



Air–sea CO₂ exchange in the Southern Adriatic Sea: assessing its role as a moderate carbon sink over the last decade (2015–2024)

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Abstract. Coastal waters contribute significantly to the total oceanic carbon uptake. In this context, the cumulative influence exerted by marginal seas may be conspicuous. However sparse and unevenly distributed observations in such regions pose a serious limit to an accurate, experimentally based quantification of carbon dynamics. The Southern Adriatic (SAd) is one of the key sites of the Mediterranean Sea where open-ocean deep water formation occurs, a process recognized as a major driver of carbon sequestration. However, observations in this region remained sparse, thus quantitative assessment of surface carbon dynamics and air–sea carbon flux are still limited. In this study, a recently validated, decade-long (2015–2024) high-resolution time series of surface partial pressure of CO₂ ($p\text{CO}_{2\text{sw}}$) and hydrographic measurements collected at the EMSO-E2M3A South Adriatic observatory, located at the centre of the Southern Adriatic Pit, has been analysed. The results showed that seasonal temperature variability and winter vertical mixing were the dominant drivers of $p\text{CO}_{2\text{sw}}$ variability, with biological processes likely contributing during the post-convective period. Air–sea CO₂ flux (FCO₂), derived from in situ observations, indicated a clear seasonal pattern, with the SAd acting as a CO₂ sink during winter and as a source during summer. Importantly, the results revealed that the SAd acted as a weak-to-moderate annual carbon sink over the last decade. However, the magnitude of FCO₂ was strongly influenced by the selected gas transfer velocity parametrization. Similarly, the use of a different wind speed input, for instance ERA5 re-analysis, also altered the estimated CO₂ flux, highlighting the importance of carefully selecting wind products for regional air–sea FCO₂ calculations. Finally, the results presented here

showed how time series such as the SAd dataset can serve as critical assets for validating operational ocean models, such as the European Copernicus Marine Service for the Mediterranean, by helping to identify discrepancies in the simulation of key processes.

1 Introduction

In the decade 2014–2023 it is estimated that the ocean has absorbed 10.5 Gt CO₂ on average each year, which corresponds to around 26 % of total carbon dioxide (CO₂) emissions (Friedlingstein et al., 2025). The concentration of CO₂ in the atmosphere has increased from approximately 278 parts per million (ppm) at the beginning of the Industrial Revolution (Gulev et al., 2021), to more than 421 ppm at the end of 2024 (Lan et al., 2025). This has led to an increasing ocean carbon uptake, which, in turn, has caused changes in seawater chemistry (Doney et al., 2009; Gattuso and Hansson, 2011) negatively affecting many marine organisms and ecosystems (e.g., Ilyina et al., 2009; Lohbeck et al., 2012; Meyer and Riebesell, 2015). Air–sea CO₂ exchange is primarily controlled by the difference between the partial pressure of CO₂ in seawater and in the atmosphere, by the solubility of CO₂, and by the gas transfer velocity. While CO₂ solubility mainly depends on temperature and salinity and is relatively well constrained (Weiss, 1974), the gas transfer velocity is controlled by a complex set of physical processes, including molecular diffusion, turbulent mixing, surface waves, bubbles, and spray. It is parameterised as a function of wind speed, and several polynomial relationships have been fitted

between the gas transfer velocity and the wind speed based on field experiments (e.g., Wanninkhof and McGillis, 1999; Nightingale et al., 2000). Because no consensus exists on the optimal gas transfer velocity parameterisation, the choice and quality of wind speed data can strongly influence air–sea CO₂ flux estimates (Wanninkhof, 1992; Naegler et al., 2006; Otero et al., 2013). In situ wind measurements are generally preferred when available (Otero et al., 2013), but they, as well as air temperature, may not be measured at the same time and location of marine CO₂ and salinity observations, especially in buoy-based observing systems. Model- or satellite-derived winds are therefore often used as alternatives, although they also introduce additional sources of uncertainty (Otero et al., 2013).

Estimates of the global CO₂ air–sea flux therefore rely on both observations and models (Gruber et al., 2023; Fay et al., 2024; Friedlingstein et al., 2025). Many efforts have been made by the scientific community to increase the number and availability of carbon measurements from different sources (e.g., from research vessels, autonomous sensors, Argo floats) into quality controlled and openly accessible data products, resulting in 44 million observations in the Surface Ocean CO₂ Atlas (SOCAT) V2026 release (Bakker et al., 2016, 2026). However, these observations cover only a small fraction of the ocean surface and the number of new observations per year in the open ocean has decreased since 2017 (Bakker et al., 2023). In situ observations are of paramount importance to provide high spatiotemporal resolution in specific areas of interest, to monitor Essential Ocean Variables (EOVs), to inform about ocean conditions throughout the water column (Tanhua et al., 2019; Schroeder and Chiggiato, 2022) and to assess the quality of different model products and satellite measurements. Ocean reanalyses have demonstrated significant potential in bridging observational gaps by providing comprehensive, three-dimensional, basin-wide datasets that enable the investigation of spatial and temporal variability across multiple scales (Cossarini et al., 2021). However, generating a coupled physical–biogeochemical reanalysis remains a complex challenge (Park et al., 2018), due to uncertainties in the representation of interactions between physical and biogeochemical processes, the limited availability of biogeochemical observations for both data assimilation and validation, and the multivariate nature of the biogeochemical system, which involves intricate relationships between observed and modelled variables (Cossarini et al., 2021). As a result, models still struggle to accurately represent sparsely sampled regions, and considerable uncertainties persist, particularly in marginal and coastal seas (Resplandy et al., 2024). Despite their small size (about 7 % of the global ocean area), marginal and coastal seas have a significant impact on the carbon cycle (Lee et al., 2011; Kapsenberg et al., 2017; Laruelle et al., 2018; Hassoun et al., 2019; Resplandy et al., 2024). Recent estimates from Roobaert et al. (2024) quantified the global coastal CO₂ flux equal to

−2.2 Gt CO₂ yr^{−1} (−0.6 Pg C yr^{−1}) which represents around 21 % of the total current CO₂ flux from the atmosphere to the ocean (10.5 Gt CO₂; Friedlingstein et al., 2025). The sea–water carbonate system in these regions is driven by complex interaction between physical and chemical processes, like the overturning circulation, ocean mixing, freshwater inputs and biological processes. These interactions vary over time and space highlighting the importance of sustained time series observations to better understand and separate their individual contributions (García-Ibañez et al., 2024).

The Mediterranean Sea is a semi-enclosed basin, where Atlantic Ocean water is exchanged through the Strait of Gibraltar. Compared to the global ocean, it is characterized by a peculiar carbonate system. As a concentration basin, where evaporation exceeds precipitation, it is characterized by high salinity and elevated total alkalinity and dissolved inorganic carbon concentrations (Álvarez et al., 2023, 2026). Together with its active overturning circulation and the presence of several dense water formation regions, these characteristics promote an efficient uptake and transport of anthropogenic CO₂ to the ocean interior. In addition, a low Revelle factor, provides a high buffering capacity against increasing atmospheric CO₂ compared to other oceanic regions (Álvarez et al., 2014; Hassoun et al., 2019; Álvarez et al., 2023). Within the Mediterranean Sea, two major overturning circulation cells contribute to transporting carbon from the surface to the ocean interior (Lee et al., 2011). In the eastern Mediterranean, the northern and southern Adriatic play a key role in sustaining the thermohaline circulation (Robinson et al., 2001) and in capturing and storing CO₂ in the deeper layers (Cantoni et al., 2016; Ingrosso et al., 2017; Urbini et al., 2020; Cantoni et al., 2024). In particular, the Northern Adriatic dense Water represents the densest and most CO₂-rich water mass in the region, significantly contributing to deep ventilation and carbon sequestration in the eastern Mediterranean basin. Despite the importance of the Mediterranean Sea for the regional carbon cycle, observational coverage remains sparse and unevenly distributed (Hassoun et al., 2022). According to the SOCAT V2026 (Bakker et al., 2026) there is a marked imbalance in data availability across Mediterranean regions, with higher spatial and temporal coverage in the northwestern Mediterranean than in the eastern basins particularly in the Adriatic Sea and the Levantine Basin.

This observational gap highlights the need for sustained high-frequency measurements to better constrain surface carbon dynamics and air–sea CO₂ flux in these regions. In this study, a recently validated in situ time series of sea surface observations from the EMSO-E2M3A South Adriatic regional facility and ICOS ERIC observatory (nominal position 41.5053° N, 18.0806° E), hereafter EMSO-E2M3A, is discussed (Dentico et al., 2026). Time series of sea water partial pressure of CO₂ ($p\text{CO}_{2\text{sw}}$, μatm), hydrography and estimated CO₂ flux (FCO_2 , $\text{mmol m}^{-2} \text{d}^{-1}$) are investigated. One of the major goals of this research is to assess the role of the Southern Adriatic (SAd) as a carbon sink or source in the

last decade. To our knowledge, this is the first comprehensive study on carbon dynamics and carbon flux in the SAd based on high resolution in situ observations. In addition, the effect of different wind forcings (in situ observations and reanalysis), varying in situ temporal resolutions, and alternative gas transfer velocity parametrizations on FCO₂ estimates are analysed. Further, it is shown how the SAd $p\text{CO}_{2\text{sw}}$ and FCO₂ time series can be a key asset for biogeochemical reanalyses. The SAd data allowed to validate the Mediterranean Copernicus Marine Service biogeochemical reanalysis representing a valid tool to reconstruct local dynamics while highlighting the presence of some differences in the amplitude of seasonal cycles of both $p\text{CO}_{2\text{sw}}$ and FCO₂.

