climate conditions were previously analyzed (Lovato et al., 2013;					
333	Galli et al., 2017), showing that the main spatial-temporal characteristics of the Mediterranean Sea physical properties					
334	reliably compared against ocean reanalysis datasets. Moreover, the physical reanalysis dataset produced by MFS16 within					
335	the Copernicus Marine Environmental Marine Service (CMEMS, Simoncelli et al., 2019) has already been coupled to the					
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	transport-reaction model OGSTM-BFM to carry out a reanalysis for the Mediterranean Sea biogeochemistry (Teruzzi et					
337	transport-reaction model OGSTM-BFM to carry out a reanalysis for the Mediterranean Sea biogeochemistry (Teruzzi et al., 2019). The latter is a biogeochemical dataset covering the 1999-2015 period at 1/16° resolution, which was already					
337 338	transport-reaction model OGSTM-BFM to carry out a reanalysis for the Mediterranean Sea biogeochemistry (Teruzzi et al., 2019). The latter is a biogeochemical dataset covering the 1999-2015 period at 1/16° resolution, which was already used for validating different biogeochemical simulations in the Mediterranean Sea, such as those based on MEDMIT12-					
<ul><li>337</li><li>338</li><li>339</li></ul>	transport-reaction model OGSTM-BFM to carry out a reanalysis for the Mediterranean Sea biogeochemistry (Teruzzi et al., 2019). The latter is a biogeochemical dataset covering the 1999-2015 period at 1/16° resolution, which was already used for validating different biogeochemical simulations in the Mediterranean Sea, such as those based on MEDMIT12-BFM (Mediterranean MIT General circulation Model-BFM at 1/12°; Di Biagio et al., 2019) and RegCM-ES (Regional					
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<ul> <li>337</li> <li>338</li> <li>339</li> <li>340</li> <li>341</li> <li>342</li> <li>343</li> <li>344</li> </ul>	transport-reaction model OGSTM-BFM to carry out a reanalysis for the Mediterranean Sea biogeochemistry (Teruzzi et al., 2019). The latter is a biogeochemical dataset covering the 1999-2015 period at 1/16° resolution, which was already used for validating different biogeochemical simulations in the Mediterranean Sea, such as those based on MEDMIT12- BFM (Mediterranean MIT General circulation Model-BFM at 1/12°; Di Biagio et al., 2019) and RegCM-ES (Regional Climate Model-Earth System; Reale et al., 2020a) modelling systems. This dataset has been recently upgraded, refining the resolution to 1/24 degree and extending the period to 2019 (Teruzzi et al., 2021; Cossarini et al., 2021). To date, no future climate biogeochemical projection of the Mediterranean Sea has been performed through this offline coupling.					

346 Figure 2 a,b shows the surface average chlorophyll-a (Chl-a) concentrations (upper 10 m) from the CTRL run compared 347 with a climatology based on satellite data available from CMEMS which covers the period 1999-2015 (Colella et al., 348 2016). The model correctly reproduces the areas in the Mediterranean region characterized by relatively high values of 349 Chl-a: the Alboran Sea, the Gulf of Lion, the coastal areas of the Adriatic Sea, and the Strait of Sicily. Moreover, the 350 CTRL simulation captures the west-east trophic gradient of Chl-a, whose existence has been pointed out in previous 351 works (D'Ortenzio and Ribera d'Alcala, 2003; Lazzari et al., 2012; Colella et al., 2016; Richon et al., 2019; Di Biagio et 352 al. 2019; Reale et al., 2020a). On the other hand, a general underestimation of approximately 50% of the Chl-a signal 353 throughout the basin and in the coastal areas is observed, probably associated with insufficient river load (Richon et al., 354 2019; Reale et al., 2020a) and with the tendency of satellite Chl-a measures to be systematically overestimated in the 355 coastal areas with respect to "in situ" observations due to the presence of particulate suspended matter in the water column 356 (Claustre et al., 2002; Morel et Gentili, 2009).

357 Figure 2 also shows the average vertical profiles, computed for the entire. Western and Eastern Mediterranean basins, of 358 Chl-a (c),  $PO_4$  (d),  $NO_3$  (e), dissolved oxygen (f), DIC (g), pH (h) and total alkalinity (i) in the CTRL compared with the 359 recent CMEMS reanalysis (only for Chl-a and pH, Cossarini et al., 2021) and EMODnet datasets (European Marine 360 Observation and Data Network; Buga et al., 2018). In spite of the tendency to overestimate the Chl-a values, the model 361 captures the DCM location, the west-east trophic gradient in the basin, and also the nutricline depths deepening between 362 Western and Eastern basin and the low nutrient surface concentrations. Mean simulated values in the first 0-200 m are 363 quite realistic for almost all the biogeochemical tracers and properties, with correlation values between observations and 364 modelled data greater than 0.93. At the same time, the CTRL overestimates the PO<sub>4</sub> concentration between 100 and 300 365 m of about 50%, and the dissolved oxygen concentration of about 15% below 200 m and underestimates, below 200 m, 366 the NO<sub>3</sub> concentration of about 20% and the pH of about 1 % between 100 and 300 m. It is worthwhile to point out that 367 the limited spatial resolution of the observations below 200 m could impact the robustness of our comparison. In general, 368 the biases in the initial conditions are originated by the spin-up simulation that allows to remove the largest part of model 369 drifts. As explained in section 2.4, these biases, which are still present in both the CTRL and scenario simulations, do not 370 affect the calculation of the climate change signals, and are generally lower than the changes observed in the scenarios at 371 the end of the century.

To summarize, although the model shows some deficiencies in simulating the vertical distribution of some biogeochemical tracers and properties, the main features of the system are reliably simulated and thus, MFS16-OGSTM-BFM is robust enough to be used to investigate the evolution of the Mediterranean biogeochemistry under different emission scenarios.



Fig.2 Average Chl-a in the first 10m in CTRL (a) for the period 2005-2020 and CMEMS-SAT (b) together with CTRL average
vertical profiles (blue lines) for the period 2005-2020 of Chl-a (c,mg m<sup>-3</sup>), PO<sub>4</sub> (d, mmol m<sup>-3</sup>), NO<sub>3</sub> (e, mmol m<sup>-3</sup>), Dissolved
oxygen (f, mmol m<sup>-3</sup>), DIC (g, µmol kg<sup>-1</sup>), pH (h) and total alkalinity (i, µmol kg<sup>-1</sup>). The averaged profiles are computed for the
entire (MED), Western (WMED) and Eastern (EMED) Mediterranean Sea. The light blue areas represent the spatial standard
deviation of the monthly model data. The model data are compared with CMEMS reanalysis (Chl-a and pH; Colella et al.,
2016: Teruzzi et al., 2021) and observations provided by EMODnet (PO<sub>4</sub>, NO<sub>3</sub>, Dissolved oxygen, DIC, total alkalinity; Buga
et al., 2018): annual mean (black squares) and related standard deviations (black bars). Depth is measured in meters.

386

### 387 **3.2** Evolution of the thermohaline properties and circulation of the Mediterranean Sea in the 21st century

388

389 Mean temperature and salinity evolution between 0-100 m and 200-600 m in the 2005-2099 period under the RCP4.5 and 390 RCP8.5 scenarios in the whole Mediterranean Sea and in the Western and Eastern basins are shown in Fig. 3. As for the 391 biogeochemical variables, these depths have been chosen as they are representative of the location of MAW and LIW, 392 respectively.

393

A warming of the surface and intermediate layers is observed at the basin scale and in both the Western and Eastern basins, whose magnitude (approximately 1.5 °C in the RCP4.5 and 3°C in the RCP8.5 scenario) agrees with what has already been observed in recent modelling studies based on single/multimodel ensembles (e.g., Adloff et al., 2015; Soto-Navarro et al., 2020).

