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Discussions

Dissolved oxygen as indicator of multiple drivers of the marine ecosystem: the Southern Adriatic Sea case study

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Abstract. Oxygen is essential for all aerobic organisms and its dynamics in the ocean involve interconnected physical and biological processes that are at the basis of the marine ecosystem functioning. Investigation of dissolved oxygen (DO) variations under multiple drivers is currently one of the main goals of climate and marine ecological scientific communities, as well as quantifying DO levels is essential for the assessment of the environmental status, especially in the coastal areas.

We investigate the 1999-2021 interannual variability of DO in the Southern Adriatic Sea, a marginal area of the Mediterranean Sea, hosting deep water formation processes that significantly contribute to the ventilation of the Eastern Mediterranean basin. Following the Marine Strategy Framework Directive that promotes the integration of different observation platforms, we use DO modelled by the latest Copernicus Marine biogeochemical reanalysis, that assimilates satellite chlorophyll and on which we apply a bias correction by using DO Argo float measurements in 2014-2020. A correlation analysis of the first three modes of variability (86% of explained variance) of the DO profiles extracted from the bias-corrected reanalysis with key meteo-marine indicators reveals a link ($r>0.4$) with net heat fluxes related to oxygen solubility, vertical mixing, biological production at surface and subsurface layers and circulation associated to the entrance of northern Adriatic waters as interrelated drivers. The alternate entrance of Levantine/Modified Atlantic Waters through the North Ionian Gyre (NIG) appears as the driver of the fourth mode of variability, that explains 8% of variance. Moreover, we find that the first temporal mode of variability is the main contributor of the 2021 negative anomaly of DO in the 0-600 m layer with respect to the 1999-2020 climatology. We ascribe the lower content of DO in 2021 to a negative anomaly of the subsurface production in the same year, in agreement with the previous correlation analysis, but not to heat fluxes. In fact, in agreement with previous studies, we observe the entrance of warmer and exceptionally saltier waters favored by the cyclonic circulation of NIG from 2019 onwards. We interpret it as a possible regime shift not captured by the time series analysis, whose possible consequences on Ionian-Adriatic system ventilation and on marine organisms should be carefully monitored in the near future.

1 Introduction

Dissolved oxygen (DO) is a key indicator to monitor the marine ecosystem functioning, since it is the result of several atmospheric, hydrodynamical and biogeochemical driving processes (i.e., air-sea fluxes, vertical convection and mixing, horizontal transport, biological production and consumption; Keeling and Garcia, 2002; Oschlies et al, 2018; Pitcher et al., 2021). Indeed, DO is currently investigated under the global warming scenarios by climate and marine ecological scientific communities (e.g. Kwiatkowski et al., 2020; Garcia-Soto et al., 2021), as oxygen depletion has been observed both at level of the global ocean and at local scale (Breitburg et al., 2018). Climate models predict a future reduction in global ocean dissolved oxygen content (Matear et al., 2000; Oschlies et al., 2008; Stramma et al., 2010, Reale et al., 2021), making this parameter of primary interest especially in those areas where oceanic processes connect surface with deep layers.

Despite being a marginal sea, the Southern Adriatic Sea (SAdr, Fig. 1a) has a crucial importance for the Eastern Mediterranean Sea ventilation, since it is an area of deep water formation (Gačić et al., 2002; Pirro et al., 2022). The Adriatic Sea (Fig. 1a) is an elongated semi enclosed and approximately north-to-south oriented basin characterized by a shallow northern shelf (depths lower than 80 m) and a deep pit in its southern part (maximum depth over 1200 m) which is connected to the Ionian Sea (central Mediterranean basin) through the Otranto Strait (with maximum depth of 800 m). The Adriatic Sea is characterized by a cyclonic circulation governed by several drivers: river runoff, wind stress, surface buoyancy fluxes and mass exchanges through the Otranto Strait (Cushman-Roisin et al., 2013). Being at the connection between Ionian and Adriatic Sea, the SAdr is strongly influenced by the seawater exchange with the Northern Adriatic Sea and by the inflow of Levantine/Modified Atlantic Waters under the alternate Northern Ionian Gyre circulation (Menna et al., 2019) and shows an intermittent pattern of surface phytoplankton blooms (Gačić et al., 2002; Civitarese et al., 2010).