2 Study area

The Southern Adriatic (SAd) is located between the Palagruža Sill and the Strait of Otranto, where maximum depth reaches about 1250 m in the Southern Adriatic Pit (SAP; Fig. 1). This area is featured by a quasi-permanent cyclonic circulation, and dense water formation takes place at the centre of the gyre through open-ocean convection (Ovchinnikov et al., 1985; Gačić et al., 2002; Mantziafou and Lascaratos, 2004; Chiggiato et al., 2016; Amitai et al., 2021) contributing to the eastern Mediterranean thermohaline circulation (Robinson et al., 2001).

The variability of physical and biogeochemical processes, including ocean carbon dynamics, is primarily related to the interaction of different water masses (Civitarese et al., 2023) and by deep convection processes (Ingrosso et al., 2017). The SAd is one of the main dense water formation regions of the eastern Mediterranean (Schlitzer et al., 1991; Roether and Schlitzer, 1991), where winter convection ventilates the water column. In addition to locally formed dense waters, the SAd also receives Northern Adriatic dense Water, which is produced during winter on the northern Adriatic shelf and eventually enters the SAP (Cardin et al., 2011). On interannual timescales, the hydrographic variability of the SAd is further influenced by the Bimodal Oscillating System (BiOS), which modulates the properties of the intermediate waters entering the basin and results in alternating periods of fresher and colder Atlantic waters or saltier and warmer waters from the Ionian Sea (Gačić et al., 2010; Civitarese et al., 2010, 2023). Finally, the SAd is characterized by oligotrophic conditions, with relatively low biological productivity compared to other Mediterranean regions (Cerino et al., 2012; Matek et al., 2023).

The variability of the biogeochemical properties and the carbonate system of the SAd were almost continuously monitored by open ocean observatories, sampling activities and by ocean Argo floats and gliders. Particularly, the EMSO-E2M3A, which is located at the centre of the SAP (Fig. 1), and it is operated by the Italian National Institute of Oceanography and Applied Geophysics (OGS), rep-

resents a key research infrastructure to study biogeochemical and hydrographical properties of the whole water column in the SAP. EMSO-E2M3A is part of the European Multidisciplinary Seafloor and water column Observatory (EMSO) and the Integrated Carbon Observation System (ICOS) and the European Research Infrastructure Consortium (ERIC) networks. It consists of a system of two moorings, with the main mooring housing the surface buoy and equipped with a meteorological station and radiometers, sensors for physical (hydrography) and chemical variables ($p\text{CO}_{2\text{sw}}$, dissolved oxygen and pH), telemetry and services (Ravaioli et al., 2016). The secondary mooring line is composed of an instrument chain with sensors at different depths for physical and chemical measurements from the seafloor to the intermediate layer (Cardin et al., 2025b). The station has been in operation almost continuously since 2006 and is the longest open sea time series in the Adriatic. Additional information on EMSO-E2M3A, such as the scheme of the surface buoy and of the deep mooring with the depths of the different instruments, are described in Dentico et al. (2026).

3 Data and Methods

3.1 In situ sea surface $p\text{CO}_2$ and CTD data

The time series of $p\text{CO}_{2\text{sw}}$ (μatm) presented in this study were measured by different Pro-Oceanus CO₂ sensors at the EMSO-E2M3A at a depth of approximately 2 m (Cardin et al., 2025a). High frequency (every 4 h) $p\text{CO}_{2\text{sw}}$ measurements spanned over a period from 2015 to 2024 with declared accuracy of $\pm 0.5\%$. This time series was complemented with $p\text{CO}_{2\text{sw}}$ measurements collected around the EMSO-E2M3A in July 2020 by an Uncrewed Surface Vehicle (USV, Saildrone Inc., USA) during the ATL2MED demonstration experiment (Martellucci et al., 2024a, 2025). Additionally, SOCAT V2026 observations in the SAd were included in the $p\text{CO}_{2\text{sw}}$ time series shown here. These data cover three years of observation in 2015 (August and September), in 2016 (August and September) and 2020 (June and July) with the latter corresponding to the ATL2MED demonstration experiment data. Hourly sea surface temperature (SST, °C), salinity (Sal) and dissolved oxygen (DO, $\mu\text{mol kg}^{-1}$) were measured by a SeaBird SBE 37-ODO with declared accuracy of $\pm 0.002^\circ\text{C}$, $\pm 0.003 \text{ mS cm}^{-1}$, $\pm 0.1\%$ full scale range, respectively. DO from SBE 37-ODO was also used to calculate the apparent oxygen utilization (AOU, $\mu\text{mol kg}^{-1}$). This value corresponds to the difference between the equilibrium saturation of oxygen concentration in seawater with the same physical and chemical properties and the measured oxygen concentration, providing an estimation of the balance between primary production and respiration. AOU has been computed using the solubility coefficients from Benson and Krause (1984) as fitted by Garcia and Gordon (1992). A detailed description of the dataset used

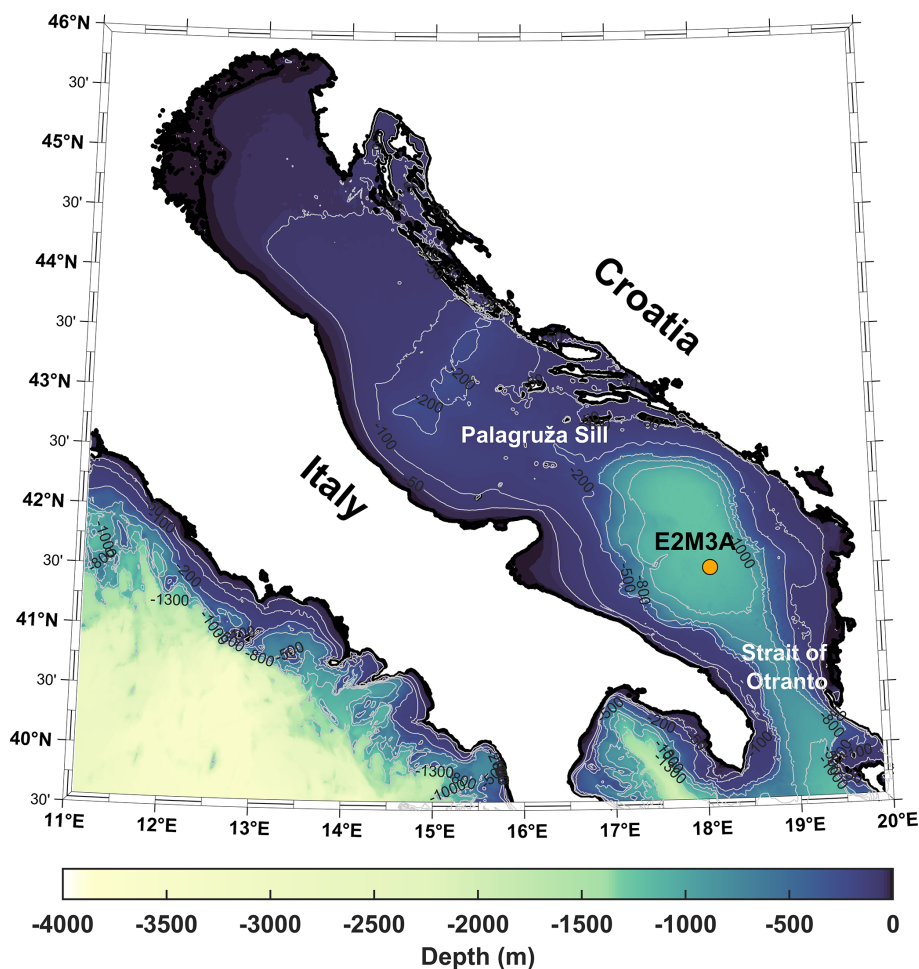


Figure 1. Map of the study area. The location of EMSO-E2M3A (nominal position 41.5053° N, 18.0806° E) moored at the centre of the SAP is shown by the orange dot. The geographical boundaries of the Southern Adriatic, i.e., the Palagruža Sill and the Strait of Otranto are also shown on the map.

here, and the quality control procedures applied to the data are available in Dentico et al. (2026).