398

399 Similar to the seawater temperature, the variation in salinity is strongly dependent on the emission scenario with more 400 intense anomalies, both negative and positive, under RCP8.5 conditions (as observed in previous modelling studies such 401 as Adloff et al., 2015 and Soto-Navarro et al., 2020). For example, salinity in the surface layer at basin scale and in the 402 Eastern basin is characterized by a decrease between 2020 and 2050 followed by a constant increase (stronger under 403 RCP8.5 scenario) until the end of the 21st century. Conversely, after 2050, the Western basin shows a freshening of the 404 surface layer with respect to the beginning of the century, in agreement with what was already observed by Soto-Navarro 405 et al. (2020). An increase in salinity also occurs in both scenarios in the intermediate layer both at the basin scale and in 406 the two main sub-basins.

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Fig.3 - Yearly time series for the period 2005-2099 of Salinity (blue) and Temperature (dark orange, in °C) under the emission scenarios RCP8.5 (solid line) and RCP4.5 (dashed line) in the Mediterranean Sea (MED, a-b), Western Mediterranean (WMED, c-d) and Eastern Mediterranean (EMED, e-f) for the layers 0-100 m (left column) and 200-600 m (right column). The yearly time series have been smoothed using 10-years running mean.

The spatial distribution of temperature variations in the surface layer (Fig. S2) shows a comparable and mostly statistically significant on basin-scale warming in RCP4.5 and RCP8.5 in the MID-FUTURE (the differences between the projected changes are lower than 2%), while, in the FAR-FUTURE, the projected changes in the RCP4.5 are approximately the 50% lower with respect those observed observed in RCP8.5 (8-12% and 17-20% respectively), with the North Western Mediterranean, Tyrrhenian, Adriatic, Ionian, Aegean Sea and Levantine, being the most affected sub-basins. Local relative maxima are observed in both scenarios, in the Gulf of Lion, in the relatively shallow and coastal areas of the Adriatic Sea and in the area of the Rhodes Gyre (Fig.S2 i,j).

423

A general freshening of the upper layers and saltening of the intermediate layers over most of the Mediterranean basin is observed during the MID-FUTURE period (Fig. S3). The projected changes are statistically significant over most of the basin with the only exception in both scenarios of the upper layer of the Adriatic Sea and Northern Ionian Sea and the intermediate layers of the Southern Ionian and Levantine Basin/Southern Adriatic and Northern Ionian Sea in the RCP4.5/RCP8.5 scenario as consequence, probably, of the river input in the Adriatic Sea and mid-Ionian Jet dynamics. 429 The latter has been recognized, in fact, as an important driver for the salinity for the upper and intermediate layers of the

- 430 Adriatic and Ionian Sea (e.g. Gacic et al., 2010). In the FAR-FUTURE, the freshening of the surface is still present at the
- 431 basin scale in the RCP4.5 scenario (although it is reduced with respect to the MID-FUTURE) and in the Western basin
- 432 in the RCP8.5 scenario. Moreover, an increase in salinity is observed in the Adriatic Sea and in the Eastern basin under
- 433 RCP8.5. The projected changes in the surface salinity in the Adriatic Sea and Northern Ionian Sea under RCP4.5 are also
- 434 435

not significant.

The decrease in salinity in the 21st century in the Western basin is driven by the salinity values imposed in the Atlantic buffer zone (Lovato et al., 2013), while the saltening of the Eastern basin, under RCP8.5 scenario, is linked to the decreasing freshwater discharge in the area (e.g., Gualdi et al., 2013; Soto-Navarro et al., 2020). In the intermediate layer, the situation is reversed: while in RCP8.5 the entire basin experiences an increase in the salinity associated with the increase in salinity in the surface water of the Eastern basin, in RCP4.5 the Eastern basin experiences a slight decrease in salinity associated again with the freshening of surface water. In fact, at the surface, both signals are transported by vertical mixing to the intermediate layers of the Eastern basin influencing the salinity of the newly formed LIW.

443

444 Figure 4 shows the temporal evolution of the Mediterranean thermohaline circulation during the 21st century using the 445 zonal overturning stream function (or ZOF; Myers and Haines, 2002; Somot et al., 2006). The ZOF has been computed 446 by the meridional integration from south to north and from the bottom to the top of the water column of the zonal velocity 447 (see Adloff et al., 2015). The domain of the integration is the same as shown in Figure 1 with the exclusion of the Atlantic 448 area outside the Strait of Gibraltar. The thermohaline circulation of the basin in the PRESENT is composed of two cells, 449 similar to the outcomes of the historical reference experiments described in Adloff et al. (2015) and Waldman et al. 450 (2018). The first cell extends from the surface to 800 m, with a clockwise circulation associated with MAW moving 451 eastwards and LIW moving westwards. The second cell is located between 500 and 2500 m in the Eastern Mediterranean 452 with a counterclockwise circulation associated with the Eastern Mediterranean Deep Water (EMDW) moving eastwards 453 and LIW moving westwards.

454

455 Under the two scenarios, during the MID-FUTURE period, there is an evident weakening of both cells and a reduction 456 of the thickness of the upper layer cell and the Eastern basin cell (less than -0.1 Sv), which splits into two sub-cells. By 457 the end of the century both cells show a similar behavior, whereas in the RCP4.5 scenario, the Eastern cell is slightly 458 more intense. The weakening of the zonal overturning stream function is similar to previous findings of Somot et al. 459 (2006) and Adloff et al. (2015). As the Mediterranean thermohaline circulation is driven by both deep and intermediate 460 water formation processes, the overall weakening of both cells is a direct consequence of the increase in the vertical 461 stratification of the water column. In fact, the evolution of the winter maximum mixed layer depth in key convective areas 462 of the Mediterranean Sea, such as the Gulf of Lion, Southern Adriatic, Aegean Sea and Levantine basin (Fig. S4), shows 463 a progressive decrease in the intensity of the open ocean convection after 2030. Only for the Aegean Sea, the changes in 464 the winter mixed layer maximum depth are less marked, with the occurrence of some maxima around 2080 (in RCP8.5) 465 or after 2090 (in RCP4.5), which could correspond to a future tendency of the thermohaline circulation of the Eastern 466 basin to produce EMT (Eastern Mediterranean Transient)-like events (Adloff et al., 2015).

- 468 The projected overall weakening of the Mediterranean thermohaline circulation leads to a reduction in the exchanges of 469 biogeochemical properties between the Western and Eastern basins through the Strait of Sicily at both the surface and
- 470 intermediate levels (Fig. S5) and to a reduced ventilation of intermediate/deep waters (Adloff et al., 2015).
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- 472



474 Fig. 4 - Mediterranean Sea zonal stream function annual mean (in Sv) averaged over the PRESENT (2005-2020), MID 475 FUTURE (2040-2059) and FAR-FUTURE (2080-2099) periods under RCP4.5 and RCP8.5 scenarios.

476

# 477 **3.3 Spatial and temporal evolution of nutrients, dissolved oxygen and chl-***a* **concentrations**

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479 Figures 5 and 6 show the spatial distribution of the magnitude and signs of the changes that will affect the dissolved 480 nutrient concentrations during the 21st century. In the FAR-FUTURE, the decreases in PO<sub>4</sub> and NO<sub>3</sub> concentrations in 481 the 0-100 m layer are almost half in RCP4.5 (approximately 7% and 13% for PO<sub>4</sub> and NO<sub>3</sub>, respectively) with respect to 482 those observed in the RCP8.5 (approximately 13% and 20% for PO<sub>4</sub> and NO<sub>3</sub>, respectively) and are particularly marked 483 and statistically significant in the Levantine basin, in the Aegean Sea, in the Central/Southern Adriatic Sea and Northern 484 Ionian Sea. Again, statistically significant relative local maxima (in absolute value) are observed in both scenarios in the 485 area of the Gulf of Lion, Southern Adriatic, Northern Ionian and Rhodes Gyre. Moreover, there are clear spatial gradients 486 affecting the statistical significance of the projected changes. For example, the projected changes in nutrient concentration

in the Northern Adriatic Sea and in many other coastal areas, influenced by river dynamics, are not significant, contrary to what is observed in the open ocean areas of the same sub-basin. Here, the projected decrease is associated with the reduced vertical mixing in the water column and reduced inflow of nutrients through the Otranto Strait (Fig. S6). Finally, the two scenarios show some significant changes in the dissolved nutrient concentrations at local scale in the Alboran Sea and in the Southern Ionian associated with changes in the intensity of mesoscale circulation (eddies) of both areas and in the intensity and spatial structure of the mid-Ionian jet (not shown).

