

1 **How extreme river discharge events shape coastal biogeochemical**
2 **dynamics: the 2024 northern Adriatic case**

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7 **Abstract.** In 2024, the northern Adriatic Sea experienced marked levels of eutrophication, as indicated by unusually high
8 surface chlorophyll concentrations observed by remote sensing and in-situ measurements. In addition, exceptionally high Po
9 river discharges, in the form of repeated and intense events, were recorded from March to June and in October.
10 We used Copernicus Marine Service satellite and model products for the Mediterranean Sea, together with a high-resolution
11 (500 m) Italian coastal model, to quantify chlorophyll anomalies in the area with respect to 1999–2022 climatology and
12 investigated the marine ecosystem functioning in connection with river discharges, phosphate input and sea surface
13 temperature as key drivers. We found that chlorophyll values exceeded 100% above climatological levels in early spring,
14 followed by sustained anomalies in summer and autumn. Primary production remained elevated from the early spring onward,
15 with a significant anomaly peaking in early summer, concurrent with renewed Po river discharges and rising sea surface
16 temperatures.
17 Our findings highlight the central importance of riverine freshwater and nutrient inputs in controlling the northern Adriatic
18 ecosystem, in combination with circulation and thermal variability. Moreover, this study shows how forecasting systems play
19 a pivotal role in monitoring eutrophication and potential biomass accumulation in the context of episodic river extremes and
20 increasing climate variability, with high-resolution coastal modeling providing additional valuable insights into spatial patterns
21 and localized eutrophication dynamics.

Product ref. no.	Product ID & type	Data access	Documentation
1	MEDSEA_ANALYSISFORECAST_BGC_006_014, Numerical models	EU Copernicus Marine Service Product (2024a)	Quality Information Document (QUID): Feudale et al. (2024) Product User Manual (PUM): Lecci et al. (2024a)

2	MEDSEA_MULTIYEAR_BGC_006_008, Numerical models	EU Copernicus Marine Service Product (2022)	QUID: Teruzzi et al. (2022) PUM: Lecci et al. (2022)
3	OCEANCOLOUR_MED_BGC_L3_NRT_009_141, Satellite observations	EU Copernicus Marine Service Product (2025a)	QUID: Colella et al. (2025a) PUM: Colella et al. (2024a)
4	OCEANCOLOUR_MED_BGC_L3_MY_009_143, Satellite observations	EU Copernicus Marine Service Product (2025b)	QUID: Colella et al. (2025b) PUM: Colella et al. (2024b)
5	MEDSEA_ANALYSISFORECAST_PHY_006_013, Numerical models	EU Copernicus Marine Service Product (2024b)	QUID: Gualtieri et al. (2024) PUM: Lecci et al. (2024b)
6	MEDSEA_MULTIYEAR_PHY_006_004, Numerical models	EU Copernicus Marine Service Product (2024c)	QUID: Escudier et al. (2024) PUM: Lecci et al. (2024c)
7	Po river discharge at Pontelagoscuro station, Observations	Regional Agency for prevention, environment and energy - Arpae Emilia Romagna SIMC (2025)	https://simc.arpae.it/dext3r
8	EFAS v5.0 river discharges, Numerical models	EU Copernicus Emergency Management Service (2025)	Joint Research Center, Copernicus Emergency Management Service (2019); Mazzetti et al. (2023)
9	National physical-biogeochemical coastal operational system (MER), Numerical models	OGS (2025)	Bruschi et al. (2021)

23 **Table 1: Table of the Products used in the present study.**

24 **1 Introduction: Po river discharges and coastal blooms in northern Adriatic Sea in 2024**

25 A Region of Freshwater Influence (ROFI) is a coastal area where riverine freshwater inputs drive stratification cycles,
26 circulation structures and biogeochemical processes such as nutrient and carbon cycles. Typical features of these areas are
27 marked salinity and nutrient gradients, buoyant plumes associated with higher productivity, and variability in the water column
28 structure from seasonal to interannual scale (Simpson, J.H., 1997; Horner-Devine et al., 2015).

29 The northern Adriatic Sea (hereafter: NAS), the shallowest marginal region in the Mediterranean Sea (with mean depth of 35
30 m), is a ROFI area mainly under the influence of Po river (e.g., Raicich, 1996; Giani et al., 2012; Lipizer et al. 2014). The Po
31 river, with a catchment area of 74000 km², has a mean discharge of 1500 m³ s⁻¹ (i.e., the third highest values among the rivers
32 flowing into the Mediterranean Sea) and shows a negative trend in discharge values, due both to climate change and to the
33 increased use of river dams for irrigation and other purposes (e.g. Marini and Grilli 2023), in addition to high annual and

34 seasonal variability (e.g., Montanari et al., 2023). Other rivers further contribute to the freshwater inputs into the NAS to a
35 lesser extent (e.g., Adige, Brenta, Piave and Isonzo have mean discharges in the 100-300 m³ s⁻¹ range; Ludwig et al., 2009;
36 Cozzi and Giani, 2011; Verri et al., 2018). These freshwater inputs influence the cyclonic circulation which characterises the
37 upper layer of the NAS, fueling the southward coastal current along the western coast (Western Adriatic Current, WAC, e.g.,
38 Raicich et al., 1996). On the eastern side of the area, a weaker and saltier Eastern Adriatic Current (EAC) flows northward
39 along the eastern coast (e.g., Poulain 2001).

40 The NAS is also subject to strong ecological impacts of human activities (e.g., agriculture, fishery, aquaculture) and between
41 the 1970s and the mid-1980s it experienced a marked increase in eutrophication, which culminated in the occurrence of
42 episodic hypoxia (e.g. Djacovac et al., 2015). In the following years, the NAS has undergone an oligotrophication phase (e.g.
43 Mozetič et al, 2010; Ricci et al., 2024), ascribed both to the decreased river discharges and to a reduced anthropogenic pressure,
44 associated with decreased phosphorus loads, mainly due a specific regulation on the production of detergents (Italian
45 Ministerial Decree n. 413 of 13 September 1988; e.g., Cozzi and Giani 2011; Marini and Grilli, 2023).

46 Given its proven sensitivity to climate and anthropogenic pressures, the NAS represents a key area for long-term environmental
47 monitoring in the Mediterranean Sea. In this context, phytoplankton chlorophyll can be used as a valuable proxy for marine
48 eutrophication (Descriptor 5 of the Marine Strategy Framework Directive, Ferreira et al., 2011; European Commission, 2020),
49 reflecting variations in key drivers (e.g., nutrient availability, water column stability, and anthropogenic input) and undesirable
50 changes in environmental conditions (e.g., oxygen depletion and excessive biomass accumulation). A continuous monitoring
51 of both chlorophyll and Po river discharges (e.g., Mozetič et al., 2010, Vona et al., 2025), is therefore essential to assess the
52 ecosystem health and to detect early signs of renewed occurrence of eutrophication or ecosystem regime shifts.

53

54 In this perspective, 2024 was an unusually wet year in the Po basin, especially in the first half of the year (Figs. 1 and A1, in
55 the Appendix). Observations at Pontelagoscuro station (i.e., 44° 53' 10''N, 11° 36' 16''E) indicate that the Po river experienced
56 consistently above-average discharges from March through July and again in October (<https://www.arpa.veneto.it/temi-ambientali/idrologia/file-e-allegati/bollettini-risorsa-idrica/2024>). In particular, the hydrological status in March - May period
57 was classified as “severe wetness” by the Italian Po River Basin Authority, on the basis of the Standardized Flow Index,
58 estimated within the range +1.5 and +2 (in comparison with historical 1991-2020 data, https://www.adbpo.it/wp-content/uploads/2024/06/Situazione_Idrologica_dettagliata_agg06062024-2.pdf) and on 21–22 October a red hydraulic alert
60 was issued in eastern Emilia Romagna region (i.e., the coastal land of the Po river basin), as the river level surpassed level 3
61 (~2.5 m), prompting local flood warnings (https://allertameteo.regione.emilia-romagna.it/singola-allerta/-/asset_publisher/FZPQSB6AzKtJ/Allerta-Bollettino/id/2838139).