While hydrodynamical and biogeochemical properties of SAdr have been widely described by several studies (e.g., Civitarese et al. 2010; Cushman-Roisin et al., 2013; Lipizer et al., 2014; Kokkini et al., 2018, 2019; Mihanović et al., 2021; Menna et al., 2022), at the best of our knowledge DO dynamics in the area and their connection with relevant driving processes over decadal time scales have not been addressed yet.

Investigating the DO multidecadal variability represents a crucial element to quantify the state of the marine environment (*sensu* MSFD; Oesterwind et al., 2016) and to understand anthropogenic impacts on marine environment. The emerging ecosystem-based management method proposed by the Marine Strategy Framework Directive (2008/56/EC) promotes the use of different observation platforms, allowing to synoptically collect information on the space-time distribution of major parameters related to water quality (Martellucci et al., 2021).

In this context, the present work integrates the state-of-the-art approach of in-situ measurements (i.e., Copernicus In Situ TAC data in 2014-2020) with the latest released Copernicus Mediterranean biogeochemical reanalysis at 1/24° horizontal resolution (Cossarini et al., 2021), with the aim of characterizing the DO dynamics in the SAdr in the 1999-2021 time period. In particular, we aim at assessing DO inter-annual variability in an area (SAdr) sensitive to multiple drivers (e.g. atmospheric forcing, Mediterranean circulation and biological processes) and to evaluate the relative importance of the different drivers in the area.

2 Data and methods

In the present study the DO concentration in the SAdr area (Fig. 1a) has been assessed by combining Copernicus Mediterranean reanalysis data (Prod1 in Table 1; Cossarini et al., 2021) in 1999-2021 and the Copernicus in situ dataset (Prod2, https://doi.org/10.13155/75807), available in the time period 2014-2020 (Fig. 1c).

In particular, we employed the BGC-Argo float measurements of in situ DO provided by the CMEMS In Situ TAC catalog to compute a bias correction to the daily DO concentration simulated by the Copernicus Marine biogeochemical Mediterranean reanalysis at 1/24° horizontal resolution. Quantile mapping, a technique largely used for climate simulations (e.g., Hopson and Webster, 2010; Themeßl et al., 2011; Gudmundsson et al., 2012), was adopted to perform the reanalysis bias correction. The quantile mapping technique adjusts the cumulative distribution of the data simulated for the past/future period by applying a transformation between the quantiles of the simulated and observed data at present. In our application, we considered the distribution of available in situ data of daily DO (Fig. 1c) within a representative area of the southern Adriatic in the period 2014-2020, and DO reanalysis data for the same days of measurements.

Then, we applied the estimated quantile transformation between the two data sets to the whole 1999-2021 reanalysis time series, by adapting the code publicly delivered by Beyer et al. (2020) at https://doi.org/10.17605/OSF.IO/8AXW9. The representative area is identified by applying a spatial autocorrelation analysis (Martellucci et al., 2021) on the biogeochemical reanalysis centered on the SAdr pit and selecting the correlation threshold of 0.9 (Fig. 1b). The temporal evolution of the combined model-in situ DO concentration profile in 1999-2021 time period used in the following analysis is reported in Fig. 1d.

We then applied the Empirical Orthogonal Function (EOF) analysis (e.g. Thomson and Emery, 2014) to the vertical profiles in Fig. 1d in order to describe the DO variability in the SAdr area in the period 1999-2021. The EOF analysis allows to identify the vertical patterns of variability (i.e., spatial modes), to describe how they change in time by means of time series (i.e., temporal modes), and to associate the explained variance to each pattern.

Finally, we conducted a correlation analysis between the EOF temporal modes in 1999-2021 and the following series of forcing indexes (reported in Fig. 2) providing evidence of the mechanisms driving the oxygen concentration and dynamics in the area:

- heat fluxes in SAdr as a proxy for thermal and mixing/stratification cycles (Fig. 2a);
- the mixed layer depth in the SAdr as a proxy for both local vertical mixing and water residence times in the pit (Fig. 2b);
- chlorophyll concentration at surface and at subsurface level in the SAdr as a proxy for biological production in spring and late spring-summer, respectively (Fig. 2c-d);

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- heat fluxes in Northern Adriatic Sea (NAdr), as a proxy for dense water oxygen-rich formation in NAdr and its transport into the pit (Fig. 2e);
- Northern Ionian Gyre (NIG) vorticity derived from satellite altimetry, as a proxy of the inflow of Levantine waters and Modified Atlantic Water (MAW) (Fig. 2f).