493

494 In contrast to the general decreasing nutrient content of the upper layer, the intermediate layer in both scenarios shows a 495 strong (milder) increase in nutrient concentration in the Southern Aegean Sea (Levantine basin, North Western 496 Mediterranean and Alboran Sea) in the 21st century driven by the reduced vertical mixing, which tends to increase the 497 nutrient content of the intermediate layers. The Tyrrhenian, Ionian and Southern Adriatic Seas are, in turn, characterized 498 by a permanent negative anomaly. In the first two areas, the anomaly can be associated with the decrease in the westward 499 transport of nutrients in the intermediate layers through the Strait of Sicily (consequences of the weakening of the zonal 500 stream function discussed in Section 3.2, Fig. S5), while in the Adriatic Sea, the projected changes are driven by the 501 increase in the nutrient export in the intermediate layer through the Otranto Strait (Fig. S6). In the North Western 502 Mediterranean, the observed positive anomalies become weaker and even negative in the FAR-FUTURE under the 503 RCP4.5 emission scenario, likely due to some convective events that take place between 2080 and 2100, as shown in Fig. 504 S4. Comparing the projected changes at the surface in the FAR-FUTURE it is observed while under RCP4.5 in most of 505 the Western Mediterranean and the Ionian Sea they are not statistically significant, under RCP8.5 emission scenario the 506 statistical significance that was initially limited to Adriatic, Aegean Sea and Levantine basin, now it also involves the 507 Ionian and Tyrrhenian Sea.





Fig. 5 - Phosphate concentration (in mmol m-3) in the layers 0-100 m and 200-600 m in the PRESENT (2005-2020, a,b,c and d), and relative climate change signal (with respect to the PRESENT) in the MID-FUTURE (2040-2059, e,f,g and h) and FAR-FUTURE (2080-2099, i,j,k and l) in the RCP4.5 (left column) and RCP8.5 (right column) emission scenario. The Mediterranean average relative climate change signal in each period (with respect to the PRESENT) is displayed by the top-left colored value (blue or dark orange when negative or positive). Values in the green boxes are the average relative climate change in each

- 515 period and in each sub-basin shown in Figure 1. Domain grid points where the relative climate change signals are not
- 516 statistically significant according to a Mann-Whitney test with p<0.05 are marked by a dot.





#### 519 Fig.6 - as Fig.5 but for Nitrate (in mmol m<sup>-3</sup>)

520 521 522

523 The temporal evolution of the mean concentrations of PO<sub>4</sub> and NO<sub>3</sub> in the RCP4.5 and RCP8.5 simulations between 0-524 100 m and 200-600 m in the Mediterranean Sea and its Western and Eastern basins for the 2005-2099 period is shown in 525 Fig. 7. In the RCP8.5 scenario, PO<sub>4</sub> and NO<sub>3</sub> concentrations within the euphotic layer of both sub-basins are substantially 526 stable for the first 30 simulated years, while a marked decline occurs after 2030-2035, with values of 0.01 and 0.1 mmol 527 m<sup>-3</sup> (compared to the beginning of the century) respectively, which is followed by a steady evolution of the concentration 528 values until the end of the century. The same behaviour is observed in RCP4.5, except for a recovery that takes place at 529 the end of the century in correspondence to an increase in the nutrient inflow into the Alboran Sea (Fig. S7). The observed 530 decline is timely in phase with the weakening of the zonal stream function discussed in Fig. 4, further pointing out the 531 importance of the vertical mixing in driving the temporal variability of nutrients in the euphotic layer. From this point of 532 view, some relative maxima of both nutrient concentrations in the Western and Eastern basins are observed for RCP4.5 533 in the 2015-2040 period (Fig. 5 c,d), associated with strong ocean convective events taking place in the Gulf of Lion and 534 Levantine basin (Fig. S4). Between 2055 and 2075, the peak in both nutrients' concentration, for RCP4.5, timely 535 corresponds to a peak in the inflow of nutrients into the Alboran Sea (Fig. S7). Additionally, in both the scenarios, the 536 intermediate layer of the Western basin, after 2035, experiences a negative tendency in the nutrient concentration (greater 537 than 0.01 mmol m<sup>-3</sup> for PO<sub>4</sub> and 0.1 mmol m<sup>-3</sup> for NO<sub>3</sub>) related to a reduced westward transport of nutrients associated 538 with LIW (Fig.S5).



540

Fig.7 - Yearly time series for the period 2005-2099 of Phosphate (blue, in mmol m<sup>-3</sup>) and Nitrate (dark orange, in mmol m<sup>-3</sup>)
anomalies for the emission scenario RCP8.5 (solid line) and RCP4.5 (dashed line) in the Mediterranean Sea (MED, a-b),
Western Mediterranean (WMED, c-d) and Eastern Mediterranean (EMED, e-f) for the layer 0-100 m (left column) and 200600 m (right column). The yearly time series have been smoothed using 10-years running mean.

The temporal evolution of chl-*a* in the two scenarios is similar to what was observed in the case of dissolved nutrients, with a high interannual variability, a decrease after 2030-2035 of approximately 0.03 mg m<sup>-3</sup> and a stable signal until the end of the century in the RCP8.5 scenario while, in the case of the RCP4.5 a recovery towards the observed PRESENT values is simulated at the end of 21st century (Fig.8). In the Eastern Mediterranean the decrease is of the same magnitude as that observed at the basin scale, while in the Western basin the chl-*a* signal appears substantially stable with respect to the present.



554 555 556

Fig. 8 as Fig.5 but for Dissolved Oxygen (blue, in mmol m<sup>-3</sup>) and Chl-*a* (dark orange, in mg m<sup>-3</sup>)

During the 21st century, a continuous decrease in the oxygen concentration is projected in both scenarios in the 557 Mediterranean Sea (Fig. 8). The simulated reduction of the oxygen values is slower in the RCP4.5 with respect to RCP8.5. 558 For example, under the RCP8.5 emission scenario, the concentration of the dissolved oxygen in the upper layer decreases 559 by approximately 15 mmol m<sup>-3</sup>, which is three times the value observed in the RCP4.5 scenario (Fig. 8). The decrease in 560 dissolved oxygen is rather uniform and almost statistically significant everywhere in both the horizontal and vertical 561 directions in all the sub-basins, with values that are half in RCP4.5 (in percentages) with respect to those observed under 562 RCP8.5 (Fig. S8). For example, the decrease in the oxygen concentrations in the Levantine basin, in the FAR-FUTURE, 563 is approximately equal to 3% under the RCP4.5 emission scenario and 6% under the RCP8.5 emission scenario. In the 564 North Western Mediterranean, these values are approximately 3% and 7% respectively. The projected decreases in both 565 scenarios are usually lower in the Alboran Sea and South Western Mediterranean with respect to the rest of the basin, as 566 a consequence of the damping effect driven by the oxygen values imposed at the Atlantic boundary. In fact, the advection 567 of dissolved oxygen associated with AW partially limits the reduction in the oxygen solubility at the surface as a 568 consequence of the warming of the water column in the sub-basins near the Strait of Gibraltar, such as the Alboran Sea.