64 With respect to the reference period considered in this paper, i.e., 1999-2022, the annual Po river discharge was approximately
65 50% higher. As shown in Figure 1, four weekly peaks above 4000 m³ s⁻¹ (two in spring and two in the early summer)
66 characterized the first half of 2024, and one above 5500 m³ s⁻¹ was detected in the autumn period (Fig. 1b). Similar values of
67 weekly discharges in the spring-early summer occurred only 6 times in the last 25 years (i.e., in 2002, 2004, 2009, 2010, 2013,

2014, Fig. 1a), but only as single events during one year. Discharges larger than the 2024 value in autumn occurred only 4 times (i.e., 2000, 2002, 2014, 2019, same Figure), and only in two cases accompanied by one event of high discharges in the spring-early summer period (i.e., 2002 and 2014). Consequently, 2024 can be considered a very anomalous year concerning Po river discharges in terms of absolute values, number of events and timing during the year.

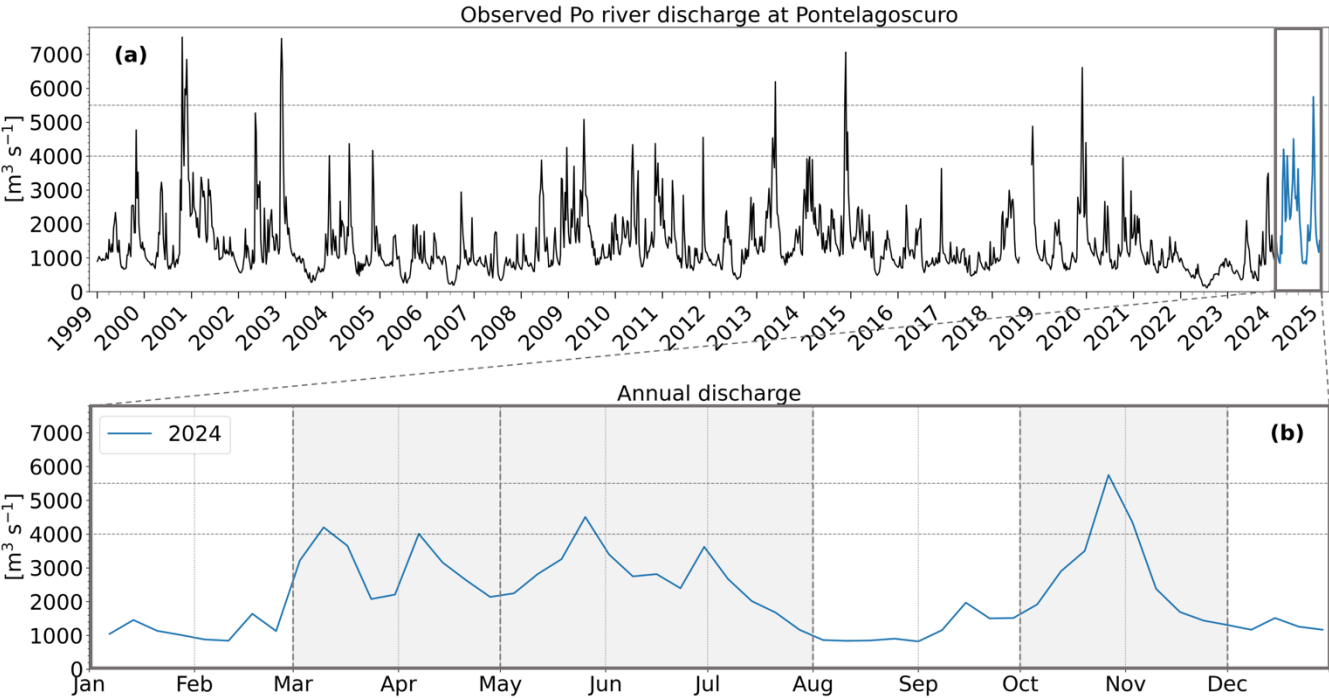


Figure 1: Po river discharge at Pontelagoscuro station (Product 7), weekly averaged: in 1999-2024 (a) and zoomed in 2024 (b). In both panels, horizontal dotted lines indicate reference values for maximum weekly discharges in 2024 spring-early summer (i.e., 4000 $\text{m}^3 \text{s}^{-1}$) and autumn period (i.e., 5500 $\text{m}^3 \text{s}^{-1}$). In panel (b), shaded areas between vertical gray dotted lines identify time periods of high discharges in 2024 (i.e., Mar-Apr, May-Jul, Oct-Nov).

At the same time, higher-than-usual chlorophyll values in the NAS were observed by remote sensing measurements (e.g., Figure S11.4 in the report by Copernicus Climate Change Service (2025)). Moreover, coastal in situ data collected in the area showed much higher than usual values of chlorophyll (i.e., higher than 10 mgChl m^{-3}) in 15 April-23 May period and, at even higher level, in 24 October - 19 November period), highlighting the anomalous characteristics of the events (<https://www.arpae.it/it/temi-ambientali/mare/report-e-bollettini/bollettini-mare>). ~~It is worth adding that, between June and August months, also massive~~ **The summer of 2024 was also marked by other anomalous phenomena: extensive** mucilage events were ~~observed~~ **reported** along the western and eastern coasts of the NAS (e.g., Vilibić et al., 2025). ~~This phenomenon~~ **Such** ~~events have~~ **events** become rare and unusual after ~~since~~ **the 1980s** eutrophication period ~~of the 1980s, and~~ **of the 1980s, and** ~~Even if a direct,~~

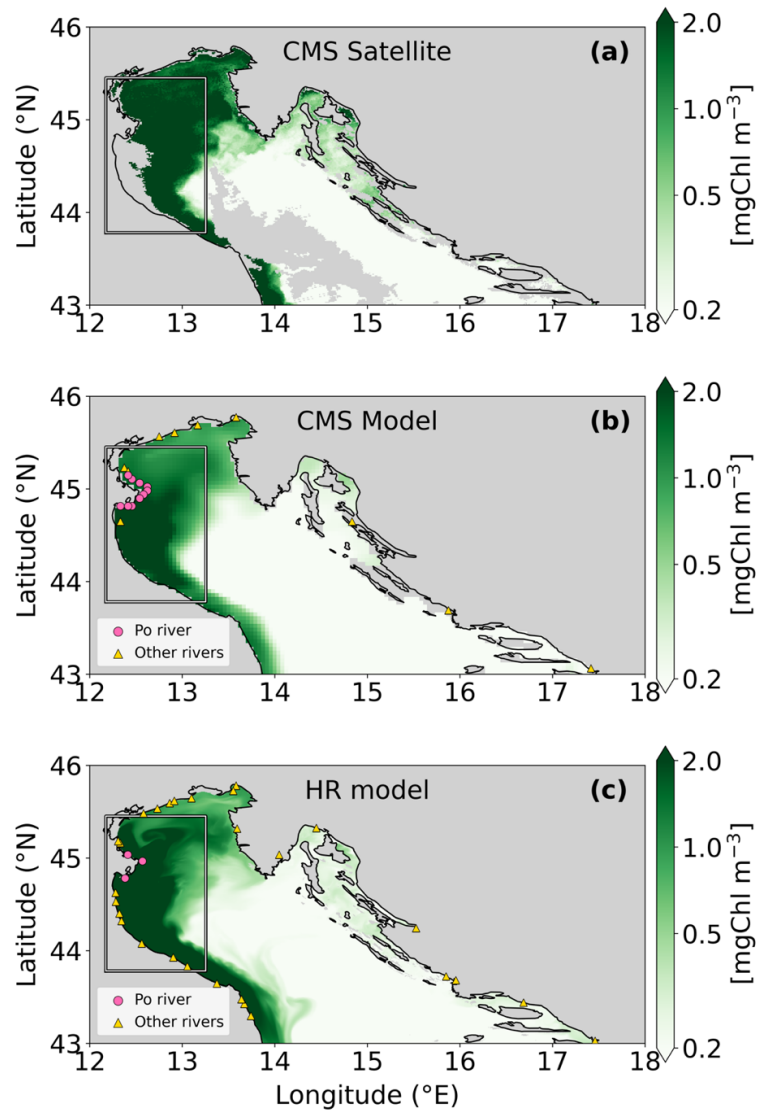
87 ~~unequivocal connection with only link between mucilage formation and~~ exceptional Po-spring discharges of the Po river can
88 not be ~~straightforwardly~~ established.; This is because mucilage ~~development~~ formations results from multiple concurring
89 ~~processes, including the massive release of~~ polysaccharide excretions by phytoplankton, ~~under during extended~~ prolonged
90 calm and sunny ~~weather~~ conditions, in ~~waters characterised by strongly vertical stratified~~ ~~edation~~ waters (Precali et al., 2005),
91 sometimes ~~after~~ following intense phytoplankton blooms (e.g., Cozzi et al., 2004). Nonetheless, its occurrence in 2024 may
92 represent another indication of the NAS system's anomalous behaviour during that year.