Mixed layer depth, chlorophyll at surface and subsurface level (30-80 m, hosting the deep chlorophyll maximum feature), were spatially averaged in the SADr area (41.6°-42.1°N; 17.6°-18.1°E); heat fluxes were calculated in both the SAdr area and in the NAdr area (44.5°-45.5°N; 13°-13.5°E), while current vorticity was computed in the Northern Ionian Sea (37°–39°N; 17°–19.5°E).

In the correlation analysis, the time series of the heat fluxes in NAdr Sea (Fig. 2e) has been temporally lagged by 2 months, as an estimated mean time for the entrance in the SAdr pit of waters originated in the Northern Adriatic area (Vilibić et al., 2013; Querin et al., 2016; Mihanović et al 2021). The current vorticity in the Northern Ionian area in Fig. 2f has been previously filtered by a low-pass filter of 13 months. The temporal phases of the NIG are defined as anticyclonic when the vorticity field is negative and cyclonic when the vorticity field is positive.

3 Results

3.1 EOF analysis

The EOF analysis was performed on the vertical profiles of the oxygen anomaly, derived by removing the mean profile in the period 1999-2021, and then normalized dividing by their standard deviation.

The temporal evolution of the first four EOF modes, which explain up to 95% of the oxygen variability in the water column, together with the corresponding spatial patterns, are reported in Fig. 3 (left and right columns, respectively).

3.2 Temporal scales of variability in connection with drivers

The interpretation of the EOFs is performed considering the correlation of the EOF temporal modes (first column of Fig. 3) with the time series of the forcing indicators reported in Fig. 2 (see Table 2), with heat fluxes in the Northern Adriatic Sea time-lagged by two months as estimated time of NAdr dense water to enter in the SAdr pit.

The first temporal mode (Fig. 3a), that accounts for almost the 50% explained variance, can be associated to the seasonal cycle of the oxygen concentration in the upper layers: it shows relative maximum values in spring, it influences mainly the first vertical levels (Fig. 3b) and it is significantly correlated (r=0.56) with the heat flux and the subsurface chlorophyll concentration (r=0.43) in the SAdr area (first column in Table 2).

The second and the third temporal modes (Fig. 3c-e), which describe approximately 20% of the variance each, influence both the upper and the deeper layers. Both modes display relative maximum values in summer, but they have different correlation coefficients with the explaining drivers. The second mode (second column in Table 2) shows significant but low correlation with multiple drivers, exceeding 0.4 only for surface chlorophyll (r=-0.41) and waters from NAdr area (r=0.48).

The third mode (third column, same Table) is strongly correlated with both surface chlorophyll (r=-0.61) and NAdr waters (r=0.68 correlation), but also with heat fluxes in the area (r=0.51), mixed layer depth (r=-0.41) and subsurface chlorophyll (r=0.48).

The fourth mode (Fig. 3g), despite displays less than 10% variance, can be mainly ascribed to the vorticity of the NIG (r=-0.44, last column in Table 2), which influences the oxygen concentration in the intermediate layer (100-500 m depth), filled by LIW, and acts in opposite direction in the upper and deeper layers (Fig. 3h).

While the first mode explains the variability (e.g. seasonal) connected with solubility, the biological contribution to oxygen dynamics is ascribed to multiple interacting modes. The first mode explains the onset of subsurface oxygen maximum (SOM) in spring, while the summer dynamics of SOM is partly related to the third mode. The second EOF, which is correlated to surface chlorophyll evolution among other factors, can explain that part of the oxygen variability that is linked to the winter surface productivity.

The SOM, recognisable in summer oxygen profiles in Figs. 1c-d at approximately 40 m depth, is a feature already observed in a great part of oligotrophic oceans (Riser and Johnson, 2008; Yasunaka et al., 2022) and of the Mediterranean Sea (e.g., Kress and Herut, 2001; Copin-Montégut and Bégovic, 2002; Manca et al., 2004; Cossarini et al., 2021; Di Biagio et al., 2022) and it constitutes an emerging property from several interacting ecosystem processes (i.e., air-sea interactions, transport, mixing and biological production/consumption) and is, indeed, captured by multiple EOFs.