569

570 The uniform decrease in the oxygen surface concentration observed in Fig. S8 is spatially coherent (also from the 571 statistical point of view) with the increase in the temperature shown in Fig. S4, confirming the importance of temperature 572 in driving the solubility of the oxygen in the marine environment (Keeling et al., 2010; Shepherd et al., 2017). Moreover, 573 a decrease in the oxygen inflow (not shown) into the Alboran Sea and an overall increase in community respiration (see 574 the analysis related to the phytoplankton respiration in section 3.4) are found, which represent additional factors 575 explaining the projected changes. Western sub-basins, deep convection areas and shallow coastal zones of the Adriatic







Fig.9 Annual rate of change of Dissolved Oxygen (mmol m<sup>-3</sup> year<sup>-1</sup>) in the Western (a,c) and Eastern (b,d) Mediterranean Sea
 in RCP8.5 (a,b) and RCP4.5 (c,d).

591

#### 592 **3.4** Spatial and temporal evolution of net primary production and living/non-living organic matter

593

594 The warming of the water column and the increase in vertical stratification affect the metabolic rate of ecosystem 595 processes including CO<sub>2</sub> fixation and community respiration. In fact, a basin-wide increase in net primary production 596 (NPP) starting after 2035 and proceeding until the end of the simulations, is projected in both scenarios (Fig. 10). In the 597 RCP4.5 scenario the NPP increase is greater than 10 gC m<sup>-2</sup> year<sup>-1</sup>, which is a value that is more than half with respect to 598 the values observed in the RCP8.5 simulation.



600

Fig.10 - Yearly time series for the period 2005-2099 of Integrated net primary production (blue, in gC m<sup>-2</sup> year<sup>-1</sup>) anomalies for
 the emission scenario RCP8.5 (solid line) and RCP4.5 (dashed line) in the Mediterranean Sea (MED, a), Western
 Mediterranean (WMED, b) and Eastern Mediterranean (c) for the first 200 m. The yearly time series have been smoothed
 using 10-years running mean.

606 The distribution of the sign of the NPP changes is not uniform across the basin and between the simulations (Fig.11). In 607 the MID-FUTURE, in both scenarios, the only areas that experience an increase (not statistically significant in all the 608 cases) in the NPP with respect to the beginning of the century are the North Western Mediterranean, the Tyrrhenian Sea, 609 the Northern Adriatic Sea, part of the Ionian Sea and of the Levantine basin. Conversely, the only statistically significant 610 projected changes are negative and are observed in the Central and Southern Adriatic Sea, part of the Northern Ionian 611 Sea and the Rhodes Gyre areas. The Aegean Sea shows a rather opposite behavior with a negative/positive anomaly in 612 RCP4.5/RCP8.5. In the FAR-FUTURE, corresponding to a more pronounced warming of the basin, the NPP increase is 613 quite uniform and statistically significant over most of the basin and is equal approximately equal to 7% in RCP4.5, which 614 is approximately the half of value observed in the RCP8.5 (approximately 17%). Under the RCP8.5 emission scenario 615 there is a 7-to-23% increase in NPP throughout the basin, with the relative local maxima observed mainly in the coastal 616 areas of the North Western Mediterranean, Levantine basin, Northern Adriatic Sea, Gulf of Lion, Aegean Sea (similar 617 results, although with lower rates, were found at the end of the 21st century by Solidoro et al., 2022). Conversely, under 618 the RCP4.5 scenario, the Adriatic Sea is still characterized by a negative and not significant anomaly (-1%), while for the 619 rest of the basin the sign of the anomaly is positive and statistically significant, with the greatest values observed in the 620 North Western Mediterranean (approximately 12%, which is almost half of the variation observed in the RCP8.5 621 scenario). In both scenarios, a negative anomaly is observed in the Rhodes gyre area, which is extremely weak in RCP8.5.

- 622 Both negative anomalies are temporally consistent with some convective events taking place in both areas after 2080 and
- 623 shown in Fig. S4.
- 624



#### NET PRIMARY PRODUCTION



Fig. 11 - Integrated net primary production variation (in gC m<sup>-2</sup> year<sup>-1</sup>) in first 0-200m in the PRESENT (2005-2020, a,b), and relative climate change signal (with respect to the PRESENT, in units of pH) in the MID-FUTURE (2040-2059, c,d) and FAR-FUTURE (2080-2099, e,f) in the RCP4.5 (left column) and RCP8.5 (right column) scenarios. The Mediterranean average relative climate change signal in each period (with respect to the PRESENT) is displayed by the top-left colored value (blue or dark orange when negative or positive). Values in the green boxes is the average relative climate change in each period and in each sub-basin shown in Figure 1. Domain grid points

where the relative climate change signals are not statistically significant according to a Mann-Whitney test with
 p<0.05 are marked by a dot.</li>

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636 As shown by Lazzari et al. (2014) and Solidoro et al. (2022), the overall warming of the water column also results in an 637 increase in community respiration. In agreement with that, Fig. S9 shows the spatial distribution of phytoplankton 638 respiration (RESP) changes in the MID-FUTURE. It is possible to observe some differences with respect to NPP. In both 639 scenarios, there is an overall decrease in the RESP with respect to the beginning of the 21st century, which is 640 approximately equal to -4% in the RCP4.5 and -2% in the RCP8.5. In both scenarios the projected changes are again 641 positive and not statistically significant in the Northern Adriatic, most of the North Western Mediterranean, Central and 642 Southern Ionian and coastal areas of the Levantine basin. As previously observed for NPP, the Adriatic Sea has an overall 643 negative and statistically significant anomaly, as well as the Northern Ionian Sea and the area of the Rhodes gyre. The 644 North Western Mediterranean is the only area where the variation has an opposite sign in two scenarios: it is negative (-645 1.4%) in RCP4.5 and positive (approximately 1%) in RCP8.5.

646

In the FAR-FUTURE, the pattern of variation is coherent with that already observed in the NPP (Fig. 11). RESP increases at the end of the 21st century over the entire basin of approximately 5% (11%) in RCP4.5 (RCP8.5). Under the RCP4.5 scenario, the Adriatic Sea, with the northern part as the only exception, and the Rhodes gyre area are still characterized by a negative anomaly while under RCP8.5, the highest values are observed in the North Western Mediterranean (this is also true for the RCP4.5 scenario), Aegean Sea and Levantine basin.

652

653 The overall increase in the respiration community has as a consequence the decrease in the organic stock matter in the 654 water column. The temporal evolution of the carbon organic matter standing stock for the 2005-2099 in RCP4.5 and 655 RCP8.5 simulations between 0-100 m and 200-600 m in the whole Mediterranean and in its Western and Eastern basins 656 is shown in Figure 12. The evolution of the carbon organic matter standing stock is similar to that observed in the dissolved 657 nutrients, with a substantially stable signal in the first 30 years of the 21st century and a decrease after 2030. Afterwards, 658 while RCP4.5 shows a recovery at the end of the 21st century, the projected decline in the RCP8.5 is approximately equal 659 to 5 mgC m<sup>-3</sup>. The same dynamics is observed in the intermediate layer, where the decline after the period 2030-2035 is 660 approximately equal to 0.3 mgC m<sup>-3</sup> for the carbon stock.