93 In this study we used Copernicus Marine Service (CMS) Mediterranean satellite and modeling products, plus other external
94 products (please see the Table 1), to: (i) quantify the anomaly of the 2024 coastal chlorophyll in the NAS ROFI area ~~with~~
95 ~~respect a reference period (1999-2022) encompassing the Ocean Colour era~~; (ii) investigate the relationships of the events of
96 high positive anomalies of chlorophyll with the Po river discharge and other drivers (e.g., sea surface temperature). Moreover,
97 we used a high resolution (500 m) Italian operational system to better characterize the eutrophication spatial patterns. Figure
98 2 shows an example of 2024 daily surface chlorophyll in the NAS ROFI area under the Po influence (boxes in the figure),
99 according to the CMS satellite (a), CMS model (b) and Italian HR model (c).

100

101 Section 1.1 illustrates in detail all the products used, their main features and internal dependencies (Subsect. 1.1.1), as well as
102 the data analysis methods we adopted (Subsect. 1.1.2). The section Results shows our evaluation of 2024 chlorophyll anomaly
103 with respect to the reference period for both satellite and model CMS products (Sect. 2.1) and then our analysis of the
104 ecosystem functioning during the 2024 year (Sect 2.2). Discussion and conclusions Section includes our general interpretation
105 of the events and their possible impacts on marine ecosystem also in the perspective of future climate change.

106



107

108 **Figure 2: Surface coastal chlorophyll in the northern Adriatic Sea, according to Copernicus Marine Service Med OCTAC L3 NRT**
 109 **satellite chlorophyll (panel a, Product 3), Copernicus Marine Service Med-MFC NRT model (b, Product 1) and the National high-**
 110 **resolution coastal operational system (c, Product 9), on 4th November 2024 as an example. The box contour identifies the Po ROFI**
 111 **region as the study area. Implemented positions of river discharge input in models are indicated by pink circles in the case of the Po**
 112 **river and by yellow triangles for the others.**

113 1.1 Data and Methods

114 1.1.1 Products used and dependencies

115 To analyse the anomalous events in the NAS ROFI area in 2024, compared with previous years, we used the state-of-the-art
 116 models and data available at the highest temporal and spatial resolution, both for the physics and for the biogeochemistry.

117 CMS Med-MFC Analysis and Forecast and Reanalysis daily products (1/24° of horizontal resolution) were used for the physics
 118 (Products 5 and 6, respectively) and for the biogeochemistry (Products 1 and 2). Modelled chlorophyll concentrations in
 119 Products 1 and 2 account for weekly data assimilation of CMS OCTAC L3 satellite chlorophyll, both in near-real time and as
 120 consistent reprocessed time series (Products 3 and 4, respectively), and such satellite data are also included in this study, in
 121 comparison with modelled data.
 122 Moreover, Analysis and Forecast physical and biogeochemical products (i.e., Products 5 and 1) currently implement daily
 123 river discharges from Copernicus Emergency Management Service (CEMS) EFAS v5 system (Product 8), providing for the
 124 first time a long-term, high frequency forcing for the freshwater input and the nutrient loads of NAS marine environment. We
 125 thus used Po river discharges from EFAS v5 to characterise the riverine input in 2024 in this study. Within the EFAS system
 126 framework, modelled data for the Po river are calibrated on observational data at Pontelagoscuro station (Product 7), and
 127 modelled and observational time series in 2024 actually show very similar statistics and temporal dynamics, despite some
 128 differences (i.e., an EFAS underestimation of river discharges in March and April and after the October peak and an
 129 overestimation of the values in September, Fig. A1 in Appendix).
 130 Finally, to provide an even higher resolution description of the spatial patterns associated with coastal dynamics, we used a
 131 novel Italian operational marine prediction system (at 500 m horizontal resolution, hereafter: HR model; Product 9), which is
 132 an evolution of that one presented in Bruschi et al., 2021. The new system employs CMS Med-MFC products as boundary
 133 conditions, assimilates weekly chlorophyll coming from the same CMS OCTAC satellite and implements daily river discharges
 134 from EFAS v5.
 135 It should be specified that both CMS and HR biogeochemical products feature the Biogeochemical Flux Model (BFM) to
 136 simulate the chlorophyll concentration, as the sum of the chlorophyll component of four phytoplankton functional types (i.e.,
 137 diatoms, nanophytoplankton, picophytoplankton, and dinoflagellates). Chlorophyll concentrations and phytoplankton
 138 functional types are extensively validated in CMS Med-MFC products (Cossarini et al., 2021; Teruzzi et al., 20022; Coppini
 139 et al., 2023; Feudale et al., 2024) and the same configuration is used in the HR model system.

140 **1.1.2 Methods for data analysis**

141 To avoid potential temporal mismatches given by the weekly frequency on Tuesday of OCTAC data assimilation by the CMS
 142 near-real-time model, the analysis of both satellite and modelled chlorophyll was carried out with weekly frequency. We also
 143 maintained the weekly basis in the reconstruction of their climatological reference (i.e., long-term average), i.e., 1999-2022
 144 time period, and in the 2024 time series of their possible drivers (i.e., river discharge, sea surface temperature, nutrient
 145 concentration) and impacts (i.e., net primary production).
 146 On the other hand, a monthly timescale is used to assess differences between the climatology and 2024 conditions for river
 147 discharges and ecosystem variables other than chlorophyll. This choice reflects the fact that the physical and biogeochemical
 148 reanalyses (i.e., Products 6 and 2, respectively) were driven by monthly climatological datasets for river discharges and nutrient

149 inputs. To mitigate potential systematic biases introduced by the use of climatological forcing in reanalyses, a bias correction
150 was applied based on the overlapping period (2023–2024) between reanalyses and corresponding NRT datasets (not shown).
151 To quantify the anomaly of 2024 chlorophyll with respect to the 1999-2022 climatology: (i) we identified the time periods in
152 which 2024 weekly chlorophyll values were above the climatology; (ii) we quantified the anomaly in each period as the weekly
153 mean difference between 2024 values and the climatological ones. In particular, we expressed the anomaly as a percentage,
154 computed as the difference between the cumulative 2024 values and the climatological values, normalized by the
155 corresponding climatological values:

156
$$\text{anomaly [\%]} = 100 \times [(\text{cumulative_2024} - \text{cumulative_clim}) / \text{cumulative_clim}].$$

157 2 Results

158 2.1 Anomaly of the 2024 events

159 Fig. 3 shows the weekly time series of CMS Med OCTAC L3 satellite chlorophyll (Fig. 3a) and Med-MFC model surface
160 chlorophyll (Fig. 3b) as values spatially averaged in the NAS ROFI area (box in Fig. 2) in 1999-2022, as the reference period
161 for the climatology, and the corresponding weekly time series in 2024 compared with the weekly climatology (Fig. 3c,d).
162 We identified Mar-Apr, May-Jul, and Oct-Nov months as prolonged time periods of chlorophyll values above the climatology
163 both for the satellite and for the model.