The third mode, which also describes the high concentration values in the deep layers in the period 2005-2006 and 2012-2014, seems also strongly connected with a multi-annual signal of the inflow of deep denser and oxygenated water from the northern Adriatic Sea (r=0.68, third column in Table 2; Querin et al., 2016). Finally, it is worth to note that an EOF analysis done on the detrended DO time series (not shown) provides pretty similar results but with the third mode only weakly correlated with the forcing indexes (r<0.4). Indeed, we can conclude that the third mode captures a signal of long term evolution of oxygen concentration connected with changes in heat fluxes and chlorophyll concentration.

3.3 The 2021 anomaly

The 2021 shows an overall negative anomaly in the oxygen concentration profile (Fig. 4b) with respect to the 1999-2020 climatological profiles (Fig. 4a). In particular, the anomaly interests a layer that became thinner during the year, moving from 0-600 m depth in winter-early spring season, to 30-400 m in late spring-summer and 0-80 m in fall. Maximum (absolute) values correspond to 25-30 mmol m^{-3} at the surface in spring and at the SOM depth in summer.

We verified that, among the EOFs, the negative anomaly of the first EOF temporal mode is the main contributor for the 2021 negative oxygen anomaly (not shown). The first EOF temporal mode (Fig. 3a) is actually negative from 2019, and it is correlated with the anomaly of only one of its drivers (i.e., lower-than-average subsurface chlorophyll).

Additionally, the 2021 negative anomaly of oxygen profile seems also to be connected to the entrance of new water masses, warmer and noticeably saltier, from the Levantine basin, starting from the end of 2019 (Menna et al., 2022), for which the temperature reached 15-16°C at 100-800 m depth and salinity 39-39.1 psu at 100-200 m, 38.9-39.0 psu at 200-800 m in the

SAdr area (not shown). Indeed, the NIG, which shows a positive vorticity since 2019, transported saltier and warmer water toward the Adriatic Sea (Mihanović et al., 2021) than during the two previous positive periods (1999-2005 and 2010-2016).

4 Conclusions

The merging of the latest Copernicus biogeochemical reanalysis in Mediterranean Sea with in situ TAC data of biogeochemical Argo floats allowed to characterize the interannual variability of dissolved oxygen in the Southern Adriatic Sea in the 1999-2021 time period. This study enriches our knowledge about the dissolved oxygen state and long term dynamics in the area, by proposing a seamless time and space perspective that is complementary to previous climatologies and data aggregation information (e.g. Lipizer et al., 2014) and adding an explanatory framework on the driving mechanisms on the marine environment.

The EOF statistical analysis we conducted on the vertical oxygen profiles showed two main results. Firstly, in contrast with a climatological view, the analysis has been able to capture most of the inter-annual oxygen variability in connection with the variability of the main drivers (i.e., heat fluxes influencing solubility; biological productivity; vertical mixing). We do not recognise a clear deoxygenation trend in the subsurface layer, while the multiannual variability is characterized by a sort of cyclicity, whose dominant correlations with the drivers for each EOF temporal mode are found in the (absolute) range 0.40-0.70. The evidence of such cyclic signals is enhanced by the relatively small volume and short residence time of the SAdr pit waters (Querin et al., 2016) with respect to other Mediterranean areas (Coppola et al., 2018).

This feature makes the SAdr a potential efficient probe to detect a fast response to long term changes in circulation and atmospheric patterns. Indeed, as our second result, the variability not explained by the EOF decomposition appears to be connected with a possible regime shift, associated with the entrance of new water masses, warmer, markedly saltier and less oxygenated, not previously observed in the analyzed time period.

The exceptional increase in salinity occurring after 2019 has been already documented (Mihanović et al., 2021; Menna et al., 2022) and observed also north of the SAdr pit. Continuing the monitoring of such anomalously high salinity values and assessing their potential impact on the marine food web is of great importance, since picoplankton groups are sensitive to this environmental variable (Mella-Flores et al., 2011) and changes in biomass and production due to salinity have been already observed in previous studies in the Adriatic Sea (Beg Paklar et al., 2020; Mauri et al., 2021). Moreover, if such a strong negative oxygen anomaly observed in 2021 will persist, it could have direct consequences on local marine organisms, as well as on the cycling of dissolved chemical elements (Conley et al., 2009) potentially altering the energy flux towards the higher trophic levels (Ekau et al., 2010). Indeed, the importance between the dissolved oxygen and the catch distribution of some marine species has already been proved in the Adriatic Sea (Chiarini et al., 2022).