661

662 Similar dynamics are also observed for plankton (both phyto and zoo, Fig. 13), bacterial biomass and particulate organic 663 matter in the euphotic layer (Fig. 14). In the RCP4.5 simulation for all these biogeochemical tracers, a recovery in the 664 biomass at the end of the 21st century is found and the projected changes are approximately 50% with respect to the 665 RCP8.5 scenario where no recovery is observed. In particular, the decrease of the phytoplankton (zooplankton) biomass 666 is approximately 2 (1.5) mgC m<sup>-3</sup> and appears to be stronger in the Eastern than in Western basin. Under RCP8.5 the 667 bacterial biomass is projected to decrease at the basin scale by the end of the century by approximately 0.5 mgC m<sup>-3</sup>, by 668 0.2 mgC m<sup>-3</sup> in the Western basin and by 0.6 mgC m<sup>-3</sup> in the Eastern basin. Finally, the decline in particulate organic 669 matter is approximately 1.5 mgC m<sup>-3</sup> at the basin scale, approximately 1 (2) mgC m<sup>-3</sup> in the Western (Eastern) basin. In 670 the intermediate layer, the decline of the bacterial biomass in the entire basin is fairly uniform and continuous until the 671 end of the 21st century, with a variation of approximately 0.3 mgC m<sup>-3</sup> with respect to the beginning of the century. For the same layer, particulate organic matter declines after the period 2030-2035 but successively the signal remainssubstantially stable and, in particular in the Western basin, tends to recover at the end of the century.





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Fig. 12 - Yearly time-series for the period 2005-2099 of Living/not Living organic Matter (in mg m<sup>-3</sup>) anomalies for the emission
 scenario RCP8.5 (solid line) and RCP4.5 (dashed line) in the Mediterranean Sea (MED, a-b), Western Mediterranean (WMED,

scenario RCP8.5 (solid line) and RCP4.5 (dashed line) in the Mediterranean Sea (MED, a-b), Western Mediterranean (WMED,
c-d) and Eastern Mediterranean (EMED, e-f) for the layer 0-100 m (left column) and 200-600 m (right column) for the 2005-

679 2099 period. The yearly time series have been smoothed using 10-years running mean.

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682 683

Fig. 13 - Yearly time series of Phytoplankton biomass (blue, in mg m<sup>-3</sup>) and Zooplankton (dark orange, in mg m<sup>-3</sup>) anomalies
for the emission scenario RCP8.5 (solid line) and RCP4.5 (dashed line) in the Mediterranean Sea (MED, a), Western
Mediterranean (WMED, b) and Eastern Mediterranean (c) for the layer 0-100m and for the 2005-2099 period. The yearly time
series have been smoothed using 10-years running mean.

688 In the two scenarios, in both MID-FUTURE and FAR-FUTURE, the areas most affected by the statistically significant 689 decline of phytoplankton (Fig. S10) and zooplankton (Fig. S11) biomasses are mainly the sub-basins of the Eastern 690 Mediterranean Sea, namely the Ionian Sea (mainly its Northern part), the Adriatic Sea (except for its Northern part), the 691 Aegean Sea and the Levantine basin (in particular the Rhodes gyre area) and the Tyrrhenian Sea (only for the 692 phytoplankton). Moreover, the negative anomaly in the area of Rhodes gyre is spatially coherent with the anomalies 693 observed in the case of NPP and RESP, consequences of the vertical convection phenomena in the area. Conversely, 694 positive but not statistically signals for both variables can be observed only at the local scale in the Strait of Sicily and 695 along the coast of the North Western Mediterranean (spatially coherent with the positive variations of the PO4 discussed 696 in section 3.3 and in both cases not significant).



Fig.14- As Fig.8 but for bacterial biomass (blue, in mg m<sup>3</sup>) and particulate organic matter (dark orange, in mg m<sup>3</sup>)
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700 Also in the case of bacterial biomass (Fig. S12) and particulate organic matter (Fig. S13) the decline, along the 21st 701 century, will mostly affect the euphotic and the intermediate layers of the Eastern basin, in both MID- and FAR-FUTURE, 702 with relative maxima observed in the Levantine basin (around 33.5% in RCP4.5 and 50% in the RCP8.5 scenario). This 703 decline is related to an increase of the respiration at community level, as observed for phytoplankton (Fig. S9). However, 704 there are some exceptions to the general decline of the bacterial biomass and particulate organic matter in the basin. For 705 example, in the Adriatic Sea, under scenario RCP8.5, the decrease of the bacterial biomass with respect to the beginning 706 of the century is only 1% with a slight positive anomaly appearing in the Southern Adriatic at the end of 21st century (not 707 statistically significant, Fig. S12). In the case of particulate organic matter, the Strait of Sicily and the Northern Adriatic 708 Sea are characterized by a permanent positive signal in both layers and scenarios as observed before for PO<sub>4</sub>, also in this 709 case not statistically significant. Moreover, in RCP4.5 simulation, in the FAR-FUTURE period, the North Western 710 Mediterranean shows an increase of the particulate organic matter content in the euphotic and intermediate layers.

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## 712 3.4 Spatial and temporal evolution of dissolved inorganic carbon (DIC) and pH

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A basin-wide continuous increase in DIC is projected until the end of the 21st century, with a stronger signal observed in the RCP8.5 scenario (Fig. 15), and more specifically, in the Eastern part of the Mediterranean basin. In fact, in the euphotic layer, the increase in DIC with respect to the beginning of the century is approximately 150  $\mu$ mol kg<sup>-1</sup> under RCP8.5 in

717 the Eastern basin, while it is approximately 120  $\mu$ mol kg<sup>-1</sup> in the Western basin. Additionally, in the intermediate layer,

718 DIC increases by approximately 120  $\mu$ mol kg<sup>-1</sup> with respect to the beginning of the century: this value is approximately

the same for both the Western and Eastern basins and is double with respect to that observed in the RCP4.5 scenario.



721 722

Fig. 15 - as Fig.14 but for Dissolved Inorganic Carbon (blue, in µmol kg<sup>-1</sup>) and pH (dark orange)

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724 Although community respiration can play a role in the increase in DIC, in the Mediterranean region a predominant 725 mechanism is represented by the air-sea CO<sub>2</sub> exchange (D'Ortenzio et al., 2008; De Carlo et al., 2013; Hassoun et al., 726 2019; Wimart-Rousseau et al., 2020). In fact, looking at the terms controlling the DIC increase, the air-sea  $CO_2$  exchange 727 shows an almost balanced condition in the present-day (D'Ortenzio et al., 2008; Melaku Canu et al., 2015), and an increase 728 throughout the 21st century as a consequence of the increase in atmospheric  $CO_2$  (Fig. 16, a,b). The  $CO_2$  flux increase is 729 almost linear and is equal in the two scenarios until 2050. Then, the RCP4.5 scenario shows a smoothing in the second 730 half of the century, which is consistent with the reduced atmospheric emissions, while the linear increase persists under 731 RCP8.5 (Fig. 16, a,b).

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The two main Mediterranean sub-basins behave quite differently: the CO<sub>2</sub> air-sea sink is three times greater in the Western part compared to the Eastern part, reflecting the influence of both DIC and temperature spatial gradients (i.e., higher values of DIC and temperature in the Eastern basin). In order to assess the temperature and DIC contributions to the pCO<sub>2</sub> temporal evolution, the carbonate system equations of the BFM model have been solved in offline mode, keeping constant, alternatively, temperature and DIC concentration. The increase in the temperature has been shown to account for 25% of the total increase in the pCO<sub>2</sub>. The remaining part of the pCO<sub>2</sub> increase can be ascribed to the DIC concentration increase. In the Western part, a less pronounced temperature effect (i.e., temperature increases slower in

- the Western part) causes an undersaturation condition of pCO<sub>2</sub> (i.e., pCO<sub>2</sub><sup>sea</sup> lower than pCO<sub>2</sub><sup>atm</sup> values) compared to the
   Eastern conditions, triggering a much higher CO<sub>2</sub> absorption in the Western Mediterranean.
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Fig.16 - Time series of atmospheric and marine pCO<sub>2</sub> (a,b), CO<sub>2</sub> air-sea exchange (c,d) and cumulative CO<sub>2</sub> absorbed and
accumulated in the water column (e,f) in the Western (a,c,e) and Eastern (b,d,f) Mediterranean Sea. Two scenarios RCP4.5
(dashed line) and RCP8.5 (continuous line) and control simulation (CTRL, gray line) are reported.