164
165 Despite biases in the absolute values of the chlorophyll time series from the model compared to satellite observations, which
166 is discussed in Sect. 3, the model is consistent with observations in predicting the periods of the highest river discharges (Fig.
167 1b) in correspondence with the highest chlorophyll anomalies (Figs. 3c,d, respectively). In fact, we estimated that the highest
168 chlorophyll anomaly in 2024, computed as the mean difference with the 1999-2022 climatology within each period, was in
169 early spring (i.e., Mar-Apr months), when the anomaly is equal or higher than 100% both for OCTAC satellite and for model
170 (Table 2). In late spring-early summer (i.e., May-Jul) and in autumn (i.e., Oct-Nov) the anomaly values were progressively
171 lower, and approximately equal to 100% for OCTAC satellite and 70% for modelled chlorophyll in the first case and 80% and
172 45%, respectively, in the second case.

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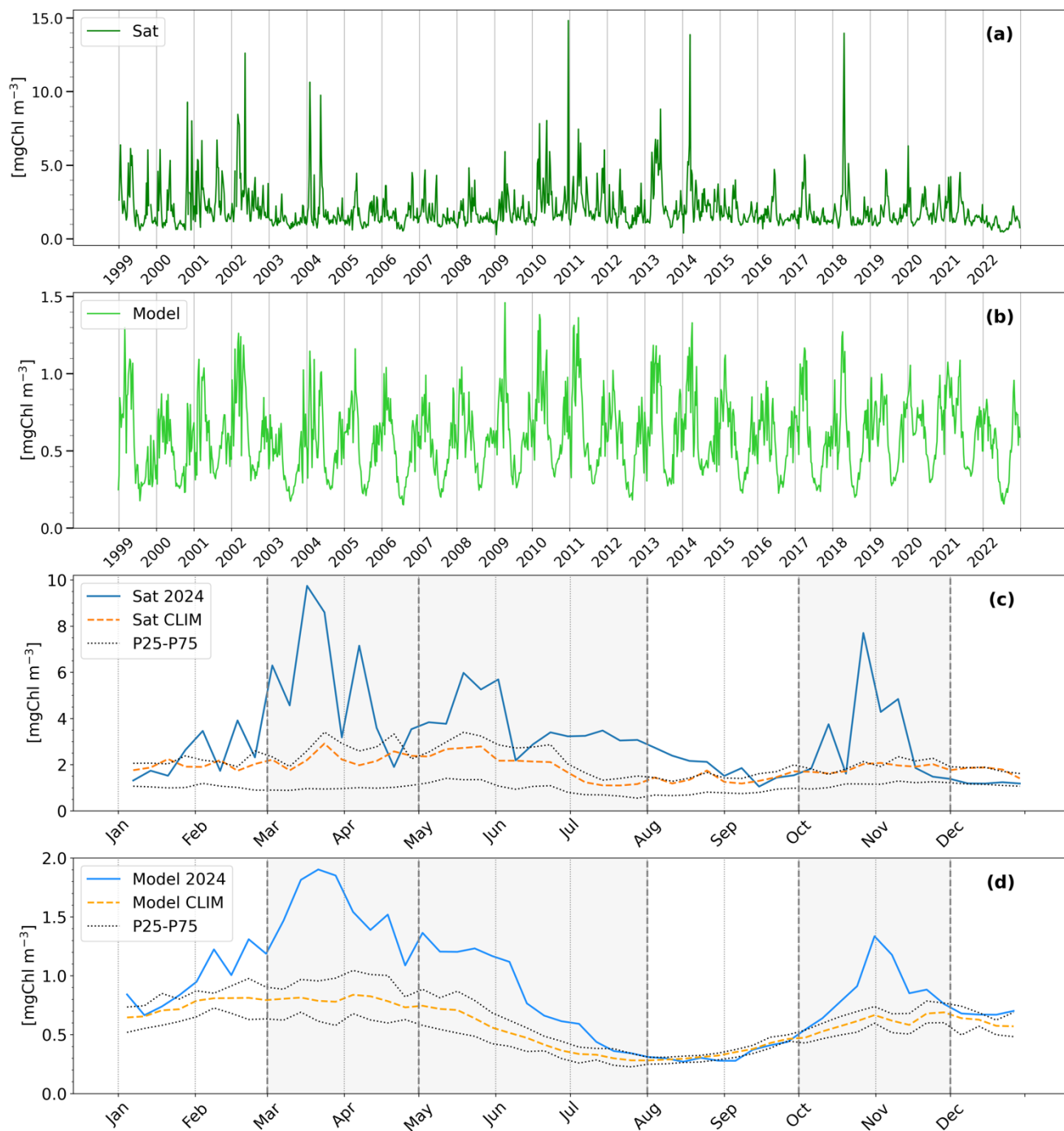


Figure 3: Weekly time series as spatial averages in the NAS box (defined in Fig.2) for: Copernicus Marine Service Med OCTAC L3 satellite chlorophyll (Product 4) and Med-MFC model chlorophyll at surface (Product 2) in 1999-2022 (panels a and b, respectively), and in 2024 (Products 3 and 1, panels c,d). Dotted lines in panels c,d indicate the 1999-2022 weekly mean as the reference climatology (orange line), plus weekly 25th and 75th percentile (black lines). Time periods of interest (i.e., Mar-Apr, May-Jul, Oct-Nov) are also indicated as shaded areas between vertical gray dotted lines.

181

2024 anomaly (%)	Mar-Apr	May-Jul	Oct-Nov
OCTAC L3 sat chl	142	107	80
Med-MFC model chl	97	68	44

182

183 **Table 2: 2024 anomaly of chlorophyll from CMS Med OCTAC satellite (Product 3) and Med-MFC model (Product 1), as estimates**
184 **of percentage increase with respect to the 1999-2022 climatology, in early spring, late spring-early summer and autumn.**

185

186 **2.2 Analysis on ecosystem functioning during 2024 events**

187 Figure 4 shows the time series of selected forcings that potentially contributed to the 2024 anomalously high chlorophyll
188 events, i.e., Po river discharges according to the EFAS v5 system (a), and CMS modelled sea surface temperature (b) and
189 surface phosphate (c) spatially averaged in the NAS ROFI area (box in Fig. 2). **Additional information on the ecosystem status**
190 **(i.e., vertical stratification of the water column, nitrate concentration, zooplankton grazing and water turbidity) is reported in**
191 **Fig. A3, in the Appendix.**

192 As mentioned in Sect. 1.1.1, EFAS v5 river discharges (Fig. 4a) show higher-than-climatology values in the periods selected
193 as the months with high chlorophyll values (i.e., Mar-Apr, May-Jul, Oct-Nov). The discharges in the first two and the last
194 months of 2024 appear instead quite in line with climatological values.

