Response to reviewer's comments

The answers from the authors are in red italic

Review #2 (RC2)

General Comments

RC2.1: This manuscript presents a new high-resolution physical-biogeochemical modeling system that is produced by coupling existing physical (SHYFEM-MPI) and biogeochemical (BFM) models that have previously been used separately in other contexts. The physical model's unstructured grid provides flexibility in balancing computational demands with resolution of complex coastal features, while the fairly complex biogeochemical model, with ?? tracers, includes many components of the biogeochemical dynamics. The model is implemented for a small regional domain in the northern Adriatic Sea. Model skill is evaluated in comparison to an observational climatology and an existing coarser resolution NEMO-based model with the same BFM biogeochemical component (although differently tuned parameter settings). While the differences in tuning are clearly justified by the differing dominant ecosystem types of the parent and child domains, the combination of physical and biogeochemical model differences between the parent and child models preclude attribution of differences in skill to one factor or the other. However, the results demonstrate the significant potential of the unstructured grid approach in the context of representation of coastal biogeochemistry. The skill assessment highlights the need for further development in order to accurately capture spatial features present in the observational climatology. Yet, the model successfully captures the timing of bloom events. The manuscript is interesting and generally provides a level of detail sufficient to understand the model's implementation. However, revision and clarification in some areas (outlined below) would be beneficial.

Response: *We thank the reviewer for the comments. We understand that the differences in both physics and biogeochemistry among the models prevents the attribution of skill differences to a single factor. We tried to minimize the set-up differences using the same forcing for both NB and SB (River inputs and atmospheric forcing). A dedicated sensitivity analysis would be required to attribute skill differences to a single factor; however, experiments designed to isolate the different contributions was beyond the scope of this work, which aims to document and validate the integrated SB system.*
We added more information about the physics of the simulations. We added in the main manuscript a new section with temperature and salinity maps of SB with differences against climatology (Fig 3; section 4.4.1) with the circulation streamlines superimposed to the temperature map.