As a result of the air-sea CO<sub>2</sub> sink, for example the RCP8.5 scenario shows a steady DIC accumulation after 2030 with values of more than 2  $\mu$ mol kg<sup>-1</sup> year<sup>-1</sup> in the first 600 m (500 m) of the water column for the Western basin (Eastern basin; Fig. 17).

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The increase in DIC in the upper layer is approximately 1.5% and 2.5% in the Western and Eastern basins, respectively, in the MID-FUTURE, and 5% and 7% in the FAR-FUTURE (Fig. S14). In the 200-600 m layer, the DIC increase follows the same pattern as that in the upper layer, but with smaller changes (i.e., approximately 1-2% less). Then, while the DIC increase does not impact the water column below 1200 m in the Western basin, DIC still accumulates until 2000 m in the Eastern basin at a rate of almost 0.5  $\mu$ mol kg<sup>-1</sup> year<sup>-1</sup> (Fig. 17). Occasional events of deep transport of DIC can be recognized (e.g. around the years 2035, 2045, 2085 and 2095, similar to what observed in the case of oxygen in Fig.9) and the water column results enriched down to 1000-1500 m with a rate of approximately 1  $\mu$ mol kg<sup>-1</sup> year<sup>-1</sup>. In the surface

760 layer (i.e., first 50-100 m), the interannual variability of atmospheric conditions (i.e. specific annual wind and temperature 761 seasonal cycles triggering the CO<sub>2</sub> fluxes) and the winter mixing produce an irregular succession of positive and negative 762 annual changes, which can partially hide the long-term effect of the increase in atmospheric pCO<sub>2</sub>. Thus, the cumulative 763 sum of the CO<sub>2</sub> absorbed through air-sea exchanges and of the carbon accumulated in the water column (Fig. 16, e,f) 764 highlight the different behavior of the two main sub-basins. The Western basin absorbs much more atmospheric CO<sub>2</sub> than 765 the Eastern basin, with even larger differences in the RCP8.5 scenario. By the end of the RCP8.5 scenario, 1.8 PgC of 766 atmospheric CO<sub>2</sub> sink in the Western basin while only 1 PgC in the Eastern basin are observed, consistent with the 767 estimates of Solidoro et al. (2022).

769 However, the fate of the absorbed carbon is quite different: the Western basin during the 21st century (RCP8.5 scenario) 770 accumulates only 0.85 PgC, while 1.7 PgC are retained in the water column of the Eastern basin. As shown in Figure 16 771 (lower panel) for the RCP8.5 scenario, the Eastern basin accumulates almost 2 moles of carbon for each atmospheric CO<sub>2</sub> 772 mole absorbed (up to 3 in the RCP4.5), while it is less than 0.5 for the Western basin. The different efficiency is eventually 773 triggered by the thermohaline circulation change: the Western Mediterranean carbon is partly exported to the Northern 774 Atlantic Ocean, while an increased quota of carbon input from rivers and across the Sicily channel are retained in the 775 Eastern basin together with the atmospheric  $CO_2$  sink after the weakening of the thermohaline circulation (Fig.4). The 776 RCP4.5 scenario shows similar dynamics to RPC8.5, with rates of CO<sub>2</sub> absorption (Fig. 16) and of DIC accumulation 777 almost halved, and the impact of the interannual variability on surface layer dynamics much more amplified (not shown). 778 As a result, the total sequestered atmospheric CO<sub>2</sub> equals to 0.8 and 0.25 PgC in the Western and Eastern basins, while 779 the increases of the carbon pool are 0.5 PgC and 0.9 PgC, respectively.



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- Fig. 17 Hovmoeller diagram of DIC (µmol kg<sup>-1</sup>, panel a,b) and annual rate of change of DIC (µmol kg<sup>-1</sup>year<sup>-1</sup>, panel c,d) in the
- 783 Western (a,c) and Eastern (b,d) Mediterranean Sea in RCP8.5 scenario.
- 784

785 Consequently, to the CO<sub>2</sub> invasion and DIC increase, the change in the carbonic acid equilibrium causes a generalized 786 decrease in pH, as also shown in Solidoro et al. (2022) in the case of the A2 scenario. The change in pH, which is 787 statistically significant everywhere and very well anti-correlated in time and space with the DIC change (on the basin 788 scale the correlation coefficient is lower than -0.90 with p<0.05; Fig.S14) and almost similar in both Western and Eastern 789 Mediterranean (as already projected by Goyet et al, 2016), is approximately by the end of the century equal to 0.1 in the 790 RCP4.5 and 0.25 pH units in the RCP8.5 scenario (Fig. 18). The largest decreases in pH are projected in both scenarios 791 in the upper layer of the North-Western Mediterranean, Tyrrhenian Sea, Adriatic Sea and Aegean Sea and in the 200-600 792 m layers of the Tyrrhenian Sea, Ionian Sea and Aegean Sea in the FAR-FUTURE (Fig. 18).







- Fig. 18 –pH in the layers 0-100m and 200-600m in the PRESENT (2005-2020, a,b,c and d), and relative climate change signal (with respect to the PRESENT, in units of pH) in the MID-FUTURE (2040-2059, e,f,g and h) and FAR-FUTURE (2080-2099, i,j,k and l) in the RCP4.5 (left column) and RCP8.5 (right column) scenarios. The Mediterranean average relative climate change signal in each period (with respect to the PRESENT) is displayed by the top-left colored value (blue or dark orange when negative or positive). Values in the green boxes is the average relative climate change in each period and in each subbasin shown in Figure 1. Domain grid points where the relative climate change signals are not statistically significant according to a Mann-Whitney test with p<0.05 are marked by a dot.
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#### 804 4. Discussions and Conclusions

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In this study, the coupled physical-biogeochemical model MFS16-OGSTM-BFM is used to simulate the biogeochemical
 dynamics of the Mediterranean Sea during the 21st century under the two emission scenarios RCP4.5 and RCP8.5, and
 to assess some climate-related impacts on the marine ecosystems of the basin.

809

810 To the best of the authors' knowledge, this work is the first one that analyzes long-term eddy-resolving projections of the 811 biogeochemical dynamics of the Mediterranean Sea under two different emission scenarios. In fact, the horizontal and 812 vertical resolution (1/16° and 70 vertical levels) of the long-term projections here analyzed is higher than that of previous 813 works available in the scientific literature that focuses on the area (e.g Lazzari et al., 2014; Macias et al., 2015; Richon et 814 al., 2019; Pagès et al., 2020; Solidoro et al., 2022). Moreover, the majority of the recent scientific works discussing the 815 impacts of climate change on the biogeochemical dynamics of the Mediterranean Sea are based on the analysis of 816 simulation that considered the worst-case emission scenario (A2 or RC8.5; Moullec et al., 2019; Richon et al., 2019; 817 Pagés et al., 2020; Solidoro et al., 2022).

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819 The use of eddy-resolving resolution and of a higher vertical resolution allows a more detailed representation of the 820 vertical mixing and ocean convection processes, which play a fundamental role in the ventilation of the water column and 821 in the nutrient supply into the euphotic layer of the basin (Kwiatkowski et al., 2020). Moreover, the use of a  $1/16^{\circ}$ 822 horizontal resolution for the projections has allowed to resolve, identify and characterize, for the first time, spatial 823 gradients existing in the same sub-basins (such as in the Adriatic Sea) or between coastal and open ocean areas (such as 824 in the North Western Mediterranean). A more detailed representation of the spatial distribution of the projected changes 825 and of their statistical significance for different biogeochemical tracers and properties represents a clear advantage for the 826 future assessment of climate change impacts on specific organisms, habitats or target areas, also at sub-basin scale.