195 A January-February positive anomaly ~~with respect to the climatology characterises both~~ in the sea surface temperature (Fig.
196 4b), **connected with low values of mixed layer depth, occurred earlier than usual (Fig. A3a in the Appendix), and the surface**
197 **phosphate (Fig. 4c), which might represents a preconditioning factor of stratification and nutrient enrichment in the area.**
198 **During the same period, an enrichment in phosphate (the limiting nutrient in the area) was observed (Fig. 4c), whereas nitrate**
199 **remained closer to climatological values (Fig. A3b) (e.g. Vilibić et al., 2025 register also higher than usual salinity values). In**
200 **the early spring, the additional supply of phosphate (Fig. 4c) and the increasing temperatures (i.e., temperature in the range**
201 **11°C - 16°C, i.e., 2 °C - 3°C above the climatology; Fig. 4b), likely further enhanced by concurrent surface turbidity (Fig. A3d**
202 **in the Appendix), promoted the large huge increase in chlorophyll shown depicted in Figs. 3c,d.**

203 The further nutrient input associated with the Po river discharges in May and June drove instead a lower increase in chlorophyll
204 both in model and satellite data. We attribute it to ~~potential~~ **enhanced** grazing pressure **(as reported in Fig. A3c, in the**
205 **Appendix)** or lower carbon-to-chlorophyll ratio due to photoacclimation (since the photosynthetically active radiation is
206 maximum in June - July period, **e.g., Lazzari et al., 2021, not shown**).

207 Residual phosphate remained above the climatology in August, and it increased again after the occurrence of higher discharges
208 in September and, above all, the maximum flow in October, when the autumn peak of chlorophyll is observed (Figs. 3c,d).
209 Since the marine ecosystem becomes light-limited in autumn, we identify this feature as the main responsible for the relatively
210 low values of chlorophyll in its autumn peak with respect to the very high values of nutrient concentration in the same period.

211 The phosphate not used is then transported out of the NAS box along the coast (Figs. A2b,d in Appendix) and the marine
212 ecosystem progressively converges toward the baseline climatological winter conditions.
213
214 In 2024, the surface net primary production, as an indicator for eutrophication impacts on the marine ecosystem, is always
215 above the monthly climatology (Fig. 5a), especially in early summer, in association with the repeated Po river discharges and
216 the high temperatures. The monthly mean maps for 2024 show that the increase was initially localised southward of the Po
217 river mouths (indicated in Fig. 2b) in March (Figs. 5b,g), and subsequently expanded to a broader area, intensifying further
218 during April and May months (Figs. 5c-d, h-i). We ascribe the decreasing values in June to the southward transport along the
219 coast (Figs. 5e,j). Finally, the effect of the late June-July Po river discharges, along with the high temperatures (2°C - 3°C above
220 the climatology), is a further increase of net primary production near the Po river mouths.
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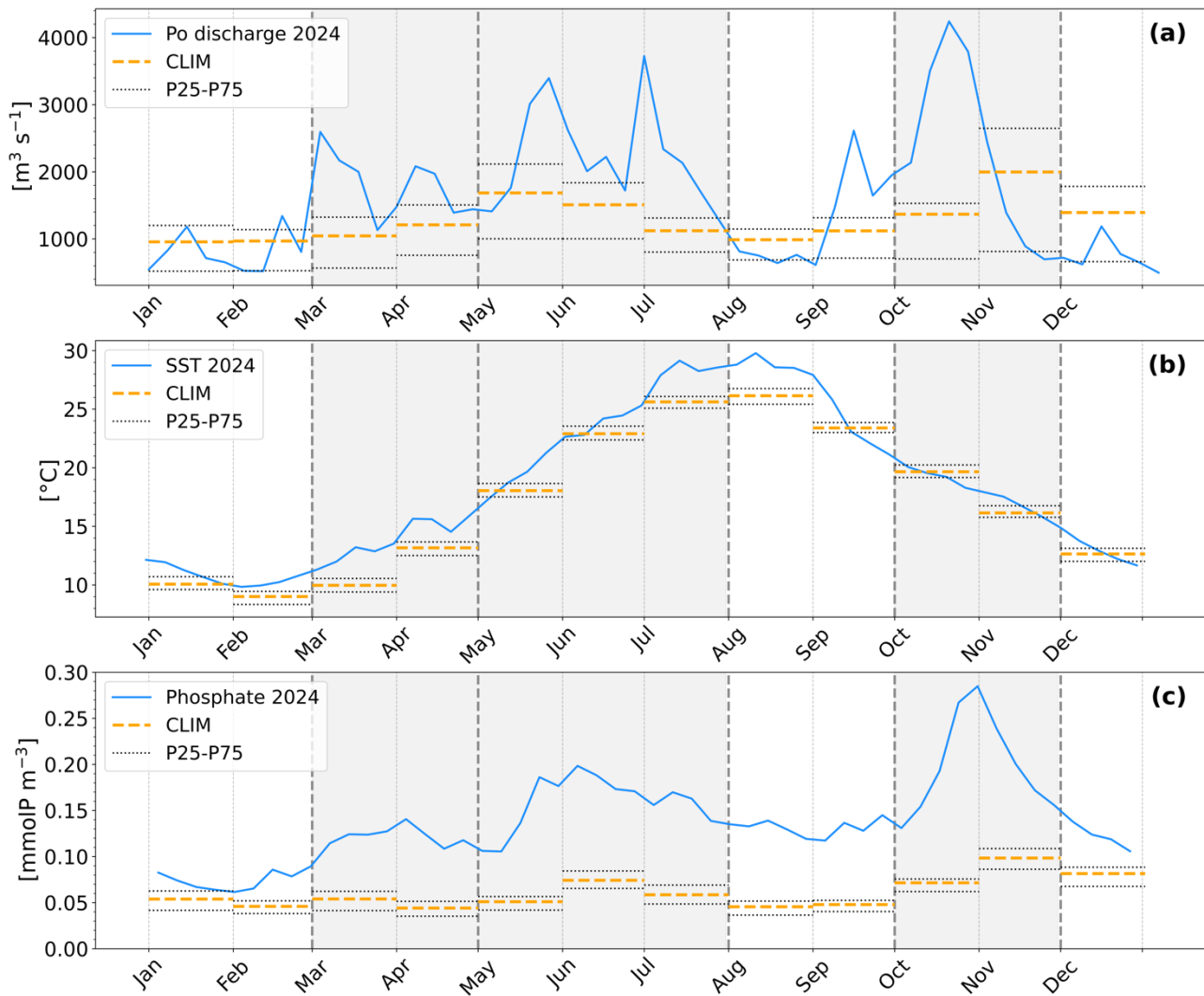


Figure 4: 2024 weekly time series (blue lines) and 1999-2022 climatology (dotted lines, orange for monthly mean, black for 25th and 75th percentile) of modelled variables: (a) Po river discharges at Pontelagoscuro (Product 8), and (b) sea surface temperature (Products 5 and 6, respectively) and (c) surface phosphate concentration (Products 1 and 2), spatially averaged in NAS box (Fig. 2). Phosphate climatology included the bias-correction illustrated in Sect. 1.1.2. Time periods of interest (Mar-Apr, May-Jul, Oct-Nov) are indicated as shaded areas between vertical gray dotted lines.