3.2 In situ atmospheric $p\text{CO}_2$ data

To calculate air–sea FCO_2 , hourly atmospheric molar fraction of CO_2 ($x\text{CO}_2$, ppm) from the ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) Station for Climate Observations on the island of Lampedusa (Marullo et al., 2021; di Sarra et al., 2025) were used. Indeed, atmospheric $p\text{CO}_2$ measurements ($p\text{CO}_{2\text{atm}}$, μatm) at EMSO-E2M3A only started in December 2023, when a ProOceanus CO_2 -Pro ATM was deployed allowing continuous measurements of both $p\text{CO}_{2\text{sw}}$ and $p\text{CO}_{2\text{atm}}$ in alternating mode. As in situ observations of $p\text{CO}_{2\text{atm}}$ were not long enough to match with $p\text{CO}_{2\text{sw}}$, Lampedusa data was chosen as it represents one of the longest oceanic time series of $p\text{CO}_{2\text{atm}}$ in the Mediterranean Sea. Moreover, these data have been used in similar studies

to compute FCO_2 at Mediterranean scale (e.g., Martellucci et al., 2024a, 2025) and in the northern Adriatic Sea (e.g., Urbini et al., 2020; Cantoni et al., 2024). From Lampedusa $x\text{CO}_2$ (indicated as $x\text{CO}_{2\text{LMP}}$), the $p\text{CO}_{2\text{atm}}$ relative to the local physical and atmospheric condition at EMSO-E2M3A (indicated as $p\text{CO}_{2\text{atm_E2M3Ar}}$) was calculated according to Weiss (1974):

$$p\text{CO}_{2\text{atm_E2M3Ar}} = x\text{CO}_{2\text{LMP}}(P - p\text{H}_2\text{O}) \quad (1)$$

where P is the air pressure (mbar) measured at EMSO-E2M3A and $p\text{H}_2\text{O}$ is the water vapour saturation (mbar) that has been calculated according to Weiss and Price (1980):

$$p\text{H}_2\text{O} = A \exp^{(B - C(100/\text{SST}) - D \log(\text{SST}/100) - E(\text{SSS}))} \quad (2)$$

where SST is sea surface temperature (K), SSS is sea surface salinity both measured at EMSO-E2M3A and the coefficients A , B , C and D can be found in Weiss and Price (1980). To assess the potential bias of using $x\text{CO}_{2\text{LMP}}$ for

the calculation of CO₂ air–sea flux in the SAd, a comparison between $p\text{CO}_{2\text{atm}}$ measured by the ProOceanus CO₂-Pro ATM sensor installed at EMSO-E2M3A ($p\text{CO}_{2\text{atm_E2M3A}}$) with $p\text{CO}_{2\text{atm_E2M3Ar}}$ was performed. This comparison was limited to a four-month period between December 2023 and March 2024, when the CO₂-Pro ATM sensor was operational. The two time series show good overall agreement, however the differences tend to be larger at higher $p\text{CO}_{2\text{atm}}$ values, while they remain smaller at lower values (Figs. S1, S2a, Supplement). A mean difference of $+2.7 \pm 3 \mu\text{atm}$ between $p\text{CO}_{2\text{atm_E2M3A}}$ and $p\text{CO}_{2\text{atm_E2M3Ar}}$ indicates that $p\text{CO}_{2\text{atm_E2M3A}}$ is on average higher than $p\text{CO}_{2\text{atm}}$ derived from $x\text{CO}_{2\text{LMP}}$. A detailed investigation of the reasons behind this difference was beyond the scope of this work. Although the analysis of the residuals indicated potential heteroscedasticity in the data (Fig. S2a, b in the Supplement), the short duration of the overlapping time series justified applying a constant bias correction of $+2.7 \mu\text{atm}$ to $p\text{CO}_{2\text{atm_E2M3Ar}}$. To evaluate the robustness of this correction, a comparison between $p\text{CO}_{2\text{atm}}$ derived from the CAMS reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF; Agustí-Panareda et al., 2023), was also considered (Fig. S3, Supplement). The difference between monthly $p\text{CO}_{2\text{atm}}$ data at Lampedusa (LMP) and at EMSO-E2M3A between 2003 and 2021 was 2 ppm which is similar to the offset estimated in the four-month period.

3.3 In situ wind speed data

Wind speed (WSPD, m s^{-1}) was measured by a Young sensor on the meteorological station at EMSO-E2M3A (Cardin et al., 2025a; Dentico et al., 2026) with a manufacturer accuracy of $\pm 0.3 \text{ m s}^{-1}$ and was used as input for CO₂ flux calculation. Given that at EMSO-E2M3A wind speed is measured at 2 m height and CO₂ air–sea flux calculation requires the standard reference height of 10 m (Wanninkhof, 2014), a conversion was performed using a logarithm wind speed profile according to:

$$u_{\text{LOG}(z)} = (\ln(z/z_0)/\ln(z_m/z_0))u_{(z_m)} \quad (3)$$

where $u_{\text{LOG}(z)}$ is the wind speed (m s^{-1}) at the desired height (10 m), z is the desired measurement height (10 m), z_m the actual measurement height (2 m), z_0 is the roughness length that for oceanic regions was set equal to 1.52×10^{-4} (Peixoto and Oort, 1992) and $u_{(z_m)}$ is the wind speed (m s^{-1}) measured at EMSO-E2M3A at 2 m height. A detailed description of the data collection and quality check of the data can be found in Dentico et al. (2026).

3.4 Model data

The European Copernicus Marine Service (CMEMS) provides regular and systematic information on the ocean physics and biogeochemistry for the global ocean and the European regional seas (Le Traon et al., 2019). Data from

different Mediterranean CMEMS products were used as an additional reference to investigate the variability of the in situ $p\text{CO}_{2\text{sw}}$ and FCO_2 . In particular, the following modelling products were used: the Sea Physics Reanalysis (PHY, Escudier et al., 2021) for the physical variables of surface temperature (SST, °C), salinity (Sal) and Mixed Layer Depth (MLD, m), the Biogeochemistry Reanalysis (RD; Cossarini et al., 2021) and the Biogeochemistry Analysis and Forecast product (AF; Salon et al., 2019) for $p\text{CO}_{2\text{sw}}$ (μatm) and FCO_2 ($\text{mmol m}^{-2} \text{ d}^{-1}$). Additionally, the Ocean Color Satellite product (Volpe et al., 2019a) for the surface chlorophyll *a* (Chl *a*, $\mu\text{g L}^{-1}$) was used as a proxy of primary production. Detailed information on the models and variables used are summarized in Table 1. The time series presented here are spatial averages of the grid points in the 10 km radius from EMSO-E2M3A from the native spatial resolution of 4.5 and 1 km for models and satellite data, respectively.

ERA5 wind product, which is the fifth generation of ECMWF reanalysis for the global climate and weather (Hersbach et al., 2023), was also used and compared with EMSO-E2M3A wind measurements. ERA5 provides hourly estimates for a large number of atmospheric, ocean-wave and land-surface quantities from 1940 to present. The spatial resolution of atmospheric data is $0.25^\circ \times 0.25^\circ$ and wind speed ($\text{WSPD}_{\text{ERA5}}$, m s^{-1}) in the subregion (30 km radius) and in the nearest point close to EMSO-E2M3A was calculated as the square root of the sum of squares of the 10 m u component (m s^{-1}), which is the eastward horizontal wind speed, and of the 10 m v component (m s^{-1}) that represents the northward horizontal wind speed.

3.5 Air–sea CO₂ flux calculation

The direction and magnitude of FCO_2 is governed by the difference between $p\text{CO}_{2\text{sw}}$ and $p\text{CO}_{2\text{atm}}$ and the air–sea CO₂ gas transfer velocity (Takahashi et al., 2002):

$$\text{FCO}_2 = k_0 k (p\text{CO}_{2\text{sw}} - p\text{CO}_{2\text{atm}}) \quad (4)$$

where k_0 is the solubility coefficient of CO₂ at in situ temperature and salinity (Weiss, 1974; Zeebe and Wolf-Gladrow, 2001) and k is the gas transfer velocity (m d^{-1}). In this study, if the $\text{FCO}_2 < 0$ the flux is from air to seawater, on the contrary if $\text{FCO}_2 > 0$ the flux is from the seawater to the atmosphere. Several algorithms for k calculation exist, here different parametrizations were used to compute FCO_2 :

$$k_W = 0.251u^2 (Sc/660)^{-0.5} \quad (5)$$

$$k_{W\&McG} = 0.0283u^3 (Sc/660)^{-0.5} \quad (6)$$

$$k_N = 0.222u^2 + 0.333u (Sc/600)^{-0.5} \quad (7)$$

where k_W is a quadratic relationship proposed by Wanninkhof (2014) and it is one of the most frequent parametrizations used in the FCO_2 estimations at both global and Mediterranean scale (Urbini et al., 2020; Cantoni et al., 2024;

Table 1. Overview of the Copernicus Marine Service (CMEMS) products used in this work.

CMEMS product name	Variables used in this work	DOI	Reference
Mediterranean Sea Physics Reanalysis (PHY)	SST, Sal, MLD	https://doi.org/10.25423/CMCC/MEDSEA_MULTYYEAR_PHY_006_004	Escudier et al. (2020, 2021)
Mediterranean Sea Biogeochemistry Reanalysis (RD)	$p\text{CO}_{2\text{sw}}$, FCO_2	https://doi.org/10.25423/cmcc/medsea_multiyear_bgc_006_008_medbfm3	Teruzzi et al. (2021), Cossarini et al. (2021)
Mediterranean Sea Biogeochemistry Analysis and Forecast (AF)	$p\text{CO}_{2\text{sw}}$, FCO_2	https://doi.org/10.25423/cmcc/medsea_analysisforecast_bgc_006_014_medbfm4	Feudale et al. (2023), Salon et al. (2019)
Mediterranean Sea, Bio-Geo-Chemical, L4, monthly means, daily gapfree and climatology Satellite Observations (1997–ongoing)	Chl <i>a</i>	https://doi.org/10.48670/moi-00300	Volpe et al. (2019a, b)

Martellucci et al., 2025; Pecci et al., 2026); $k_{\text{W\&McG}}$ is a cubic wind speed dependence from Wanninkhof and McGillis (1999); and k_{N} is a mixed (linear and quadratic) dependency from Nightingale et al. (2000) used in the literature (for example in Gulf of Biscay; Otero et al., 2013). In Eqs. (5), (6) and (7) u is the wind speed (m s^{-1}) corrected at 10 m height and Sc the Schmidt number for CO₂. Different temporal resolutions of u have been used to compute Eq. (5), (6) and (7) including hourly, 6 h averages and daily averages. From these, daily k values have been calculated to have daily FCO_2 values. Additionally, 6 h averages ERA5 wind speed data have been used to calculate the different parametrizations of k . ERA5 wind speed data were selected for two main reasons: (i) wind reanalysis products, unlike in situ time series, provide continuous spatial and temporal coverage without observational gaps; (ii) ERA5 wind data are used as the wind forcing input in the Mediterranean Sea Physical and Biogeochemistry Reanalyses. Thus, considering that CO₂ air–sea flux in the CMEMS products (Salon et al., 2019; Cossarini et al., 2021) and in the present work was computed following the same Wanninkhof (2014) formulation, the use of the same wind dataset, allowed a focus on the analyses of $p\text{CO}_{2\text{sw}}$ difference between in situ data and model outputs. In summary, different wind products (EMSO-E2M3A versus ERA5), different formulations of k and different temporal aggregation of wind speed data were used to compute the FCO_2 and to assess their impact on annual and seasonal estimates.