827

The analysis of the thermohaline properties and circulation of the Mediterranean Sea under emission scenarios RCP4.5 and RCP8.5 found different levels of warming of the water column and weakening of the thermohaline circulation cell, with different parts of the basin being characterized by contrasting saltening and freshening conditions as a function of the considered scenarios. Moreover, different levels of weakening of the open ocean convection in the most important convective areas of the basin are projected, with the only exception of the Aegean Sea, where episodes of deep convection similar to the EMT could be observed at the end of the 21st century (see also Adloff et al., 2015). All the projected kanges are in agreement with those already depicted in recent model studies (e.g. Somot et al., 2006; Adloff et al., 2015;

Waldman et al., 2018; Soto-Navarro et al., 2020).

836

A comparison of the model outputs with available data in the present climate, together with previous studies performed with the same model system, support the conclusion that the coupled model MFS16-OGSTM-BFM has a reasonably good ability in reproducing the main biogeochemical features of the Mediterranean Sea and can be used as a tool for assessing the future biogeochemical dynamics of the basin and its changes in response to climate change. The use of the biasremoving protocol is often advocated as a good practice in climate studies, but rarely implemented in biogeochemical or ecosystem projections (e.g., Solidoro et al., 2022) and it adds further robustness to our results.

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851

844 Our projections for the biogeochemical tracers and properties at the end of the 21st century shows several signals (see 845 Table SP1 for a synthetic overview) that are mostly in agreement with previous studies, at least with those based on the 846 use of the worst-case emission scenarios. The magnitude of the projected changes has been shown to be, in general, 847 scenario-dependent with the largest deviations from the present climate state observed in the RCP8.5 emission scenario 848 (Table SP1). On the other hand, the analysis of the projections under RCP4.5 found in most of the biogeochemical 849 variables (for example dissolved nutrients and biomasses) by the end of the 21st century a tendency to recover the values 850 observed in the present climate (Table SP1).

852 As shown in the previous sections, our simulations, by covering also the RCP4.5 scenario, highlight how an intermediate 853 greenhouse emission scenario produces results that are not simply an average between the present condition and the 854 RCP8.5, but (at least for some variables) something quantitatively different. For example, the temporal evolution of pH 855 (Fig.15) is similar in two scenarios in the first 30 years of the 21st century. Conversely, after 2050, pH undergoes a 856 substantial decrease under RCP8.5 while it remains almost stable under RCP4.5 with a final projected variation lower 857 than the half with respect to the worst-case scenario. This supports the idea - possibly based on the existence of a certain 858 buffer capacity and renewal rate in a system like the Mediterranean Sea - that the implementation of policies of reducing 859 CO<sub>2</sub> emission could be, indeed, effective and could contribute to the foundation of ocean sustainability science and 860 policies.

861

862 The decline in the dissolved nutrients at the surface under RCP8.5 scenario is comparable with that observed in Richon 863 et al. (2019). However, they project an overall increase in the concentration of both nutrients at the surface after 2050, 864 which is ascribed by the authors to river and Gibraltar inputs that are not constant over time (as in our case) but are based 865 on a global climate scenario simulation. As highlighted by Richon et al. (2019), the sensitivity of the biogeochemical 866 fluxes at the river loads and Gibraltar exchanges is of paramount importance, and surely worthy of further investigation. 867 Nevertheless, the increase in the concentration of nutrients in the intermediate layers of both the Western Mediterranean 868 and Levantine basin can be also traced back to the reduced vertical mixing resulting from the increase in the vertical 869 stratification (Somot et al., 2006; Adloff et al., 2015; Richon et al., 2019).

870

871 Different levels of increase in the net primary production and respiration are projected in both scenarios although many

872 recent studies in the Mediterranean region have shown a different response of integrated net primary production to climate

873 change in both Western and Eastern basins (e.g. Macias et al., 2015; Moullec et al., 2019; Pagès et al., 2020). In fact, this

874 response may vary according to the sensitivity of the assumptions (model equations) for primary production and recycling

875 processes to changes in temperature (Moullec et al., 2019). In the BFM model temperature regulates most of the metabolic 876 rates with a Q10 formulation (Vichi et al., 2015). The increase in net primary production is a consequence of such 877 dependence. In other studies (Eco3M-Med model; Pages et al., 2020) organisms are always optimally adapted and no 878 temperature dependence is accounted for in the physiology. This different parameterization could be connected to the 879 different results in terms of trends; in fact, the scenarios based on the Eco3M-Med model results in a reduction of net 880 primary production. In this case surface nutrient reduction, rather than temperature, affects the net primary production 881 trend producing a decrease. The relative impact of different drivers (nutrient supply versus organism's adaptation to 882 average water temperature) could be explored with dedicated sensitivity experiments.

883

884 Our projections of net primary production and biomass dynamics show how different levels of warming of the water 885 column and consequent stratification have a direct impact on the ecosystem functioning by increasing the metabolic rates. 886 Similar to the results obtained in Lazzari et al. (2014) and Solidoro et al. (2022), the increase in metabolic rates augments 887 both primary production and respiration, but with the net effect of reducing living and non-living particulate organic 888 matter, as suggested from theoretical considerations in O'Connor et al. (2011). The decoupled formulation of carbon 889 uptake and net growth in the BFM model induces a further mechanism related to how carbon is channeled in the food 890 web. In fact, the decrease in biomass is partially compensated by an increase in dissolved organic matter production in 891 the basin by the end of the century (Solidoro et al., 2022; results not shown here).

892

893 Basin-wide deoxygenation tendencies are found in both scenarios and are comparable to trends observed on the 894 Mediterranean scale by Powley et al. (2018) and, under RCP8.5, on the global scale by CMIP6 simulations (Coupled 895 Model Intercomparison Project Phase 6; Kwiatkowski et al., 2020). The former, using a box model, found a decrease in 896 the oxygen content of the intermediate layer in the range of 2-9% as a consequence of different projected changes in the 897 solubility (due to the temperature increase) and in the thermohaline circulation of the basin. Furthermore, the projections 898 show that, in both our scenarios, deoxygenation is higher in the Eastern than the Western basin, where the Atlantic 899 boundary condition might have dumped the deoxygenation trend, and in several coastal areas such as the Northern 900 Adriatic (until -25 mmol m<sup>-3</sup>). As also observed by Powley et al. (2018), the main driver of deoxygenation is the change 901 in solubility, whereas changes in the circulation (i.e., weakening of the thermohaline circulation) should not substantially 902 affect deep ventilation, and it is unlikely, even in the worst-case scenario, to reach hypoxia conditions in the deep layer 903 of the basin by the end of the century. On the other hand, the greatest threat for the oxygen water content might be linked 904 to the combination of surface warming and faster respiration processes in the coastal areas of the basin which could result 905 in lower oxygen conditions and, thus, alteration of the local marine ecosystem functioning and structures (Bindoff et al., 906 2019).

907

An increase in the dissolved inorganic carbon content and acidity of the water column (Solidoro et al., 2022) is found in both scenarios. The overall accumulation of CO<sub>2</sub> in the basin resulted in an acidification of the Mediterranean water with a decrease in pH of approximately 0.23 units in the worst-case scenario, which is slightly lower than the 0.3 projected on a global scale (Kwiatkowski et al., 2020) and lower than the value provided in Goyet et al. (2016), who projected, using thermodynamic equations of the CO<sub>2</sub>/carbonate system chemical equilibrium in seawater, a variation of 0.45 pH units in the basin under the worst SRES case scenario (and 0.25 pH units in the most optimistic SRES scenario). However, this last estimate probably tends to overestimate the future acidification of the basin, as it does not consider the decrease in 915 the exchanges and the penetration of CO<sub>2</sub> across the ocean-atmosphere interface due to the warming of the water column 916 (MedECC, 2020).