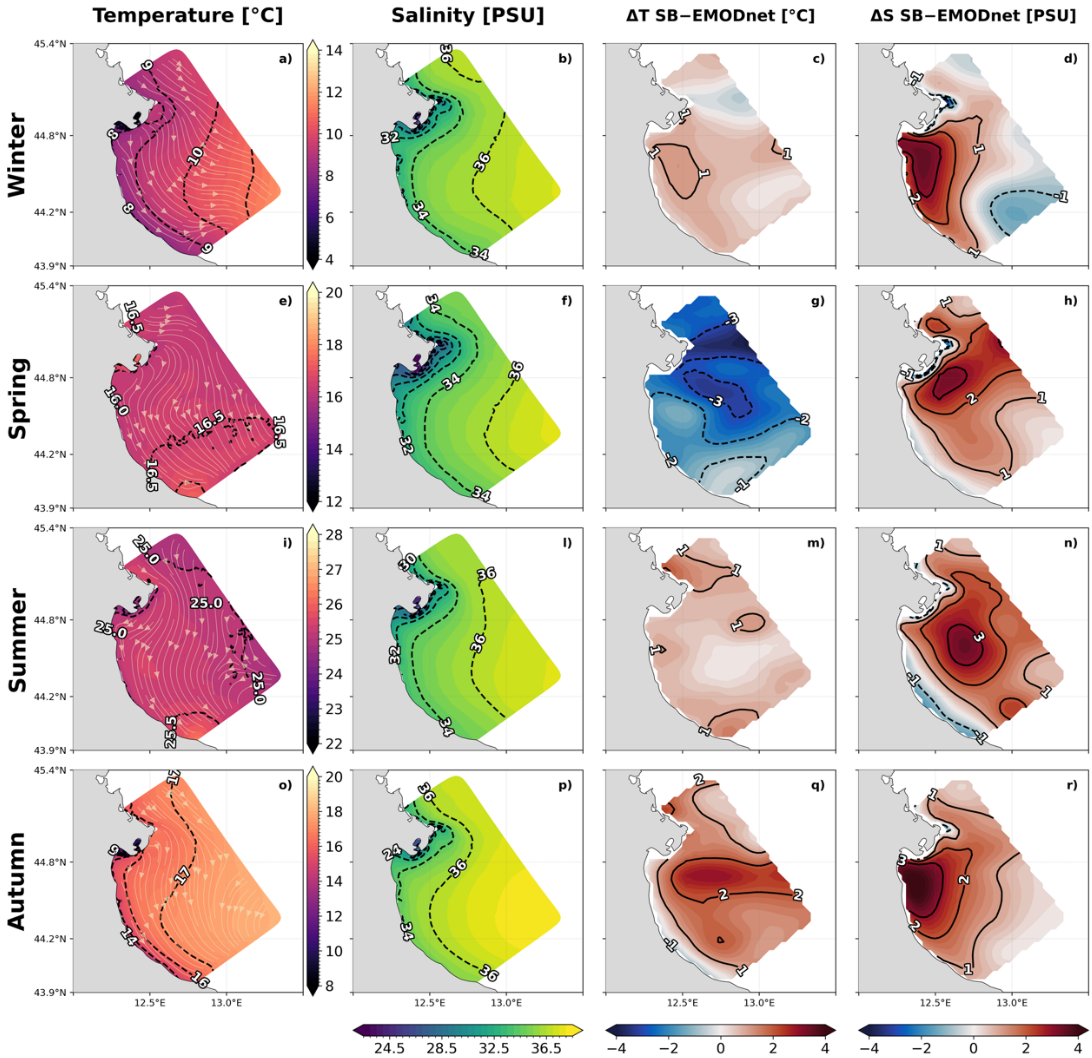

Figure 3: Seasonal surface maps of temperature with superimposed mean circulation (a, e, i, o) and salinity (b, f, l, p) for SB and differences against EMODnet climatology for temperature (c, g, m, q) and salinity (d, h, n, r).

We added temperature and salinity plots for NB in the supplementary information (SI 2; Fig. SI2.3).