3.6 Thermal and non-thermal component of $p\text{CO}_{2\text{sw}}$

Thermal ($p\text{CO}_{2\text{sw_T}}$, μatm) and non-thermal ($p\text{CO}_{2\text{sw_NT}}$, μatm) components of $p\text{CO}_{2\text{sw}}$ were estimated according to Takahashi et al. (2002). The thermal

component is associated to the effect of temperature on $p\text{CO}_{2\text{sw}}$, while the non-thermal component can be attributed to other factors not strictly related to temperature, as biological activity (photosynthesis and respiration), changes in dissolved inorganic carbon (DIC), mixing or advective processes and gas exchange with the atmosphere. $p\text{CO}_{2\text{sw_T}}$ and $p\text{CO}_{2\text{sw_NT}}$ have been computed using the following equations:

$$p\text{CO}_{2\text{sw_T}} = \text{mean}(p\text{CO}_{2\text{sw}})\exp^{0.0423(\text{SST}_{\text{obs}} - \text{SST}_{\text{mean}})} \tag{8}$$

$$p\text{CO}_{2\text{sw_NT}} = p\text{CO}_{2\text{sw}}\exp^{0.0423(\text{SST}_{\text{mean}} - \text{SST}_{\text{obs}})} \tag{9}$$

where, “mean” refers to yearly mean values of sea surface temperature (SST, °C), while the other variables ($p\text{CO}_{2\text{sw}}$ and SST_{obs}) refer to the daily values measured during the study period.

4 Results and Discussion

4.1 $p\text{CO}_2$ dynamics and hydrography in the SAP

The time series of the daily surface $p\text{CO}_{2\text{sw}}$ between 2015 and 2024 is presented in Fig. 2a. The incomplete coverage of the full seasonal cycle in several years, prevented a detailed assessment of interannual variability. Therefore, the discussion presented in this section mainly focuses on the seasonal patterns and their main drivers, and, when possible, on interannual differences of the seasonal cycle. Mean winter values were around 380 μatm and mean summer values reached around 484 μatm , resulting in a seasonal amplitude of about 100 μatm . This pronounced seasonality reflected the combined influence of thermal and non-thermal processes (Fig. 2b). During winter, low sea surface temperature ($\text{SST} < 15^\circ\text{C}$; Fig. 2c) increases CO₂ solubility,

leading to lower $p\text{CO}_{2\text{sw}}$ (Fig. 2b). However, during winter convection the upward transport of DIC-rich intermediate and deep waters (Touratier et al., 2016; Ingrosso et al., 2017) led to an increase of surface $p\text{CO}_{2\text{sw}}$ as shown by the $p\text{CO}_{2\text{NT}}$ component (Fig. 2b). This was particularly evident between late December and late February of 2016–2017, 2017–2018, 2020–2021, and 2023–2024 (Fig. 2a). Positive AOU values observed during these periods (Fig. 2d) further support this interpretation, indicating the upward displacement of oxygen-depleted intermediate waters during vertical mixing, also described in Martellucci et al. (2024b). The post-convection periods (Fig. 2e; usually from March to May–June) were characterised by a phytoplankton bloom (Fig. 2f). Although direct $p\text{CO}_{2\text{sw}}$ observations were limited during this period, the decrease in AOU and the increase in DO concentration at the surface (Fig. 2d) provided indirect but consistent evidence of primary production. These observations suggest that biological CO₂ uptake likely contributes to lowering $p\text{CO}_{2\text{sw}}$ following winter mixing, acting as an additional non-thermal driver of the seasonal variability. In spring, surface warming began, leading, in summer, to maximum SST values ($> 25^\circ\text{C}$; Fig. 2c) and strong stratification. During this period, $p\text{CO}_{2\text{sw}}$ reached its annual maximum, closely following the $p\text{CO}_{2\text{sw,T}}$ component and indicating a dominant thermal effect (Fig. 2b). The comparison between the Saildrone and EMSO-E2M3A observations further confirmed this pattern, showing coherent short-term variations with the EMSO-E2M3A time series ($r = 0.77$, p value < 0.01) and a nearly constant offset of $16\text{ }\mu\text{atm}$ (Fig. 2a). Similarly, SOCAT V2026 observations showed very good agreement with the EMSO-E2M3A measurements during August–September 2015 (mean difference of approx. $8.4\text{ }\mu\text{atm}$; Fig. 2a). In contrast, larger differences (mean difference approx. $40\text{ }\mu\text{atm}$) were observed during the same period in 2016. The SOCAT observations in 2016 are located along the eastern side of the SAd, therefore, the discrepancies may reflect differences in the hydrographic conditions and water mass distribution between the two surveys, resulting in the sampling of waters with different physical and biogeochemical characteristics. However, further analyses would be required to confirm this hypothesis. Interestingly, higher $p\text{CO}_{2\text{sw}}$ values were recorded in summer 2022, with a peak in July 2022, coinciding with the occurrence of a Mediterranean Marine Heatwave. In the SAP, Pirro et al. (2024) detected positive temperature anomalies across the whole water column, with the strongest warming at the surface. Thus, the elevated $p\text{CO}_{2\text{sw}}$ observed in this period might be linked to the increased stratification that limited vertical exchange favouring the accumulation of respired carbon in surface waters. This behaviour was consistent with recent observations in the northwestern Mediterranean Sea (e.g., Metzl et al., 2025), which highlighted that the exceptional warming observed in summer 2022 impacted not only thermodynamic processes but also stratification, wind field

(Pecci et al., 2026) and biological activity, with consequences for the variability of $p\text{CO}_{2\text{sw}}$ and air–sea CO₂ flux.

The annual cycle of surface $p\text{CO}_{2\text{sw}}$ in the SAd was comparable to other regions of the Mediterranean Sea with generally lower values than those observed in the SAd (Dentico et al., 2026). Similar seasonal variations especially in winter were described for the northern Adriatic shelf (Ingrosso et al., 2016; Urbini et al., 2020; Cantoni et al., 2024), where intense Bora wind events and vertical mixing periodically disrupt water column stratification, promoting an efficient exchange between bottom and surface $p\text{CO}_{2\text{sw}}$. Seasonal $p\text{CO}_{2\text{sw}}$ variability was reported between $200\text{ }\mu\text{atm}$ in winter up to $500\text{ }\mu\text{atm}$ in summer (e.g., Cantoni et al., 2024). However, unlike the SAd, the riverine inputs in this area also play a key role in modulating the carbonate system dynamics (e.g., Giani et al., 2023). In the convective region of the northwestern Mediterranean Sea, several studies have emphasized the importance of vertical mixing, horizontal advection and biological productivity in driving $p\text{CO}_{2\text{sw}}$ variability (e.g., Merlivat et al., 2018; Fourrier et al., 2022; Ulses et al., 2023). Here winter values were comparable to the SAd (around $350\text{ }\mu\text{atm}$) and summer values around $500\text{ }\mu\text{atm}$ (Merlivat et al., 2018; García-Ibáñez et al., 2024) or higher, as reported for the DYFAMED site in the Ligurian Sea (Coppola et al., 2020) where values exceeded $550\text{ }\mu\text{atm}$. In the SAd the effect of biological activity was less clear because of data gaps. Nevertheless, further investigations could be essential to clarify the role of biological processes in shaping the local carbon cycle as highlighted in previous studies (Turchetto et al., 2012; Cerino et al., 2012). Non-convective regions such as the eastern Mediterranean Sea, exhibited a stronger thermal control on seasonal $p\text{CO}_{2\text{sw}}$ variability. The first $p\text{CO}_{2\text{sw}}$ time series from the Cretan Sea showed that temperature was the dominant driver of $p\text{CO}_{2\text{sw}}$, while the non-thermal component was mainly associated with evaporation, water mass mixing, and biological remineralisation-production processes (Frangoulis et al., 2024). Similarly, in the southeast Levantine, seasonal $p\text{CO}_{2\text{sw}}$ was found to be tightly correlated with sea surface temperature indicating that its seasonal cycle is largely controlled by thermodynamic processes (Sisma-Ventura et al., 2017). In contrast to the Levantine Basin, where $p\text{CO}_{2\text{sw}}$ variability is strongly influenced by warming and evaporation, the Southern Adriatic is affected by recurrent deep convection and higher biological activity (e.g., Pérez et al., 2024; Tsiaras et al., 2024). Nevertheless, seasonal variations were similar ranging between $350\text{ }\mu\text{atm}$ in winter and around $500\text{ }\mu\text{atm}$ in summer (Frangoulis et al., 2024). The analysis of hydrological data showed the highly dynamic characteristics of the region. First, the intensity and occurrence of convection in the SAd have varied substantially among years (Fig. 2e). Depending on atmospheric forcing and water column preconditioning, the depth of vertical mixing ranged from relatively shallow mixing in the intermediate layers ($< 400\text{ m}$ depth) to deeper convective events ($> 800\text{ m}$ depth). Weaker