917 This difference in the response to climate change between the Western and Eastern basins has been also observed for the 918 dissolved inorganic carbon accumulation and reflects indeed different factors such as the different ventilation and 919 residence time of water masses in the two basins as well as the exchanges in the Strait of Gibraltar (e.g. Alvarez et al., 920 2014; Stöven and Tanhua, 2014; Cardin et al., 2015; Hassoun et al., 2019). Results show that, in both scenarios, the 921 Western basin, while adsorbing greater quantities, accumulates only a half of the atmospheric carbon stored by the Eastern 922 basin because in the former the carbon is partly exported to the Northern Atlantic Ocean, while in the latter, it is also 923 affected by a more intense reduction of the thermohaline circulation and therefore in the vertical transport processes, the 924 carbon is retained together with the atmospheric CO<sub>2</sub> sink. Additionally, in our case, the use of a high resolution for the 925 biogeochemical projections has allowed to show that in many coastal areas the observed acidification is lower by 926 approximately 8% with respect to the open ocean due to damping effects of alkalinity input from the rivers (not shown 927 here).

The decline in many biogeochemical tracers and properties in the euphotic layer begins in the 2030-2035 period, in correspondence to the weakening of the thermohaline circulation in the basin (Fig. 4), and it is particularly marked in the Eastern basin. This shows that the modification of the circulation resulting from future climate scenarios has substantial effects on the biogeochemical properties of the basin. Changes in the thermohaline circulation of the basin also explain the increase in the nutrient concentration in the intermediate layer of the Levantine basin, which is a result of the weakening of the westward transport of nutrients through the Strait of Sicily (Fig.S5).

934

935 Similar to all previous modelling cited studies (e.g. Lazzari et al., 2014; Macias et al., 2018; Richon et al., 2019; Pagès et 936 al., 2020), some sources of uncertainties for our projections need to be considered. As discussed before, MFS16 937 adequately reproduces the distribution of key physical properties and the thermohaline circulation of the basin. On the 938 other hand, recent studies based on multi-model ensembles (Adloff et al., 2015; Richon et al., 2019; Soto-Navarro et al., 939 2020) have suggested that atmospheric forcing and boundary conditions can strongly affect the dynamics of the basin, 940 particularly the vertical mixing, which plays a primary role in the distribution of nutrients in the euphotic layer, therefore 941 affecting the dynamics of low trophic levels. Additional sources of uncertainties in the modelling framework can be traced 942 back to the BFM biogeochemical model. For instance, in the present climate the model tends to overestimate the 943 chlorophyll-a at the surface and, even more, the oxygen concentration below 200 m (section 3.1). These overestimations 944 can be propagated by the integration into the future projections. However, the conclusions of the present work should not 945 be significantly affected by that because, at the same time, the CTRL simulation is also removed from both the scenario 946 simulations. Moreover, the signs of the projected changes (not their absolute values) result from different physical and 947 biogeochemical processes (e.g., temperature and respiration increase, weakening of the thermohaline circulation, increase 948 in the stratification) which are linked to the climate forcing and are independent from model uncertainties that generate 949 the biases discussed in section 3.1.

950

951 Furthermore, the set-up of the boundary conditions, namely the atmospheric deposition at the surface, the rivers nutrient 952 loads and the vertical profiles in the Atlantic boundary can be very critical, especially in the land-locked Mediterranean 953 basin. Atmospheric deposition is an important source of nutrients for the basin and it has been shown that the 954 biogeochemical dynamics of the Mediterranean Sea is influenced by aerosol deposition (e.g. Richon et al., 2018, 2019), 955 especially during periods of stratification. The projected lower nutrient supply from sub-surface waters caused by climate-956 driven stronger stratification, could likely increase the importance of the atmospheric deposition as a source of nutrients 957 for the euphotic layer (Gazeau et al., 2021). Thus, possible future changes in the deposition of aerosols could influence 958 the biogeochemistry of the basin and the nutrients concentration at the surface as projected for the 21st century and 959 depicted in Section 3.3. However, in both RCP4.5 and RCP8.5 simulations, a present-day phosphate and nitrogen 960 deposition is used. Potential improvements will be achieved indeed by the inclusion of more accurate deposition 961 information derived from CMIP6 global estimates for the 21st century (O'Neill et al., 2016).

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963 Similarly, the lack of river nutrient load projections under the prescribed emission scenarios can affect the projected 964 nutrient budget of the Mediterranean basin. A climatology derived from the Perseus project (see Section 2.3) is here 965 adopted, which is, to our knowledge, the most reliable information. Indeed, it is reasonable to assume that land-use and 966 runoff changes might impact future nutrient loads, although the magnitude and even the sign are presently unknown. Our 967 river runoff was based on projections (Gualdi et al., 2013; Section 2.1) which estimated an average decrease by the end 968 of the 21st century. Thus, the increase of nutrients observed in Fig. 9 and Fig. 10 in the Northern Adriatic and several 969 coastal areas of the Western basin can be partially related to the mismatch between a constant nutrient load and a 970 decreasing runoff. However, it might be worth remembering that the amount of nutrients entering the basin through its 971 boundaries ultimately depends on the economic policies and land use/coverage scenarios and therefore they may be 972 intrinsically subjective.

973

974 With DIC as the only exception, for the 21st century, a single vertical profile based on the present-day condition data is 975 used and no future evolutions are considered for the boundary conditions at the Strait of Gibraltar. If this approach allows 976 to point out the effects of the changes in the basin circulation on the nutrient budgets, it could miss the influence on 977 nutrients or other biogeochemical properties of a possible different future evolution of the exchanges in the Strait of 978 Gibraltar due to changes in the tracer concentrations in the Atlantic Ocean. Moreover, the use of the same Atlantic 979 boundary conditions for the two scenarios (section 2.3) could have led to an underestimation of a potential difference 980 between the two scenarios in the areas most influenced by the Atlantic boundary (e.g. Alboran Sea and South Western 981 Mediterranean). Recent physical simulations have shown an increase of 3.7% in the surface flow at the Strait of Gibraltar, 982 which could imply an increase in the inflow of nutrients in the surface layer at Strait of Gibraltar (Richon et al., 2019; 983 Pagès et al., 2020), thereby eventually damping the decrease in the nutrient concentration at the surface projected for the 984 21st century. As previously observed, this could explain the observed differences among different studies that analysed 985 future projections of the biogeochemistry of the basin.

986

To conclude, the methodology and results here presented, provide a robust picture of the evolution of the Mediterranean Sea biogeochemistry for the 21st century. Clearly, the new generation of Regional Earth System Coupled Models (RESM), with eddy-resolving ocean models such as the one exploited here, may partially reduce the limitations of using external (and possibly misaligned) sources of information for atmospheric and land input to the ocean. Indeed, by directly resolving the coupling between the Mediterranean Sea, the regional atmospheric domain and the hydrological component, a regional earth system coupled model (e.g., as in Sitz et al., 2017, and Reale et al., 2020a) allows the simulation of the different components of the climate system at the local scale, including aerosol and river loads.

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1003						
1004	Data availability					
1005	Data produced in the numerical experiments are available through the portal dds.cmcc.it for both physical					
1006	(https://dds.cmcc.it/#/dataset/medsea-cmip5-projections-physics) and biogeochemical					
1007	(https://dds.cmcc.it/#/dataset/medsea-cmip5-projections-biogeochemistry) components.					
1008						
1009	Author contribution					
1010	GC, PL, SS, MR and CS conceived the study. They designed the experiments together with TL. MR, GB and TL					
1011	performed the numerical simulations. MR, GC, SS, TL and PL performed the analysis of the simulation results. MR					
1012	prepared the first draft of the manuscript under the supervision of SS, GC, PL and CS and with the contribution from all					
1013	the authors. All the authors discussed the results and contributed to the revision of the manuscript.					
1014						
1015	Competing interest					
1016	The authors declare that they have no competing interests.					
1017						
1018	References					
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