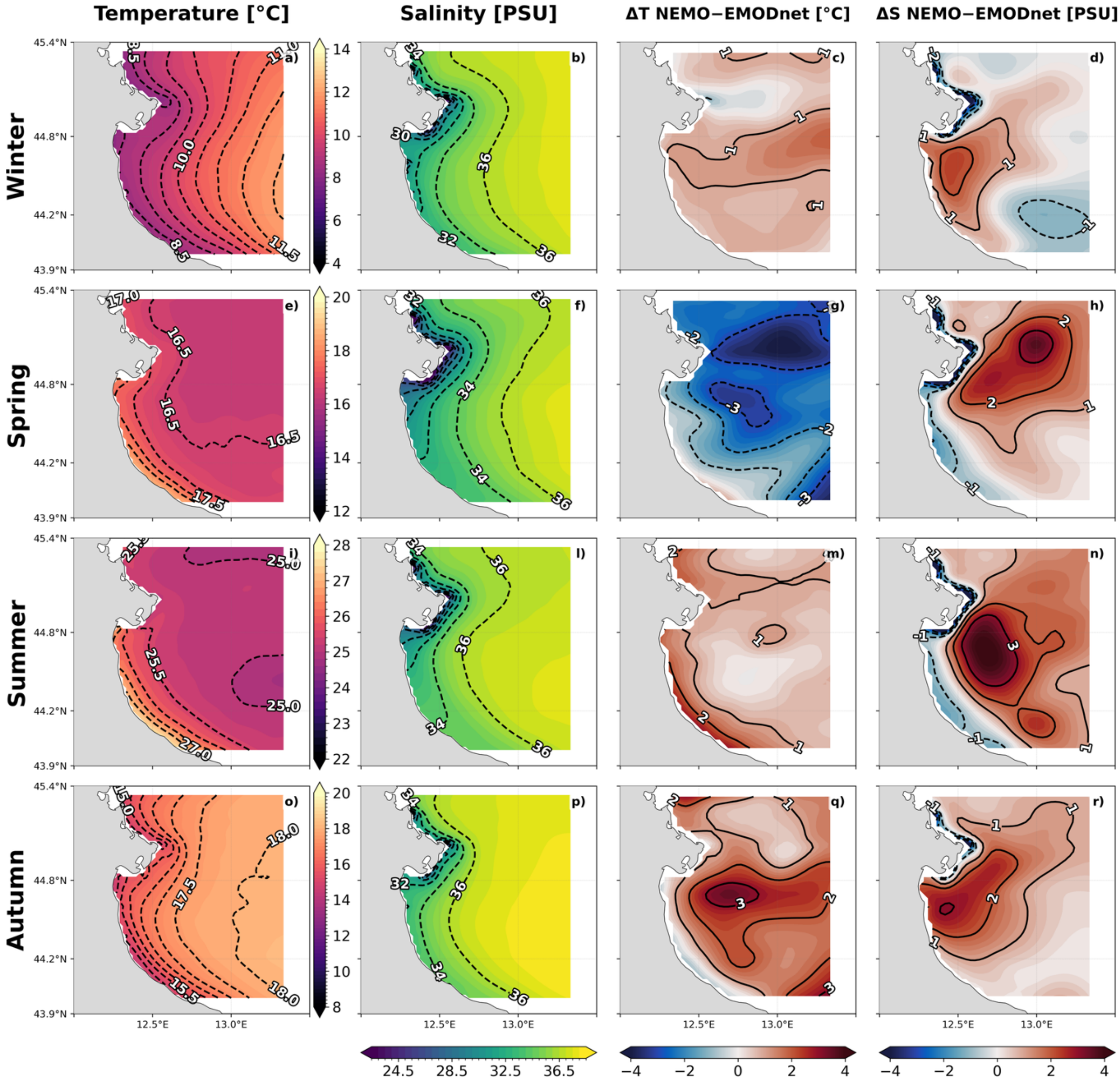

Figure SI2.3: Seasonal surface maps of temperature (a, e, i, o) and salinity (b, f, l, p) for NB and differences against EMODnet climatology for temperature (c, g, m, q) and salinity (d, h, n, r).

An additional plot of the circulation for SB and NB and the relative difference was added in SI 2 (Fig. SI2.6).