events were recorded in 2015, 2016, 2019, and 2020, whereas deeper mixing (> 600 m) occurred in more recent years (especially after 2022; Fig. 2e). This interannual variability resulted from strong/weak air–sea interactions, where stronger heat losses could occur especially under the influence of the cold and dry Bora wind (Le Meur et al., 2025). Variations in the regional hydrographic structure, particularly changes in salinity (Amorim et al., 2024; Le Meur et al., 2025), also affected the stability of the water column and the depth of convection. This variability in salinity (Fig. 2g) was associated with the inflow of Levantine/Ionian surface water, which is regulated by changes in the Northern Ionian Gyre (NIG) vorticity (Gačić et al., 2010; Rubino et al., 2020; Menna et al., 2022; Civitarese et al., 2023). The influence of NIG in the SAd was evident in the salinity measurements (Fig. 2g), which showed periods of higher salinity (> 39 in 2017, 2021, 2022) and lower salinity (< 38.5 in 2015, 2018). Through its impact on stratification and preconditioning, this large-scale circulation variability likely modulates the intensity of winter mixing and, indirectly, $p\text{CO}_{2\text{sw}}$ variability.

4.2 CO₂ flux: source-sink dynamics

Daily FCO_2 in the SAd shown in Fig. 3 were computed using a reference configuration based on Eqs. (4) and (5) using as input $p\text{CO}_{2\text{sw}}$, $p\text{CO}_{2\text{atm_E2M3Ar}}$ (Sect. 3.1) and 6 h averaged wind speed data from EMSO-E2M3A corrected at 10 m height (Sect. 3.3). The gas transfer velocity was calculated using the Wanninkhof (2014) parameterisation to allow a more consistent comparison with previous studies and model data (Sect. 4.4). FCO_2 estimates obtained using different wind products, wind temporal resolutions, and gas transfer velocity parameterisations are discussed in Sect. 4.3. Based on the reference configuration, CO₂ air–sea flux in the SAd presents two dominant phases: a source period, generally associated with post-convection/summer months (positive values in Fig. 3a), and a sink period, typically occurring during winter and during episodes of winter convection (negative values in Fig. 3a). While the intensity of daily values during sink and source phases exhibited high interannual variability, the timing of the transition months, i.e., the periods when the SAd shifts from a source (May) to a sink (October), occurred regularly (Fig. 3b).

Monthly averages were computed for those months with at least 14 valid daily values. The mean over the full period was subsequently obtained from these monthly values (Fig. 3b). Given the observed variability (i.e., high daily variability with a regular annual cycle) and the presence of substantial data gaps in the FCO_2 time series, an additional computational approach was applied to derive robust estimates of mean CO₂ fluxes in the SAP over the past decade (Table S1 in the Supplement). Notwithstanding the potential limitations derived by data availability, over the last decade, the SAd has functioned predominantly as a weak-to-moderate carbon sink with mean annual FCO_2 val-

ues of about $-0.97 \text{ mmol m}^{-2} \text{ d}^{-1}$ for the period 2015–2024. Across the Mediterranean, air–sea carbon flux is spatially uneven: the western basin takes up more CO₂ than the eastern basin, while some southeastern sectors show weak release or near-neutral behaviour (Cossarini et al., 2021). Although the values reported here for the SAd were modest in magnitude compared to other Mediterranean regions, they pointed to a net CO₂ uptake, underscoring the potential role of the SAd in regional carbon sequestration, as suggested by Inghrosso et al. (2017). While the present analysis does not directly address the carbon export below the mixed layer, the occurrence of recurrent convection events suggests that part of the CO₂ absorbed at the surface may be transferred to intermediate and deep waters. In this context, our results are consistent with observations from other Mediterranean deep-water formation regions. For instance, the northern Adriatic Sea has been reported to act as an effective CO₂ sink during winter, spring, and autumn, with mean daily fluxes of about $-2.9 \text{ mmol m}^{-2} \text{ d}^{-1}$ (Catalano et al., 2014; Cantoni et al., 2024) reaching however the highest CO₂ flux during winter ($-14.2 \text{ mmol m}^{-2} \text{ d}^{-1}$; Urbini et al., 2020). Dense waters formed in the northern Adriatic can eventually flow towards the SAP, suggesting that the Southern Adriatic may act as a regional collector of carbon-enriched waters from upstream regions in addition to locally vertical transfer of CO₂ during convection events. Similarly, in the Gulf of Lions, Ulses et al. (2023) showed that the area functions as a net CO₂ sink on an annual scale, with an estimated carbon sequestration rate of approximately $-1.29 \text{ mmol m}^{-2} \text{ d}^{-1}$ (estimated mean was $-0.47 \text{ mol C m}^{-2} \text{ yr}^{-1}$). Here higher uptake is also linked to Atlantic inflow and spring primary production that lowers surface $p\text{CO}_2$ (Martellucci et al., 2025). Finally, comparable FCO_2 values could be also found between the SAd and the Central Mediterranean (Pecci et al., 2026) where estimates at the Lampedusa observatory, indicate a net CO₂ sink activity corresponding to $-1.76 \pm 0.11 \text{ mmol m}^{-2} \text{ d}^{-1}$ for a 1-year period (i.e., 2022).

4.3 Impact of different wind inputs in FCO_2 estimates

This section examines the influence of different wind products (in situ observations and ERA5 reanalysis), different temporal aggregations of the wind data (hourly, 6-hourly, and daily averages), and alternative gas transfer velocity parameterisations (Eqs. 5, 6 and 7) on the estimation of FCO_2 . Flux estimates obtained using these different methodological choices are compared on both annual basis and for two extended seasonal periods representing the main hydrographic phases of the Southern Adriatic: the winter/convective period, from October to March, and the summer/post-convective period, from April to September. For each new estimate, the annual and seasonal averages were derived using the same approach of the nominal estimate (i.e., considering months with at least 14 valid daily observations). Annual and seasonal averages were then calculated from these