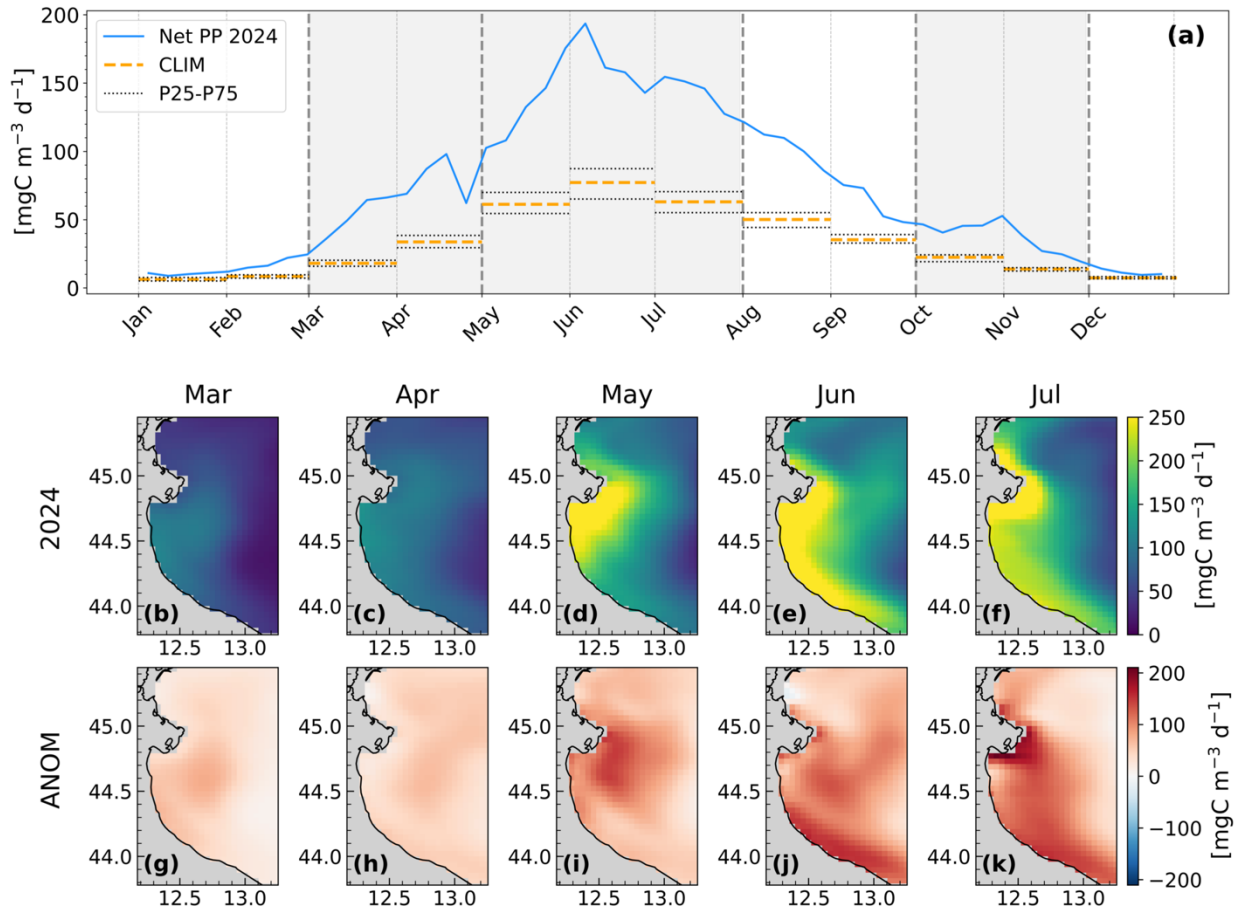


Figure 5: CMS modelled surface net primary production in the NAS box (Fig. 2) as: (a) spatially averaged weekly time series in 2024 (blue line, Product 1) compared with 1999-2022 monthly bias-corrected climatology (Product 2) (orange dotted line for the mean, black for 25th and 75th percentile); (b) monthly mean maps between March and July (b-f panels) and corresponding monthly anomalies according to the 1999-2022 bias-corrected climatology (Product 2) (g-k panels).

The analysis carried out so far highlighted that both chlorophyll patterns displayed by CMS satellite and model system (Fig. 2a,b), as well as modelled net primary production maps and anomalies (Fig. 5b-k) in the NAS area display strong coastal-offshore gradients and fronts, down to mesoscale (i.e., $O(10 \text{ km})$ in the NAS area).

To better quantify the spatial variability of coastal processes and Po river plume we benefitted from the novel HR model system developed for Italian seas like the Adriatic Sea, with horizontal resolution of 500 m (Product 9), and used the chlorophyll maps within the box in Fig. 2b,c as a representative example of simulated patterns. The Po river plume extension toward the Istrian coast actually appears simulated more in detail by the HR model (Fig. 2c), as well as the coastal belt of high chlorophyll along the WAC. Indeed, the HR simulation captures horizontal variability at approximately twice the spatial detail of CMS, as quantified by the squared coefficient of variation and the characteristic correlation length scale (Table 3).

Model	SCV	Lcorr
CMS	1.200.46	4624 km
HR	0.461.20	2416 km

Table 3: Statistics of spatial variability (SCV) and spatial scale (Lcorr) of the chlorophyll patterns of the two models CMS and HR (Fig. 1b,c, respectively). SCV is the squared coefficient of variation (i.e., the ratio between the spatial variance and the spatial squared mean), and LCorr is the correlation length of the patterns.

3 Discussion and Conclusions

The present study investigated the anomalously high values of surface phytoplankton chlorophyll observed in the NAS in 2024, as a possible indicator of eutrophication state, benefitting from state-of-the-art modeling and observational CMS products on the Mediterranean Sea and a novel HR coastal model system (Fig. 2), with a particular focus on Po river discharges as the main driver of these anomalies (Fig. 1 and Fig. 4a).

~~On the long-term timescale, Despite positive correlations between a negative trend in of the Po river outflow and a negative chlorophyll trend have been reported are established in the literature studies (e.g., Vona et al., 2025). On the other hand, our study aims to quantify at quantifying the connection between anomalous chlorophyll events and anomalies in of Po river discharge and, as well as other environmental drivers, on a the high-frequency timescale (e.g., weekly) of relevant to phytoplankton processes. In this perspective, the newly added feature of daily river discharges from CEMS EFASv5 model system implemented in the latest releases of CMS Med-MFC products constitutes an essential requirement to simulate coastal dynamics at high temporal frequency. It is worthy to specify that we based our analysis on the weekly scale, to avoid possibly flawed interpretations of the results due to the weekly assimilation of satellite chlorophyll. Another potential source of uncertainties in our estimations is related to the use of modelled Po river discharges instead of observations, but sIn fact, the simulated EFAS discharge time series of discharges at the Pontelagoscuro station displays a good generaloverall agreement with the observed seriesone in terms of both magnitude and timing of discharge peaks (Fig. A1), despite an underestimation of the mean annual flow (mean discharge is approximately 10% lower than observed) and of early spring peaks (EFAS values are about 25% lower than observed).~~

Within our modeling framework, we estimated and quantified 2024 anomalies in surface chlorophyll in early spring, early summer and autumn months, with decreasing values across the three periods (i.e., from 100% to 45% chlorophyll anomaly), coherently with anomalies estimated from satellite. However, these latter ones show higher percentages (from 140% to 80%). While our CMS model is very consistent with satellite in terms of temporal evolution (Fig. 3), the biases in terms of absolute values are due to limitation in the assimilation procedure of very high value of chlorophyll (i.e., values higher than 3 standard