Our study, by integrating model and in situ data, demonstrates the importance of following up the oxygen content in a seamless spatial and temporal way, since it is a fundamental indicator of good environmental status (GES, Oesterwind et al., 2016) and a factor significantly affecting fishing activities and economy.

Data availability

Publicly available datasets were analyzed in this study. Modelling and in situ data can be found at the Copernicus Marine Service, with references and DOIs indicated in the Table 1 of the manuscript.

Author contribution

VDB and GC conceived the idea. VDB, RM and MM conducted the analysis. VDB, RM and GC wrote the first draft, with contributions from the other co-authors. All the authors discussed and reviewed the submitted manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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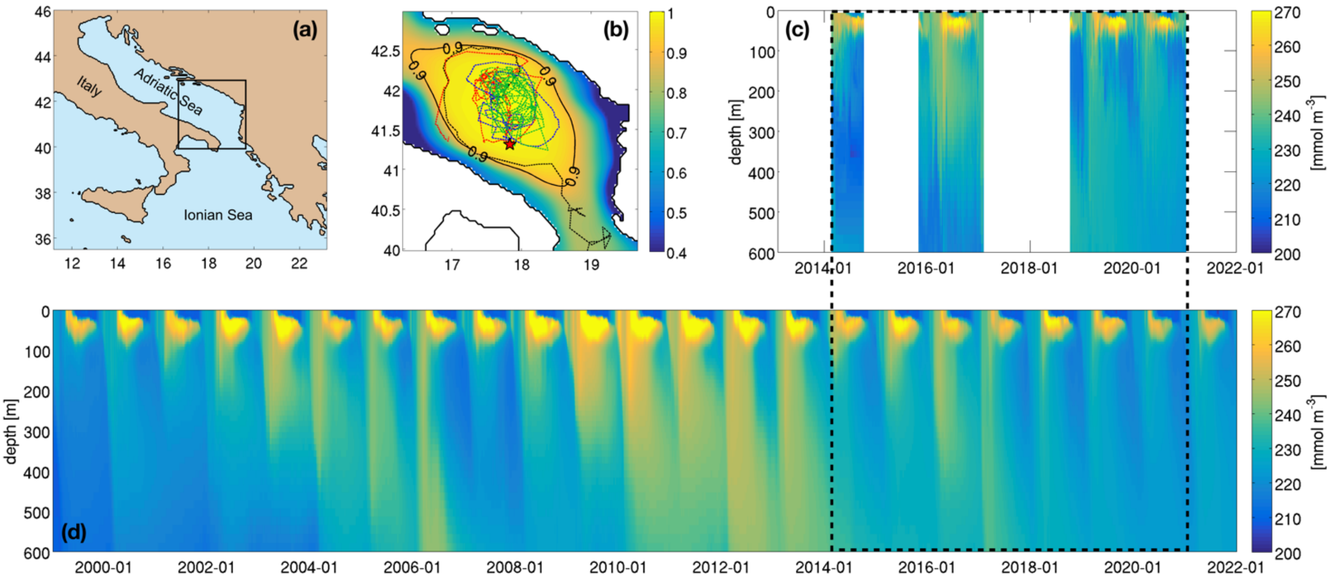
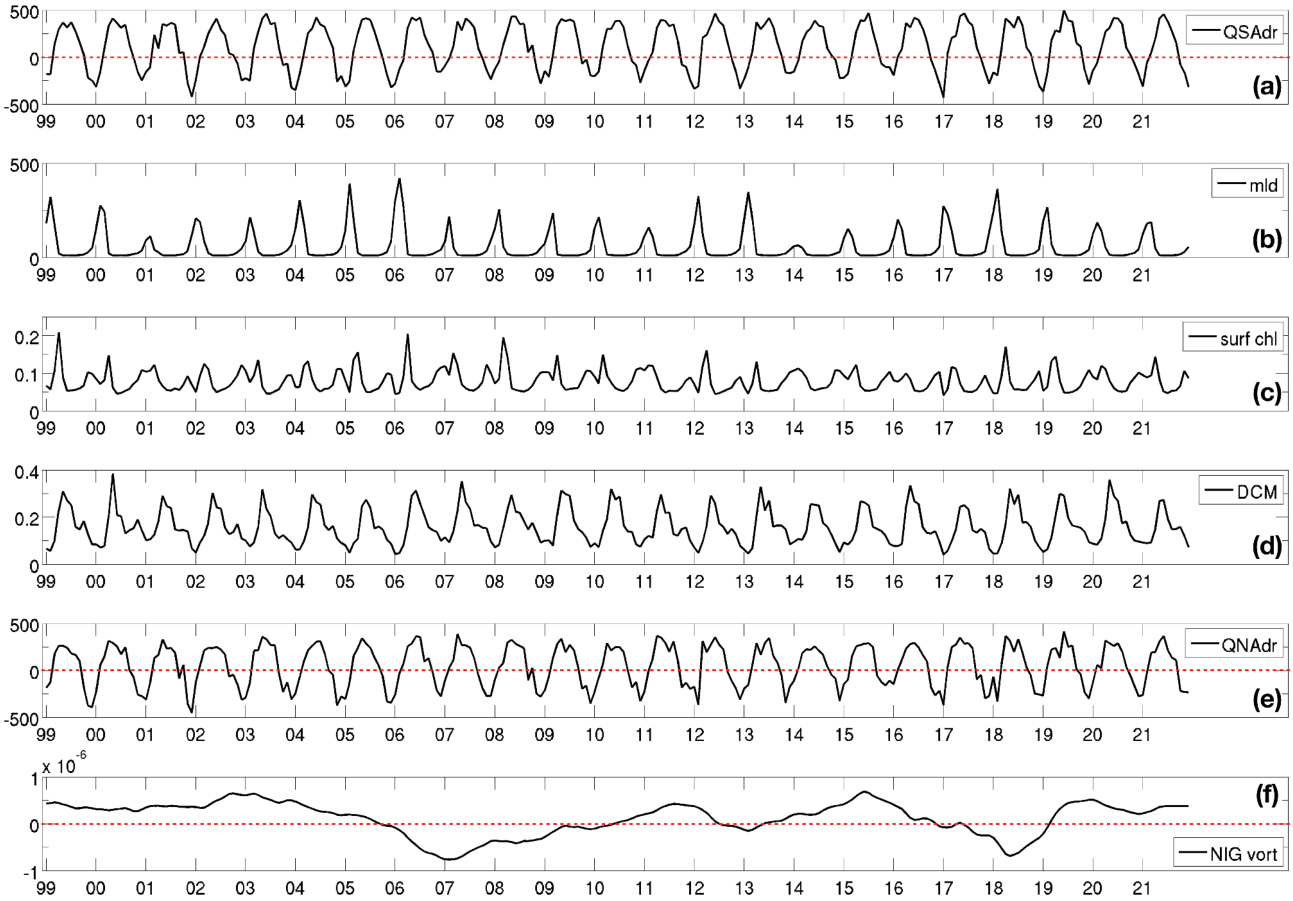