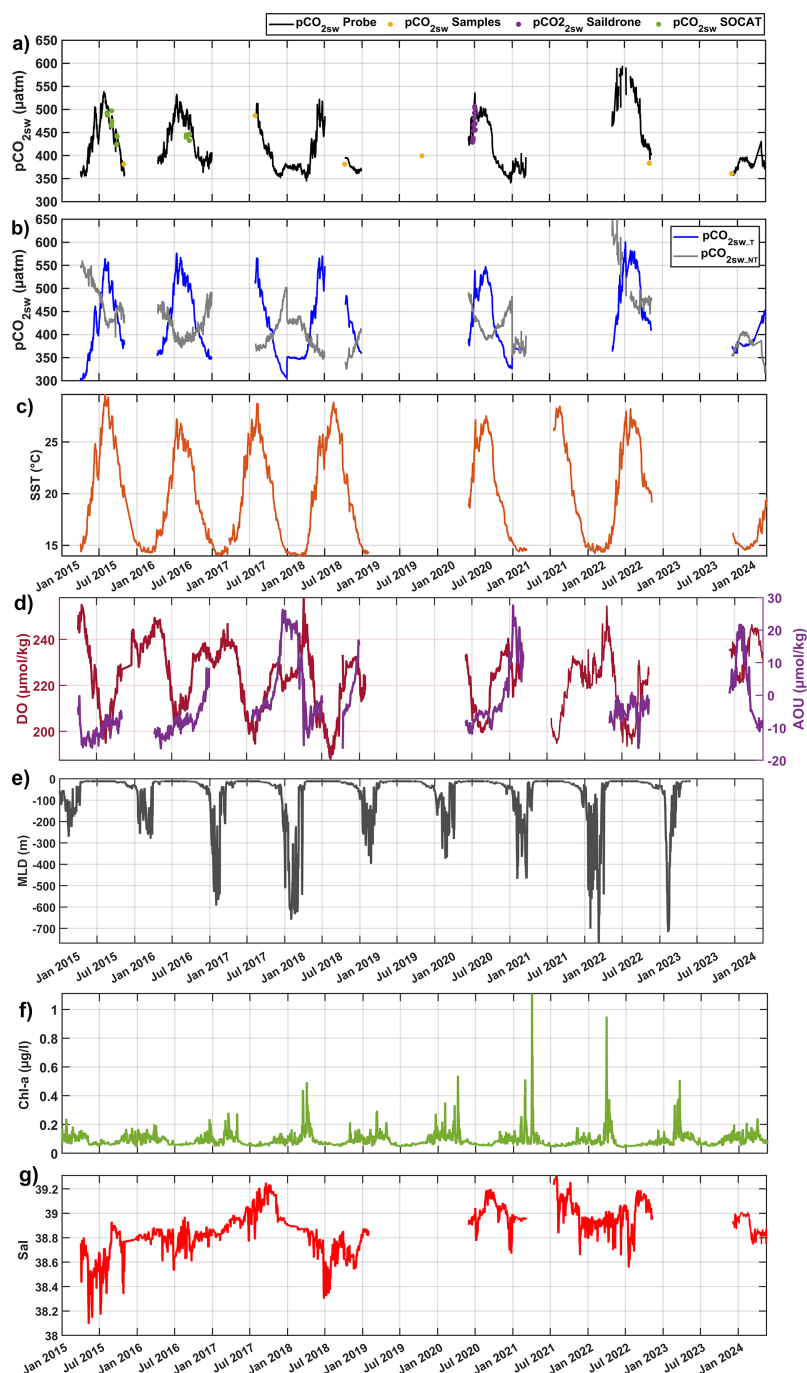


Figure 2. Time series of daily (a) Partial pressure of CO₂ in seawater ($p\text{CO}_{2\text{sw}}$ Probe, μatm) measured by the Pro-Oceanus sensor represented by the black solid line, partial pressure of CO₂ in seawater derived from the analysis of water samples using the pair pH and total alkalinity ($p\text{CO}_{2\text{sw}}$ Samples, μatm), partial pressure of CO₂ in seawater measured by the Saildrone ($p\text{CO}_{2\text{sw}}$ Saildrone, μatm), and partial pressure of CO₂ in seawater from SOCAT in the SAd ($p\text{CO}_{2\text{sw}}$ SOCAT, μatm) represented by the yellow, violet and green dots respectively; (b) Thermal ($p\text{CO}_{2\text{sw_T}}$, μatm) and non-thermal ($p\text{CO}_{2\text{sw_NT}}$, μatm) components of $p\text{CO}_{2\text{sw}}$ (μatm) blue and grey respectively; (c) Sea surface temperature (SST, $^{\circ}\text{C}$); (d) Dissolved oxygen (DO, $\mu\text{mol kg}^{-1}$) and Apparent Oxygen Utilization (AOU, $\mu\text{mol kg}^{-1}$) derived from DO measured by the SBE37 ODO sensor in dark red and violet respectively; (e) Mixed Layer Depth (MLD, m) from the CMEMS Mediterranean Sea Physics Reanalysis; (f) Chlorophyll *a* (Chl *a*, $\mu\text{g L}^{-1}$) used here as a proxy of primary production from the CMEMS Mediterranean Sea, Bio-Geo-Chemical, L4, monthly means, daily gapfree and climatology Satellite Observations (1997–ongoing); and (g) Sea surface salinity (Sal). Time series (a, b, c, d, g) refers to the data measured by several instruments deployed at 2 m depth at EMSO-E2M3A between April 2015 and May 2024. Data gaps in the series were mostly due to maintenance operations and/or discarded data because they failed the quality-control procedures described in Dentico et al. (2026). Modified from Dentico et al. (2026).

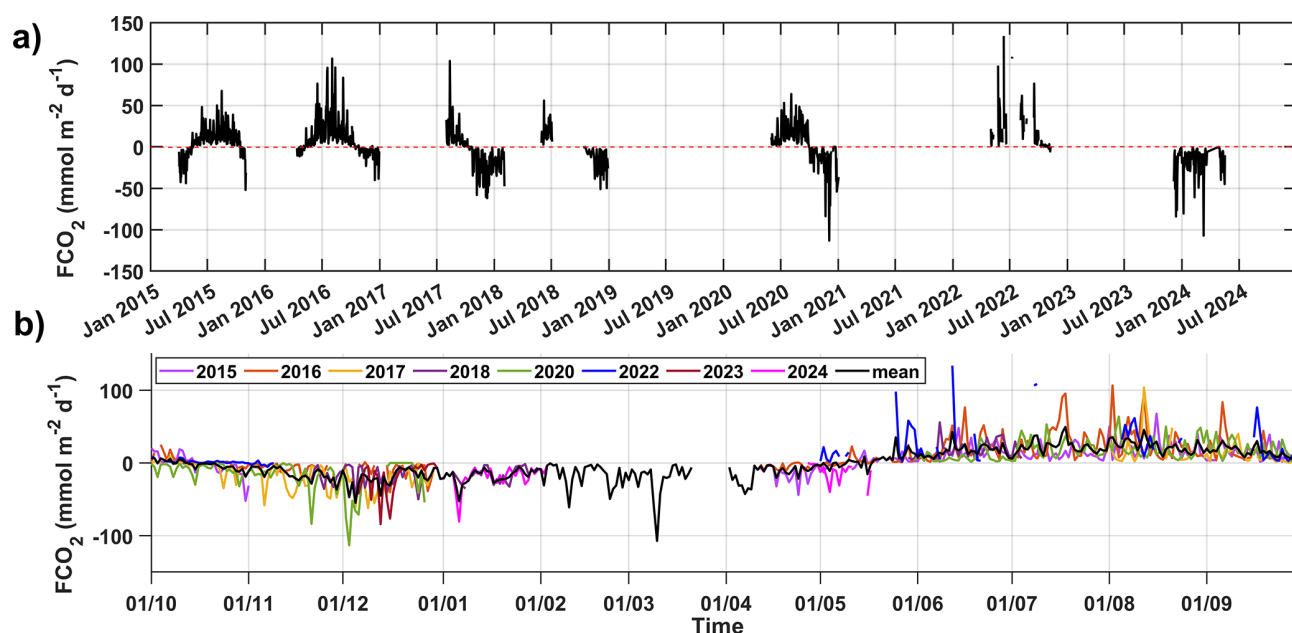


Figure 3. (a) Time series of daily CO₂ flux (FCO_2 , $\text{mmol m}^{-2} \text{d}^{-1}$) calculated with in situ measurements in the period 2015–2024 at EMSO-E2M3A; (b) Daily averages of CO₂ flux calculated in the different years (coloured lines) and the mean daily FCO_2 ($\text{mmol m}^{-2} \text{d}^{-1}$) over the entire period (2015–2024; black line). Negative flux represents CO₂ influx from the air to the sea and positive flux represents CO₂ outgassing from the sea to the air.

monthly values. The resulting annual and seasonal FCO_2 estimates are summarized in Table 2. All configurations based on in situ observations consistently indicated a net annual uptake of atmospheric CO₂ by the Southern Adriatic, although the magnitude of the estimated flux varied depending on the methodological choices adopted (Table 2). Annual mean FCO_2 ranged from -0.90 to $-3.92 \text{ mmol m}^{-2} \text{d}^{-1}$. The choice of the gas transfer velocity parameterisation had a larger influence on the annual flux estimate than the temporal aggregation of the wind data. While the results using k_W or k_N with any temporal aggregation produced comparable results, the use of $k_{W\&McG}$ produced higher results. For example, using the pair 6-hourly in situ wind speed and $k_{W\&McG}$ produced an annual uptake four times larger than estimates obtained with the pair 6-hourly in situ wind speed and k_W or k_N . The influence of wind temporal aggregation was generally limited for k_W or k_N but became more pronounced for $k_{W\&McG}$, which is inherently more sensitive to high wind speeds that can be smoothed out due to the daily aggregation of the data. At the seasonal scale, winter CO₂ uptake was consistently larger than summer outgassing regardless of the selected parameterisation or wind temporal aggregation. Winter mean FCO_2 ranged from -14.55 to $-19.26 \text{ mmol m}^{-2} \text{d}^{-1}$ using in situ winds, whereas summer values ranged between 8.75 and $13.96 \text{ mmol m}^{-2} \text{d}^{-1}$. The relative standard deviation of the summer estimates was, however, systematically higher than that of the winter period. This behaviour mainly reflects the inclusion of May in the summer period. As shown in Fig. 3b, May represents a

transition month during which the Southern Adriatic shifts from winter sink conditions to summer source conditions. Although October also marked a seasonal transition, its influence on the winter mean was less pronounced because it was followed by several months characterized by persistent CO₂ uptake. In contrast, the summer period included only four months (from June to September) that consistently behave as a CO₂ source. These results suggested that the annual net CO₂ uptake in the Southern Adriatic is favoured not only by the higher winter CO₂ flux but also by the longer duration of the sink period relative to the source period. A different behaviour emerged when ERA5 wind data were used. Using ERA5 wind fields together with k_W and k_N parameterisations resulted in a weak annual CO₂ source, whereas the use of the nearest ERA5 grid point to the EMSO-E2M3A observatory instead of the spatial average resulted in a weak annual sink. This sign reversal highlighted the strong dependence of FCO_2 estimates on the representation of the local wind field. The difference was particularly evident during winter, when ERA5 spatially averaged winds produced CO₂ uptake estimates about 25 %–40 % lower than those obtained using the nearest ERA5 grid point. This suggests that spatial averaging may smooth high wind events, which strongly influence k because of its nonlinear dependence on wind speed (Takahashi et al., 2002). A more detailed analysis on the performance of ERA5 wind in the region revealed that the largest discrepancy between ERA5 and in situ observations (Figs. S4 and S5) occurred during strong wind events (high Beaufort conditions).

Table 2. Air-sea CO₂ flux (mmol m^{−2} d^{−1}) in the Southern Adriatic calculated using different wind speed inputs from in situ observations (EMSO-E2M3A) and ERA5 reanalysis. ERA5 wind speed was tested both as a spatial mean over a 30 km radius around the observatory (ERA5 30 km spatial mean) and as the nearest grid point to EMSO-E2M3A (ERA5 single point). Different gas transfer velocity parametrizations (k_W , $k_{W\&McG}$, and k_N) and temporal aggregations of the wind data (hourly, 6-hourly, and daily averages) were compared. Flux estimates are reported as annual means and as seasonal means $\pm$ standard deviation for two extended periods: winter/convective period (October–March) and summer/post-convective period (April–September).