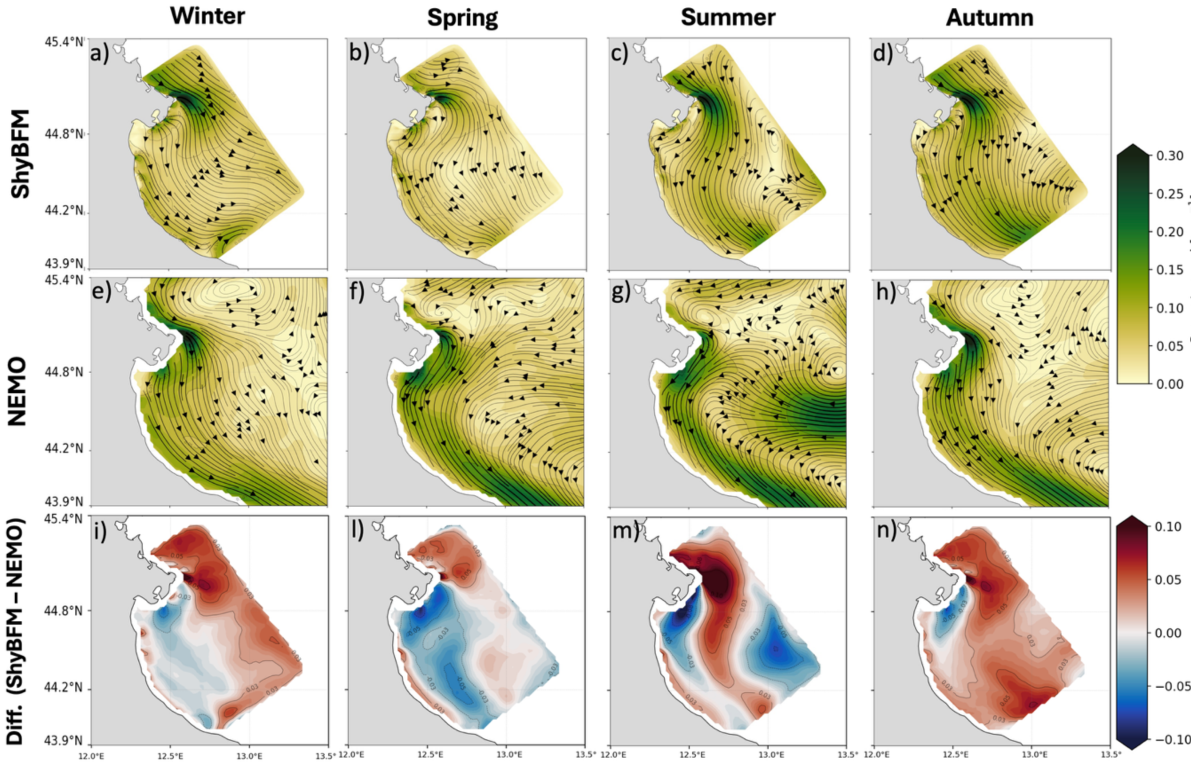

Figure SI2.6: Seasonal near-surface circulation for SB (a, b, c, d), NB (e, f, g, h) and speed difference (SB-NB; i, l, m, n).

The main southward circulation is well represented by both SB and NB, with some discrepancies in the offshore extent of the current maximum, which lies closer to the coast in NB than in SB, probably owing to a different representation of the river plumes. These circulation differences are nonetheless limited. Temperature and salinity biases show similar patterns for SB and NB, although the negative coastal salinity bias evident in NB (Fig. SI2.3h, n) is reduced in SB (Fig. 3h, n), bringing it closer to the climatology, possibly as a result of these circulation differences. Without dedicated sensitivity experiments, however, it is difficult to attribute differences in the biogeochemical variables between SB and NB to differences in the dynamics. Overall, the maps show that SB and NB produce consistent circulation, temperature and salinity fields (compare Fig. 3 with Fig. SI2.3 and Fig. SI2.6).
We added few comments on temperature and salinity in the discussion (lines 484-496; see RC2.3).
Below we respond point by point to the specific comments; manuscript line numbers refer to the revised version unless stated otherwise. The text that was added to the manuscript is reported here between quotes (" "). Please note that we added a new figure in the manuscript (Fig. 3) so from figure 3 on they all shifted by 1 number, so the old Fig. 3 is now Fig. 4, Fig. 4 became Fig. 5 and so on.

Specific Comments

RC2.2: A settling velocity is included in equation 1a but not in section 2.1, except in equation 5. I find the apparent switching between considering and ignoring tracer sinking velocities confusing and suggest adding additional clarifying information or perhaps correction. I would have expected, for example, that a no-flux surface boundary condition might reflect a balance between sinking, vertical turbulent diffusion, and possibly motion of the free surface, and that the bottom boundary condition for sedimented organic matter would reflect the sinking flux (eg eqs 98-99 here: https://getm.eu/files/GETM/doc/html/node78.html).

Response: *We thank the reviewer for this suggestion that provides a correction in the definition of the boundary conditions. Following the reviewer suggestion, we added the terms related to the bottom sinking flux in eq. 5 and then we added the sinking fluxes in the vertical boundary conditions defined in eq. 6, 7 8 and 9. We specified that since no tracers crosses the air-sea interface, the settling flux vanishes at the surface (line 107). We rephrased lines 110-113 to highlight the role of the settling velocity in the bottom boundary conditions, where the benthic return parameterization is applied. We report here the part of section 2.1 that was changed:*