Figure 1: (a) Southern Adriatic area (black square) within Mediterranean Sea; (b) Autocorrelation map of surface oxygen, nitrate and chlorophyll concentration provided by Copernicus biogeochemical reanalysis (Prod1, Table 1) in the Southern Adriatic area with respect to the central point of the pit indicated by the red star; the black contour line delimits the area with autocorrelation equal or higher than 0.9; dashed lines indicate the trajectories of BGC-Argo floats (In Situ TAC data, Prod2) passing the area. (c) Hovmöeller diagrams of the dissolved oxygen concentration from In Situ TAC data (Prod2) within the area of autocorrelation equal to 0.9 (panel (b)). Data have been interpolated for sake of plot readability. (d) Hovmöeller diagrams of the dissolved oxygen concentration from Copernicus biogeochemical reanalysis (Prod1), spatially averaged in the area of autocorrelation equal to 0.9 (panel (a)) in 1999-2021 time period, after the bias correction procedure based on the In Situ TAC data (Prod2).



375 **Figure 2: Time series of the main forcing in the 1999-2021 time period: (a) net heat fluxes in SAdr (Prod6 in Table 1), in W m^{-2}, (b) mixed layer depth (Prod3), in m, (c) surface chlorophyll concentration (Prod1), in mg m^{-3}, (d) subsurface chlorophyll concentration (30-80 m layer hosting deep chlorophyll maximum, Prod1), in mg m^{-3}, (e) net heat fluxes in NAdr (Prod6), in W m^{-2}, (f) NIG vorticity (Prod4 and Prod5), in s^{-1}.**

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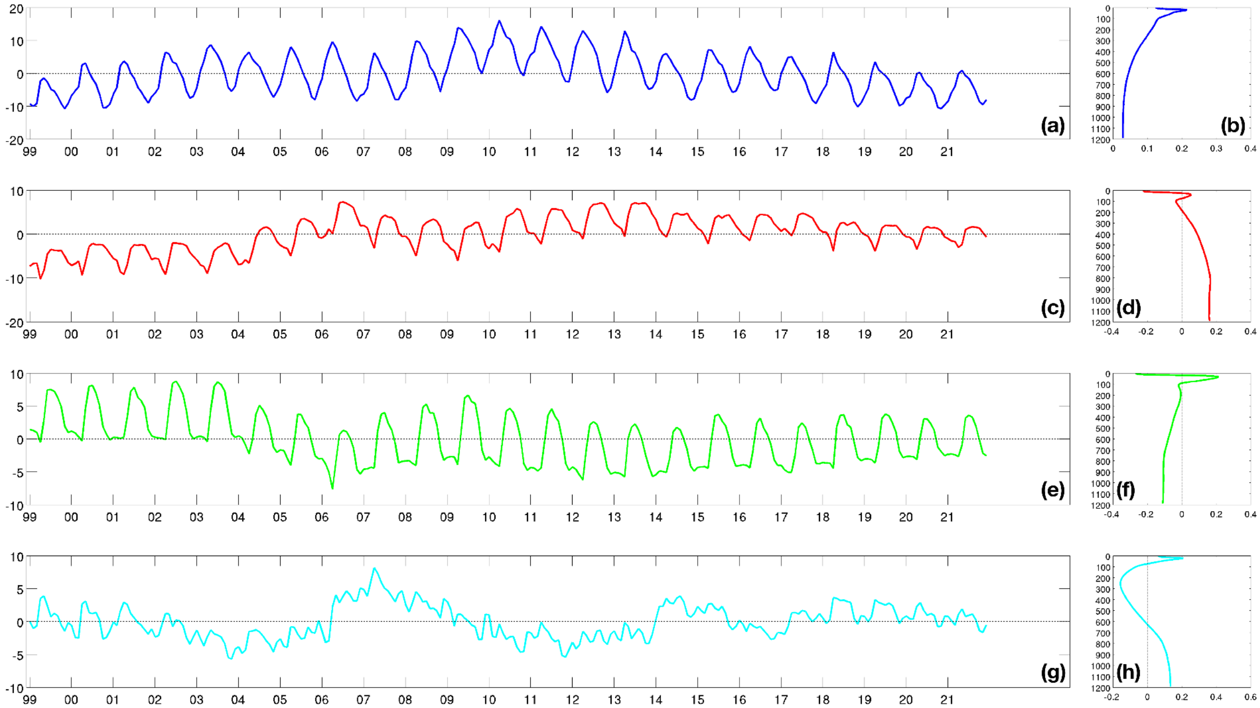

Figure 3: First four EOF temporal (a, c, e, g) and spatial (b, d, f, h) modes computed on the bias-corrected dissolved oxygen concentration in the Southern Adriatic area shown in Fig. 1d. The explained variances of the four modes are: 48.9%, 19.7%, 17.7%, 8.4%.