		EMSO-E2M3A			ERA5	ERA5
					30 km spatial mean	single point
		Hourly	6 h	Daily	6 h	6 h
Annual	k_W	−0.9	−0.97	−1.29	0.27	−1.11
	$k_{W\&McG}$	−3.92	−3.87	−3.26	−0.53	−2.81
	k_N	−0.97	−1.01	−0.9	0.49	−0.75
Winter (convective)	k_W	−14.56 $\pm$ 7.02	−15.90 $\pm$ 7.77	−14.55 $\pm$ 7.02	−8.91 $\pm$ 4.18	−12.27 $\pm$ 6.09
	$k_{W\&McG}$	−19.26 $\pm$ 9.85	−18.09 $\pm$ 9.12	−15.27 $\pm$ 7.55	−7.61 $\pm$ 3.56	−12.69 $\pm$ 6.53
	k_N	−15.91 $\pm$ 7.77	−15.51 $\pm$ 7.54	−14.56 $\pm$ 7.03	−9.27 $\pm$ 4.36	−12.37 $\pm$ 6.12
Summer (post-convective)	k_W	12.75 $\pm$ 13.73	13.97 $\pm$ 14.97	11.97 $\pm$ 13.13	9.45 $\pm$ 10.32	10.05 $\pm$ 10.75
	$k_{W\&McG}$	11.43 $\pm$ 13.67	10.36 $\pm$ 12.56	8.75 $\pm$ 10.69	6.55 $\pm$ 7.73	7.06 $\pm$ 8.16
	k_N	13.96 $\pm$ 14.97	13.47 $\pm$ 14.51	12.76 $\pm$ 13.73	10.26 $\pm$ 11	10.86 $\pm$ 11.43

4.4 $p\text{CO}_{2\text{sw}}$ and FCO_2 : in situ data and model comparison

The in situ $p\text{CO}_{2\text{sw}}$ and physical data proved to be a reliable asset for model validation, thus a comparison between the RD and AF CMEMS products for $p\text{CO}_{2\text{sw}}$ and FCO_2 was computed. The comparison between daily $p\text{CO}_{2\text{sw}}$ from CMEMS (Sect. 3.4) and $p\text{CO}_{2\text{sw}}$ measured by the probe for a decade-long period highlighted a coherent temporal evolution (Fig. 4). A RMSE of 35.96 μatm and a significant correlation coefficient of 0.82 (p value < 0.01) between the two datasets was found. Nevertheless, during summer, model data were on average higher than $p\text{CO}_{2\text{sw}}$ from the probe, with a mean difference between RD and the probe data of +34.22 μatm . The only exception was in 2022, when $p\text{CO}_{2\text{sw}}$ from the probe was higher than CMEMS data (both RD and AF). As discussed in Sect. 4.1 in 2022 a marine heatwave was detected in the region (Pirro et al., 2024). The strong difference in $p\text{CO}_{2\text{sw}}$ between the probe and the model was likely driven by the combined effects of warming, enhanced stratification, and biogeochemical processes which are difficult to represent in current biogeochemical models. On the contrary, in winter RD data were on average lower than the probe, with a mean difference between the two datasets of −26.87 μatm . This discrepancy was mainly associated with the increase in the $p\text{CO}_{2\text{sw}}$ recorded by the probe between late December and late February, which was not fully resolved by the model and was underestimated by approximately 45 μatm . This mismatch may be partly attributed to the limited vertical resolution of the model and to the parameterization of vertical mixing processes, which may smooth or underestimate the upward transport of DIC to the

surface during convection events (as discussed in Sect. 4.1). By contrast, with lower intensity, the AF product was able to capture this increase (Fig. 4). Similarly to RD, also AF was not able to consistently reproduce the higher $p\text{CO}_{2\text{sw}}$ values measured by the probe in summer 2022. Finally, in autumn and spring the mean differences were smaller (+5.13 μatm and −16.12 μatm , respectively).

The comparison between FCO_2 derived from in situ data and from the model is presented in Fig. 5. Both datasets consistently capture the two main seasonal phases of the region, with a source period during summer and a sink period during winter. However, notable differences in absolute values emerged, particularly in summer. A main factor in these differences was related to the $p\text{CO}_{2\text{sw}}$ measurements as discussed in the previous section. Additionally, in both seasons, the different wind forcing used by the model (ERA5) could also be a contributing factor of the FCO_2 difference (see Sect. 4.3 and Fig. S5, Supplement). On the contrary, the difference between model and in situ temperature and/or salinity was not considered a driving factor of the in situ and RD FCO_2 difference (Fig. S6, Supplement). Nevertheless, an RMSE of 16.89 mmol m^{−2} d^{−1} with a correlation coefficient of 0.89 (p value < 0.01) was calculated between FCO_2 from RD and FCO_2 derived from observational data.

Considering the relatively good performance of the RD, and the temporal bias in the in situ FCO_2 time series (e.g., the winter periods were by far under sampled with respect to summer periods), it was used to clarify the role of the SAd as a source or sink of CO₂. The mean annual FCO_2 using exclusively CMEMS RD resulted in −4.3 mmol m^{−2} d^{−1}. The spatial distribution of the mean annual FCO_2 further highlighted that spatial differences in the basin existed

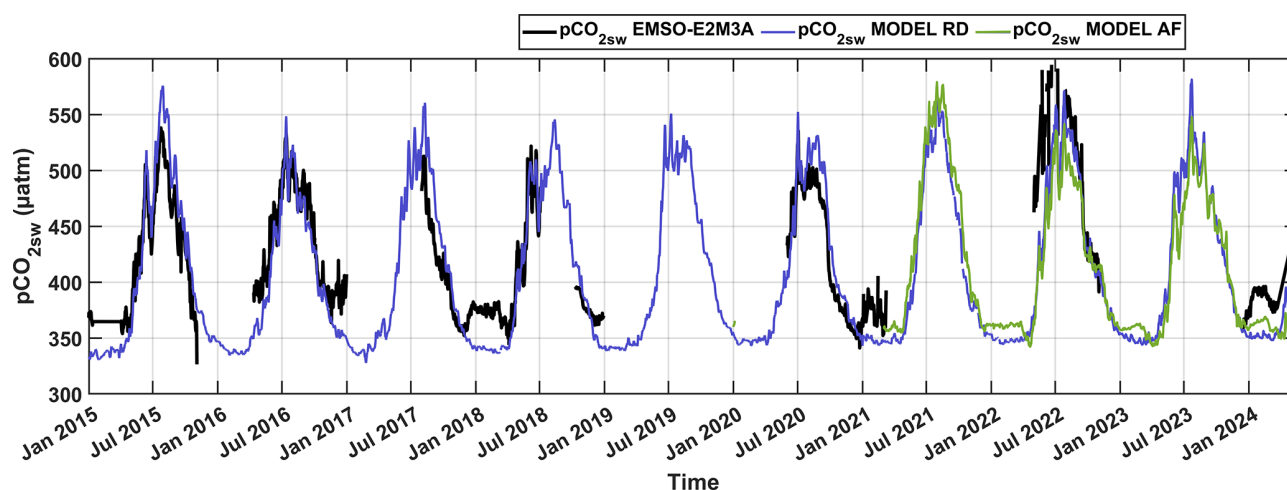


Figure 4. Time series of daily $p\text{CO}_{2\text{sw}}$ (μatm) measured at the EMSO-E2M3A regional observatory in black, $p\text{CO}_{2\text{sw}}$ (μatm) from the Mediterranean Sea Biogeochemistry Reanalysis (RD) in blue and the Mediterranean Sea Biogeochemistry Analysis and Forecast (AF) in green. RD data after July 2022 were integrated with the interim reanalysis.

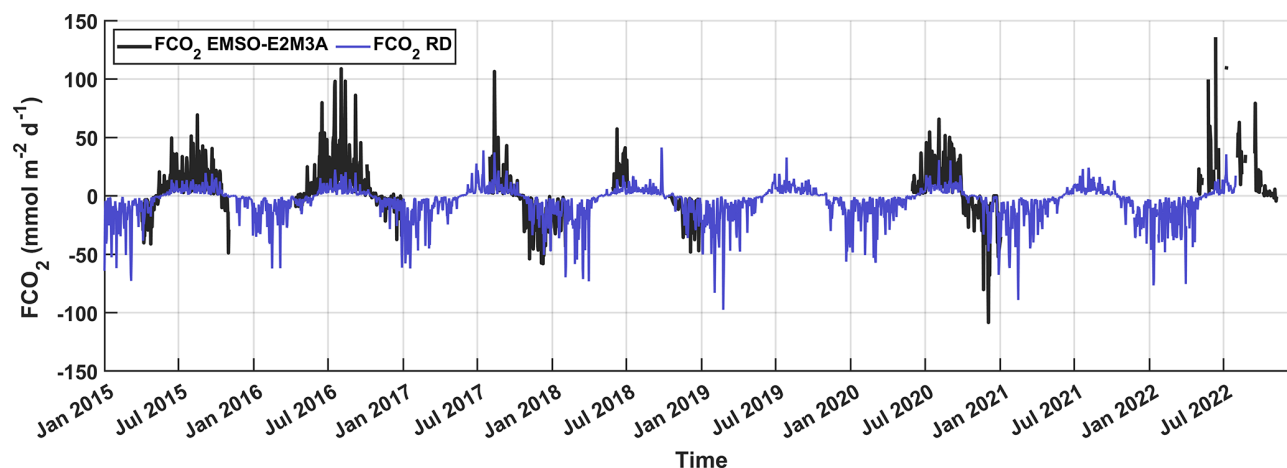


Figure 5. Time series of daily FCO_2 ($\text{mmol m}^{-2} \text{d}^{-1}$) calculated with in situ data measured at the EMSO-E2M3A and FCO_2 ($\text{mmol m}^{-2} \text{d}^{-1}$) from the Mediterranean Sea Biogeochemistry Reanalysis (RD) represented by the black and violet curves respectively. Model data after July 2022 were integrated with the interim reanalysis.