"The surface boundary conditions for the tracers can be deduced by taking the volume integral of (1) which gives:

$$\frac{\partial}{\partial t}\int_V C\,dV + \int_\Omega d\Omega\,\nabla_h \cdot \int_{-H}^{\eta} \vec{u}_h C\,dz - \int_{-H}^{\eta} k_h \nabla_h C \cdot \nabla_h \eta\, d\Omega =$$

$$\int_\Omega \left\{ -w_s|_{z=\eta} C_\eta + w_s|_{z=-H} C|_{z=-H} - C_\eta (E - P - R) + k_v \frac{\partial}{\partial z} C|_{z=\eta} - k_v \frac{\partial}{\partial z} C|_{z=-H} \right\} d\Omega + \int_V \frac{\partial C}{\partial t}|_{bio}\, dV \quad (5)$$

where V and Ω are the volume and area of the model region, respectively. Conserving the tracer in a laterally and vertically closed domain, imposes that:

$$k_v \frac{\partial}{\partial z} C|_{z=\eta} = C_\eta (E - P - R) + w_s|_{z=\eta} C_\eta \quad (6)$$

$$k_v \frac{\partial}{\partial z} C|_{z=-H} = w_s|_{z=-H} C|_{z=-H} \quad (7)$$

Assuming no net reaction rates in the volume.

In the case of surface inputs of tracer, wet deposition by precipitation, C_{pw}, dry deposition, F_g, and rivers, C_{rw}, the most general vertical flux boundary condition is:

$$k_v \frac{\partial}{\partial z} C|_{z=\eta} = C_\eta (E - P - R) + R C_{rw} + P C_{pw} + F_g(C) + w_s|_{z=\eta} C_\eta \quad (8)$$

Since no tracer crosses the air-sea interface, the settling flux vanishes at the surface, $w_s|_{z=\eta} C_\eta = 0$. Here the rivers are assumed to discharge the tracer only at the surface which is a widely used assumption in other modelling systems (Madec et al., 2024). Each symbol in (8) is explained in Table 1.

The bottom boundary conditions for tracers use a benthic return parameterization. The settling flux, $w_s|_{z=-H} C|_{z=-H}$, deposits particulate organic matter (POM) into the benthic compartment, where the sedimented POM is remineralized using constant rates and returned to the water column as a nutrient flux, $F_b(C)$:

$$k_v \frac{\partial}{\partial z} C|_{z=-H} = F_b(C) + w_s|_{z=-H} C|_{z=-H} \quad (9)''$$

RC2.3: The spatial patterns in nutrients look quite different between SB and the observational climatology. Is this reflected in the temperature and salinity as well? It could be informative to also present the same figures for temperature and salinity. Are riverine nutrient inputs near the center of the domain's coastline underestimated?

Response: *We now added a new section (4.4.1) where we put temperature and salinity surface maps and the differences with the climatology (Fig. 3; see answer to RC2.1) with circulation streamlines superimposed on the temperature field. The following is the text added for section 4.4.1:*

""Seasonal temperature and salinity surface maps are shown in Fig. 3, where also differences against EMODnet climatology were reported. Temperature ranges between a minimum of around 8 ℃ in winter (Fig. 3a), along the coast, to a maximum of 25-26 ℃ in summer (Fig. 3i). Stronger coast-to-offshore gradients are shown in winter (Fig. 3a) and autumn (Fig. 3o), with the shallow coast that is 3-4 ℃ colder than the offshore area. The differences against the climatology show in general a slight overestimation of temperature, except for spring (Fig. 3g), which shows temperature underestimation, with a maximum difference of more than -3 ℃ in front of the Po River. The maximum temperature overestimation is shown in autumn with almost 3 ℃ more than EMODnet in the central part of the domain (Fig. 3q).
Salinity maps show a constant sharp coast-to-offshore gradient that strengthen in Spring due to increased river discharge (Fig. 3f). The salinity differences show in general two different patterns. In winter and autumn (Fig. 3d, r) the larger overestimation (more than 3 psu) is just in front of the ER coast, while in the south-east part of the domain the difference decreases or becomes even negative in winter (Fig. 3d). In spring and summer (Fig. 3h, n) the salinity is overestimated (from 1 to 3/3.5 psu) except than along the ER coast where a slight underestimation is shown (-0.5/-1 psu). Temperature and salinity maps for EMODnet climatology and NB are available in SI 2 (Fig. SI2.1; Fig. SI2.3). The seasonal mean surface circulation is superimposed to the temperature maps (Fig. 3a, e, i, o, u) to provide an indication of the circulation patterns in the area, that is mainly southward due to the wind and river forcing. Seasonal circulation maps for SB and NB and their comparison can be found in SI2 (Fig. SI2.6). In general, both SB and NB show consistent fields of circulation, temperature, salinity."