275 deviations from climatological values are not assimilated, Teruzzi et al., 2021) and by potential limitation of the BFM model,
 276 whose 4 phytoplankton groups which have been optimized to simulate trophic open sea conditions across the Mediterranean
 277 Sea (Salon et al., 2019), to reproduce very high values of specific phytoplankton groups which can occur only in coastal areas
 278 near the major rivers. On the other hand, potentially satellite observations exhibit high uncertainties according to values of the
 279 quality index which are higher than 3 in large areas in the daily maps of the events (not shown).
 280
 281 We actually interpreted the anomalies in chlorophyll values in light of the anomalies in Po discharge (Fig. 4a) values, and to
 282 the associated nutrient loads, represented by the concentrations of CMS modelled phosphate as the limiting nutrient in the
 283 Mediterranean Sea and in the NAS (Fig. 4c). Moreover, the high levels of phosphate with respect to climatology (Fig. 4c), as
 284 well as and the high temperatures (with respect to the climatology, Fig. 4b) and an earlier-than usual and strong vertical
 285 stratification (Fig. A3 in the Appendix), already present in January and February 2024, further enhanced the spring peaks of
 286 chlorophyll. On the other hand, lower levels of light naturally present in autumn prevented high chlorophyll peaks, despite
 287 huge amounts of phosphate supplied by the Po river flood at the end of October, whose residual amount was transported
 288 southward from the coastal Western Adriatic current (WAC).
 289 We propose the use of net primary production as an indicator to assess potential disfunctioning of the coastal marine ecosystem
 290 in terms of accumulation of organic matter. Even if a detailed analysis is out of the scope of the present publication due to
 291 length constraints, the particulate organic matter produced during intense positive anomalies of net primary
 292 production with respect to the climatology, especially in early summer (Fig. 5a), is either transported along shore and/or settles
 293 on the sea bed and or undergoes remineralization, is consumed, potentially causing This process leads to oxygen depletion in
 294 the subsequent times-period. The model reproduces a northward evolution of the spatial extent of the impacted area (Fig. A4,
 295 in the Appendix), although simulated oxygen concentrations remain above the hypoxia levels observed during the 1980s and
 296 1990s as already observed in previous periods (e.g., Djacovac et al., 2015). Additionally, potential impacts on the marine
 297 ecosystem extend beyond organic matter accumulation and associated oxygen consumption (e.g., effects on higher trophic
 298 levels and fisheries) should also be carefully assessed in future studies.
 299 Despite Although the CMS model has not been designed to simulate all the processes and substances associated with the
 300 formation and accumulation of mucilage aggregates (that were observed in summer 2024 in the NAS during summer 2024),
 301 our findings about the on marine ecosystem functioning are in agreement with Vilibić et al., 2025, who They highlighted, in
 302 particular, the importance of the intense vertical stratification that started in February 2024 (also shown in Fig. A3, in the
 303 Appendix) as an important potential preconditioning factor for strong vertical stratification (as one of the main drivers of
 304 mucilage events), further enhanced by the high and repeated Po river discharges and elevated high temperatures (2°C-3°C
 305 above the climatology, according to our estimations).
 306 In the perspective of climate change, we indeed could expect a decrease in the Mediterranean river discharges in the late spring
 307 and early summer, due to a decrease in snowfall driven by increasing temperatures (as already observed, e.g., by Bozzoli et
 308 al., 2024), and an enhanced dependence on precipitations, especially on the short-term heavy ones (as also noticed by Cavallini

et al., 2024). Po river might thus exhibit a different hydrological regime in the future, oscillating between extremely dry conditions (possibly further exacerbated by the increasing water withdrawals for irrigation, Montanari et al., 2023) and episodic extreme precipitation events (Zittis et al., 2021, Tojčić et al., 2024) with anomalous impacts in the coastal dynamics as described in the present paper and that might represent a threat for the marine coastal organisms resilience (Hassoun et al., 2025).

In presence of rapidly changing meteo-hydrological conditions (e.g. huge Po river discharge in October 2024), coastal forecasting systems able to provide near-real-time and reliable information on eutrophication-related ecosystem variables can be powerful resources for early warning alerts dedicated to the coastal environmental management and socioeconomic stakeholders (e.g. aquaculture farmers) and tools for assessing impact on ecosystem functioning. In particular, high spatial characterization of offshore-coastal gradients and frontal structures is a fundamental aspect to set-up prevention and containment measures. The novel Italian operational model, which can be considered that represents a natural extension of the operational CMS Med-MFC system products, featuring with EFAS v5 river discharges as boundary conditions, actually proved has demonstrated the ability to reproduce finer more accurately the spatial structures associated with the Po river plume and has the potential to provide a more accurate representation of the coastal dynamics related to extension of the eutrophication pattern.

Appendix

The appendix includes selected additional figures supporting the discussion of the model results. In particular: the comparison between EFAS and observations for Po river discharges (Fig. A1), 2024 anomalies with respect to the long-term mean for other key environmental variables (Figs. A2 and A3) and the time evolution of oxygen depletion at 30m depth in the area during the summer period (Fig. A4).

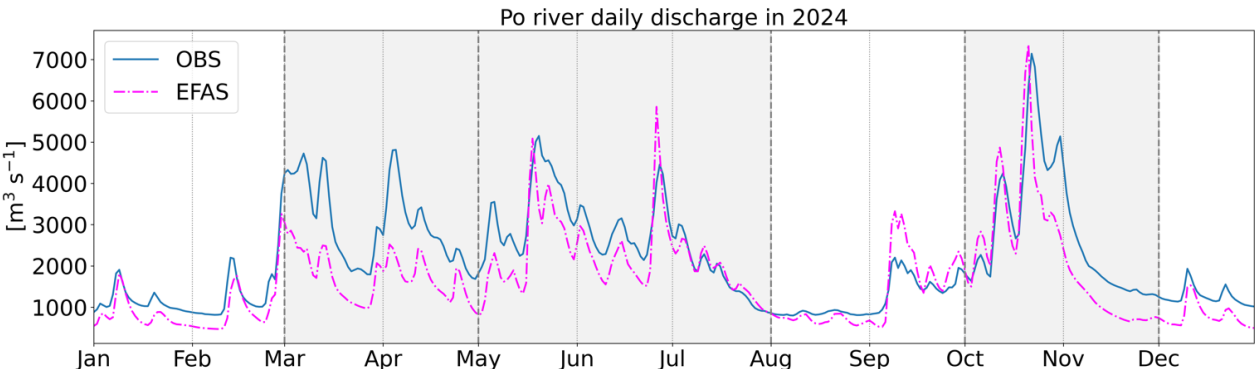
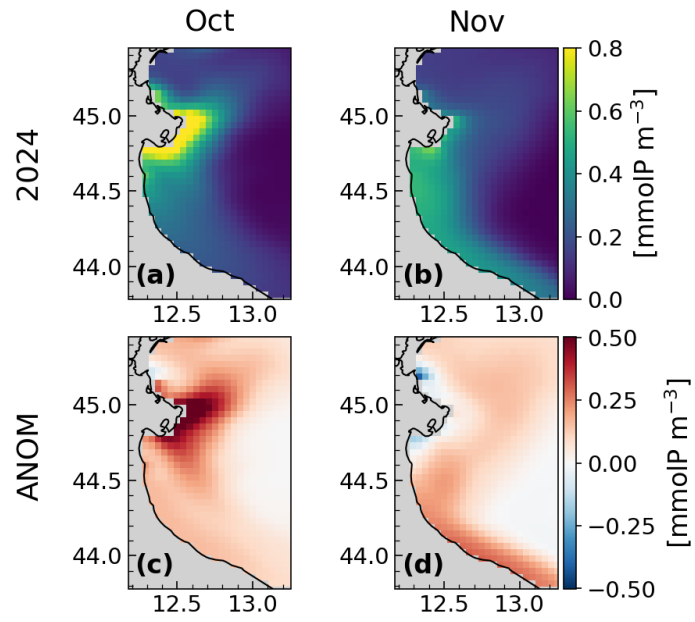


Figure A1: Daily time series of Po river discharge in Pontelagoscuro station in 2024, according to observations (blue line, Product 7) and to Copernicus Emergency Management Systems (CEMS) EFAS v5 data (magenta dotted line, Product 8).