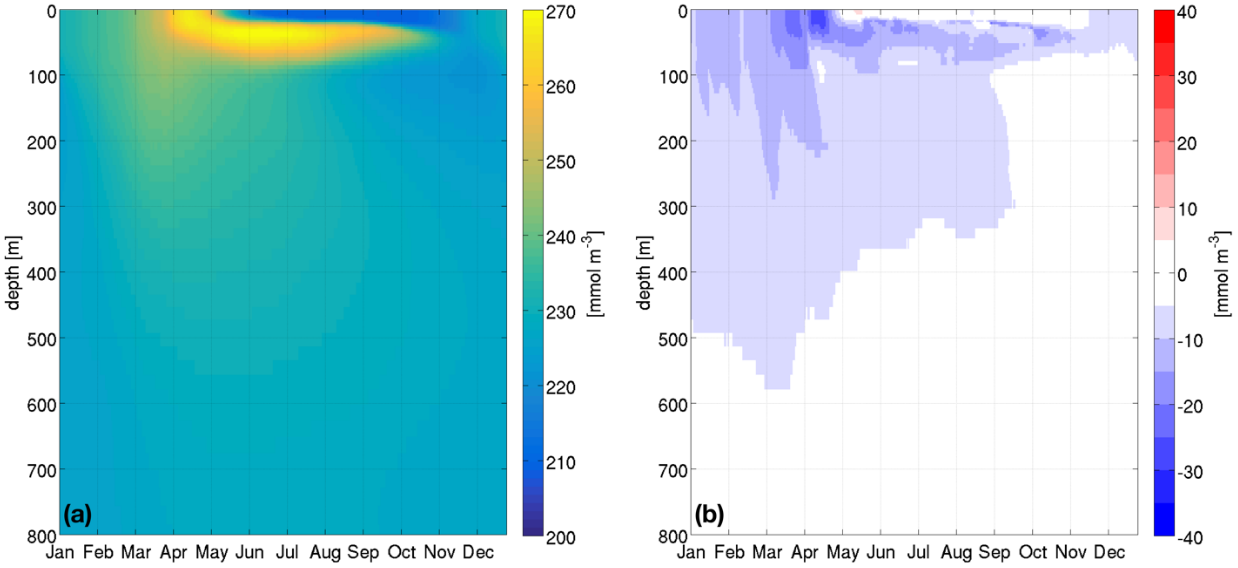

Figure 4: Hovmöeller diagrams of: climatological mean of daily oxygen concentration computed from Copernicus biogeochemical reanalysis (Prod1, Table 1) after the bias correction procedure based on the In Situ TAC data (Prod2) in 1999-2020 time period (a) and anomaly in 2021 with respect to the reference period (b).

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Product id	Dataset name	Type	Reference and dataset doi
Prod1	Copernicus Marine MEDSEA_MULTIYEAR_BGC_006_008	Mediterranean biogeochemical reanalysis	Cossarini et al., (2021) https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_BGC_006_008_MEDBFM3 https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_BGC_006_008_MEDBFM3I
Prod2	Copernicus Marine INSITU_MED_NRT_OBSERVATIONS_013_035	Mediterranean in situ measurements	Copernicus Marine in situ TAC (2021). Copernicus Marine In Situ TAC quality information document for Near Real Time In Situ products (QUID and SQO). https://doi.org/10.13155/75807
Prod3	Copernicus Marine MEDSEA_MULTIYEAR_PHY_006_004	Mediterranean physical reanalysis	Escudier et al., (2021) https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1 https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1I
Prod4	Copernicus Marine SEALEVEL_EUR_PHY_L4_MY_008_068	European sea level gridded data based on altimetric measurements	https://doi.org/10.48670/moi-00141
Prod5	Copernicus Marine SEALEVEL_EUR_PHY_L4_NRT_OBSERVATIONS_008_060	European sea level gridded data based on altimetric measurements	https://doi.org/10.48670/moi-00142
Prod6	Copernicus Climate ERA5	Global climate and weather reanalysis	Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D.,

			Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2018): ERA5 hourly data on single levels from 1959 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on 07-06-2022) https://doi.org/10.24381/cds.adbb2d47

Table 1: Datasets used in the present work, with reference and doi. Complete references for the articles in Prod 1 and Prod 3 are reported in the bibliography.

	mode 1	**mode 2**	**mode 3**	**mode 4**
HFlux (SAdr)	0.56	0.15	0.51	0.32
MLD (SAdr)	n.s.	-0.28	-0.41	-0.25
surf chl (SAdr)	n.s.	-0.41	-0.61	n.s.
subsurface chl (SAdr)	0.43	0.13	0.48	0.34
Hflux NAdr (2-months lagged)	n.s.	0.48	0.68	0.16
NIG vorticity (NIon)	n.s	-0.36	0.26	-0.44

Table 2: Correlations between the first four temporal modes of EOFs (first column in Fig. 3) and the forcing fields (Fig. 2, with heat fluxes in the Northern Adriatic Sea time-lagged by two months). Not significant correlations are identified by a significance level higher than 0.05 and indicated by "n.s." acronym in the table.