(Fig. 6). The strongest uptake is found in the central and deep part of the basin, where FCO_2 reaches values close to $-5 \text{ mmol m}^{-2} \text{d}^{-1}$ while weaker sink activity was shown particularly along the eastern part of the basin with values being between 0 and $-2 \text{ mmol m}^{-2} \text{d}^{-1}$ (Fig. 6). Nevertheless, despite the spatial differences in the magnitude of the annual CO₂ fluxes, the overall basin scale behaviour derived from the CMEMS reanalysis is consistent with the in situ observations. Although local fluxes vary across the basin, the EMSO-E2M3A can be considered a representative site for capturing the main carbon dynamics of the Southern Adriatic. Secondly, the use of the CMEMS RD product to compute the overall FCO_2 average filling the gaps of the in situ data was tested. A bias (B) using the CMEMS RD was calculated as the difference between the mean flux over the entire period

(2015–2024) and the mean flux considering only the days with observations being equal to $-3.7 \text{ mmol m}^{-2} \text{d}^{-1}$. B was then added to the mean flux calculated with in situ observations, resulting in a mean annual flux of $-4.5 \text{ mmol m}^{-2} \text{d}^{-1}$. Even if these estimates should be considered with caution, they further confirm that the Southern Adriatic acted as a moderate carbon sink over the last decade.

5 Conclusion

A time series of $p\text{CO}_{2\text{sw}}$ and hydrography from autonomous sensors over the past 10 years were analysed to estimate $p\text{CO}_{2\text{sw}}$ and carbon flux in the dense water formation site of the Southern Adriatic. The data were collected by several

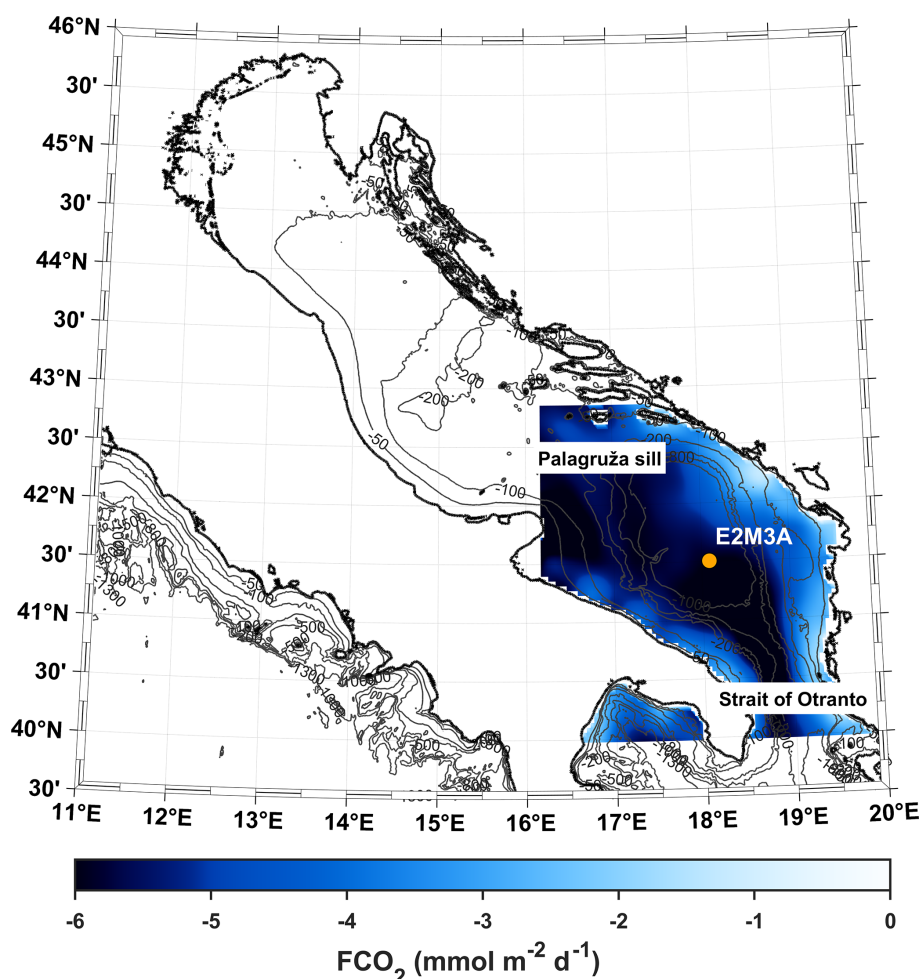


Figure 6. Spatial distribution of mean annual CO₂ flux (FCO_2 , $\text{mmol m}^{-2} \text{d}^{-1}$) in the Southern Adriatic from CMEMS RD data. Negative values indicate a net uptake of atmospheric CO₂. Strongest FCO_2 was observed in the central deep basin, while weaker FCO_2 occurred along the eastern margins of the basin. Bathymetric contours are also shown. The EMSO-E2M3A mooring site, located in the central Southern Adriatic Pit, is indicated by the orange marker. The Palagruža Sill and the Strait of Otranto are included as geographical limits of the study area.

sensors deployed at the EMSO-E2M3A South Adriatic regional facility and ICOS ERIC observatory which is located in the central and deepest part of the SAd, the SAP. Surface $p\text{CO}_{2\text{sw}}$ dynamics were characterized by strong seasonal fluctuations, with a difference of $100 \mu\text{atm}$ between winter and summer. In winter, average $p\text{CO}_{2\text{sw}}$ was $\sim 380 \mu\text{atm}$, with marked increase especially during wintertime convection periods when CO₂-rich intermediate and deep water were upwelled to the surface. In summer, average values increased up to around $500 \mu\text{atm}$ driven by higher sea surface temperatures. The effect of biological processes was difficult to identify due to lower availability of data during post-convection/bloom periods. CO₂ fluxes were characterized by two distinct regimes of post-convection/summer CO₂ released to the atmosphere (mean summer month/source flux of $+12.43 \text{ mmol m}^{-2} \text{d}^{-1}$) and convection/winter CO₂ ocean uptake (mean winter months/sink flux of

$-15.82 \text{ mmol m}^{-2} \text{d}^{-1}$). One of the key results of this study was to demonstrate that over the past decade the SAd acted as a moderate carbon sink with mean annual FCO_2 values of about $-0.97 \text{ mmol m}^{-2} \text{d}^{-1}$. To evaluate the robustness of the flux estimates, additional FCO_2 calculations were performed using different wind products, temporal aggregations of the wind data, and gas transfer velocity parameterisations. All configurations based on in situ wind observations consistently indicated a net annual CO₂ uptake, despite differences in the magnitude of the estimated fluxes. Among the tested methodological choices, the gas transfer velocity parameterisation exerted the largest influence on the annual flux estimate, whereas the temporal aggregation of the wind data had a comparatively smaller effect. Conversely, the use of ERA5 wind products highlighted the importance of accurately representing the local wind field, as using a spatially averaged wind field instead of the nearest grid point to EMSO-E2M3A

changed the annual CO₂ budget from a sink to a weak source. Thus, careful consideration must be given to the wind product selected as many oceanic areas lack in situ wind observations, model-derived wind products (e.g., ERA5, CCMP) are used instead (Nickford et al., 2024). By proving to be an important asset for model validation, the $p\text{CO}_{2\text{sw}}$ and hydrographic time series allowed to quantify existing specific discrepancies in the regional CMEMS model product such as a lack in winter $p\text{CO}_{2\text{sw}}$ increase, and over/under-estimation of the seasonal amplitude. Nevertheless, the integration of model and observational data further confirms that the SAd was a site of moderate atmospheric CO₂ sink in the last decade. The spatial distribution of modelled annual CO₂ flux indicated that, despite regional heterogeneity and areas of weaker uptake, the Southern Adriatic overall behaved as a CO₂ sink on annual basis. This also supports the relevance of the EMSO-E2M3A observatory as a representative site for investigating the main carbon flux dynamics in the central part of the region. The SAd, as many other regions in the Mediterranean Sea, is currently undergoing profound physical changes, including increasing sea surface temperature, rising salinity, and the potential intensification of extreme events (Iona et al., 2018). These trends are likely to affect convection intensity and timing, with potential consequences for carbon dynamics in the basin on a climatic scale. In this context, the long-term monitoring carried out in the region, by combining sustained in situ observations with modelling approaches, is necessary to fully understand the complex interplay between physical forcing, biogeochemical processes, and carbon dynamics in the context of climate change.

Data availability. The in situ data used in this study are freely accessible at the National Oceanographic Data Center (NODC) of the National Institute of Oceanography and Applied Geophysics (<https://doi.org/10.13120/y2hw-1j63>; Cardin et al., 2025a). Model data are also publicly available through the Copernicus Marine Service website following the links provided in the manuscript.

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