333
 334 **Figure A2: Monthly maps of CMS modelled surface phosphate concentration (Product 1) in 2024 in October (a) and November (b)**
 335 **and corresponding anomalies with respect to the 1999-2022 bias-corrected climatology (Product 2) (c and d, respectively).**

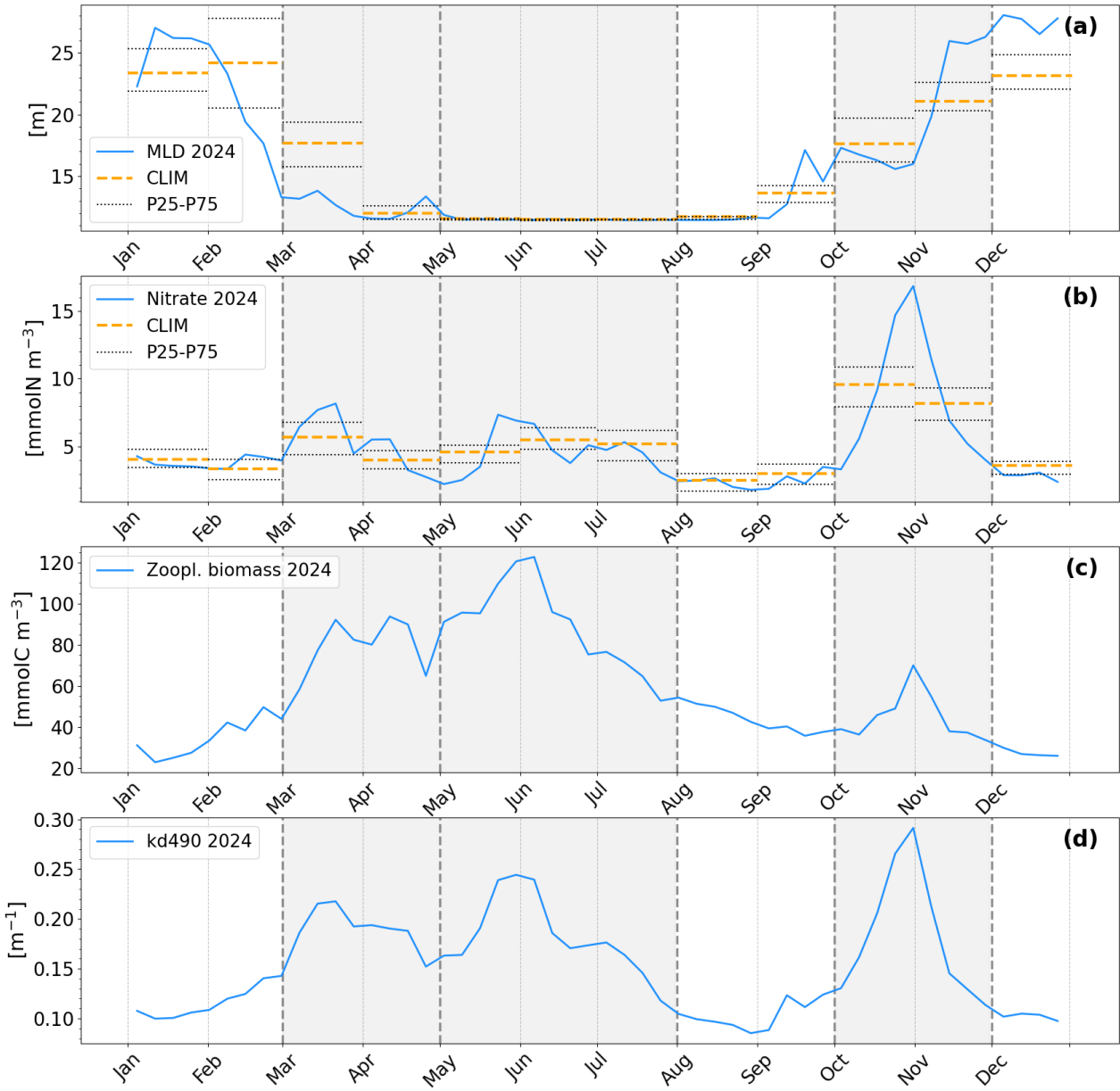


Figure A3: 2024 weekly time series (blue lines) and 1999-2022 climatology (dotted lines, orange for monthly mean, black for 25th and 75th percentile) of modelled variables: (a) mixed layer depth (Products 5 and 6, respectively), (b) nitrate concentration at surface (Products 1 and 2, respectively), (c) zooplankton carbon biomass at surface (Product 1), and diffuse attenuation coefficient of the downwelling irradiance at 490 nm (Product 1), spatially averaged in NAS box (Fig. 2). Nitrate climatology included the bias-correction illustrated in Sect. 1.1.2. Time periods of interest (Mar-Apr, May-Jul, Oct-Nov) are indicated as shaded areas between vertical gray dotted lines.

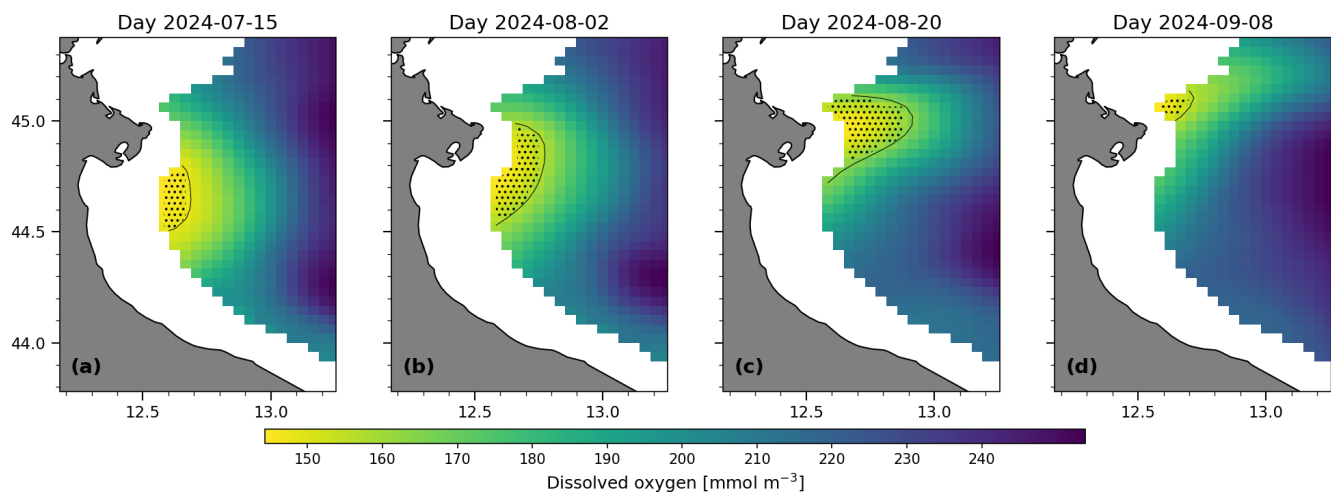


Figure A4: Selected daily maps of dissolved oxygen concentration at 30 m depth in the period July-September 2024; shaded areas refer to values lower than the precautionary threshold of 5 mg l⁻¹ (i.e. 156 mmol m⁻³) for oxygen depletion identification (Vaquer-Sunyer & Duarte, 2008). Data from Med-MFC Analysis and Forecast Biogeochemistry (Product 1).

Data availability

Products 1-8 are publicly available datasets and can be found by following the references indicated in the Table 1 of the manuscript. Product 9 is available upon request.

Author contribution

VDB and GC conceived the idea. GB, SP, SS and SQ performed the simulations. LF and CA validated the simulations. VDB conducted the formal analysis. GC and SQ supervised the work. VDB and GC wrote the first draft, with contributions from all 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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