The differences in temperature are not explicitly reflected in the biogeochemical patterns. We interpreted this as indicating that, in this area, river inputs and open-boundary conditions exert stronger control on phytoplankton than temperature does. We stated this in the discussion in lines 484-489:

"Temperature influences phytoplankton and zooplankton growth through the metabolic (Q10) dependence in BFM, yet the temperature differences in Fig. 3 do not map onto the chl-a differences in Fig. 5: the winter underestimation of chl-a coincides with a slight warm bias (~1 °C; Fig. 3c), while a much larger spring cold bias (~−3 °C; Fig. 3g) leaves the chl-a difference (Fig. 5e) essentially unchanged from the other seasons. This suggests that phytoplankton biomass here is controlled less by temperature than by river inputs and open-boundary conditions."

We also analysed the discrepancies in surface salinity attributing the differences to uncertainty in the river discharge and in possible bias in the circulation, that however is impossible to verify due to the lack of data. We add this in the discussion in lines 489-496.

"Discrepancies in salinity (Fig. 3) can be attributed primarily to uncertainty in the prescribed river discharge, which sets the freshwater input and hence the strength and extent of the low-salinity plume. In addition, biases in the simulated coastal circulation, which advects the plume southward along the shelf, may displace the freshwater signal relative to observations; however, in the absence of current measurements this contribution cannot be quantified directly. SB and NB show similar temperature and salinity patterns (Fig. SI2.3) and vertical profiles (Fig. 7), indicating that these features are largely inherited from the shared forcing and boundary conditions rather than introduced by the differences in the modelling framework (grid, coupling, numerics, etc.)."

The riverine inputs are affected by high uncertainty but is not clear if in general they are underestimated. The behavior of the nutrients analyzed show different patterns (Fig. 5). We show here an updated version of Fig. 5:

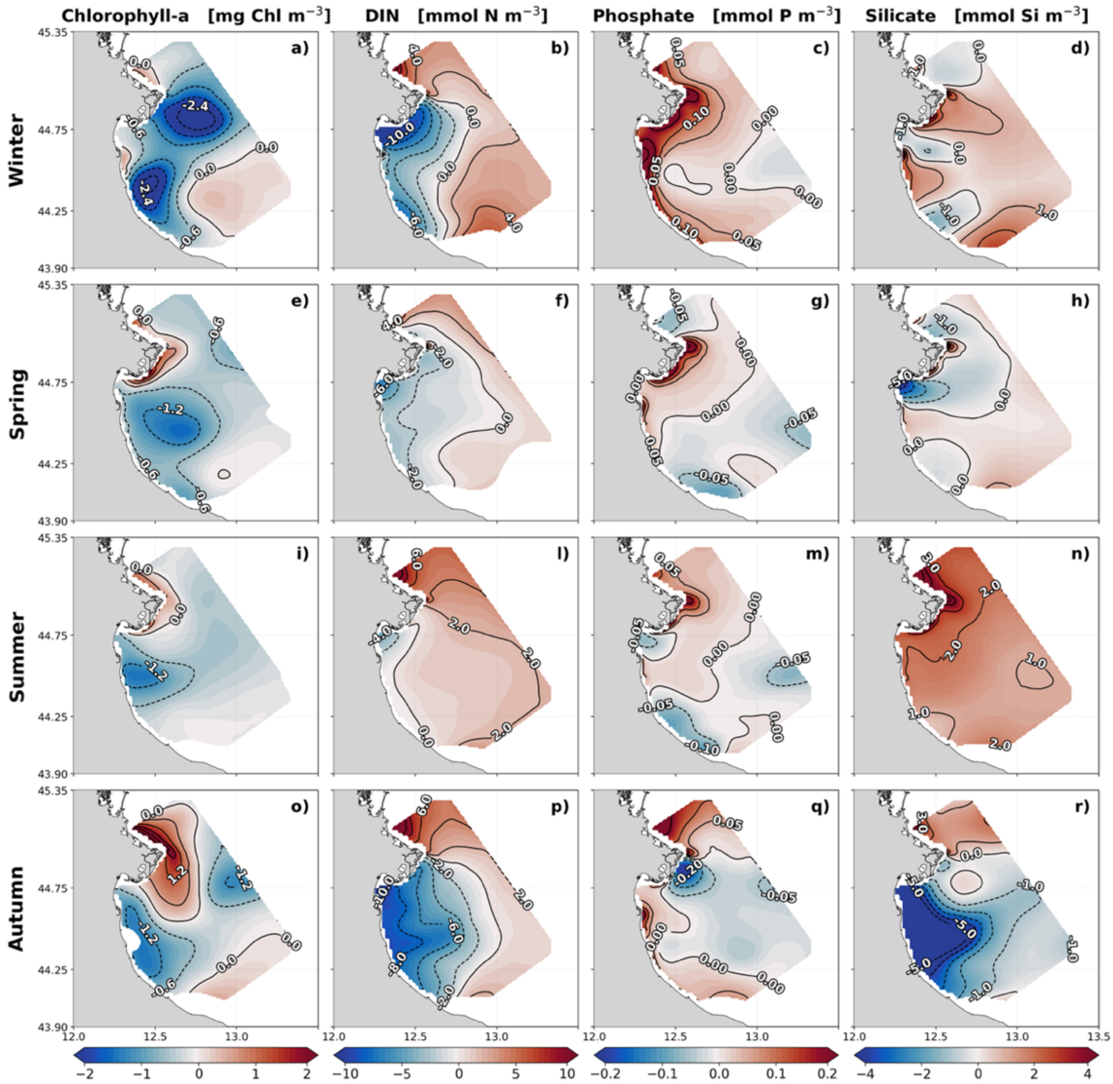

Figure 5: Seasonal near-surface differences between SB and EMODnet of chl-a (a, e, i, o), DIN (b, f, l, p), phosphate (c, g, m, q) and silicate (d, h, n, r).

DIN is in general underestimated along the central part of the coast, while phosphate and silicate show alternate positive and negative bias with a maximum overestimation in winter for phosphate (Fig. 5c) and a strong underestimation of silicate in autumn (Fig.5r). We stated the uncertainty and the low frequency of measurements in riverine nutrient inputs as one important issue in different part of the manuscript in the discussion, in lines 431-434:

"The surface comparison of chl-a with EMODnet (Fig. 5) shows similar patterns for spring, summer and autumn with a positive bias around the Po mouth and a negative bias along the coast. This pattern can be observed also in other variables of Fig. 5 and may result from uncertainties in the river nutrient loads."

In lines 447-452 and 460-462:

"The coupled model of Scroccaro et al. (2022) reported a substantial overestimation of phosphate in the ER coastal area, where chl-a overestimation was also found, attributing this discrepancy to high uncertainty in land-borne river nutrient loads. Consistently, the

comparison with EMODnet in Fig. 5 shows that the largest phosphate discrepancies occur around the Po mouth and along the coast, where several Apennine rivers discharge, supporting the role of uncertainty in river nutrient inputs."

"However, silicate loads are highly uncertain due to a lack of continuous measurements. Furthermore, riverine silicate inputs are often estimated using indirect methods (Ludwig et al., 2009), which are less reliable than direct observations."

Eventually, we suggested the increase of the frequency of the river nutrient loads measurements as way to generate a more consistent forcing and reduce uncertainty (line 546-548).

"*A higher frequency of river nutrient loads measurements would be of great benefit to generate a more consistent forcing and reduce uncertainty."*

RC2.4: Table SI1: This table could be more informative if the original parameter values in the parent domain were also specified.

Response: *We now added a column to Table SI1.2 with the original parameters used for the NEMO-BFM simulations. We will include the new table SI1.2 in the revised SI 1 document.*

RC2.5: line 397 suggests that the upwind horizontal advection scheme may not be optimal, but does not say why (although numerical diffusion is mentioned at line 464). Is there evidence of numerical diffusion in the results? How would it lead to a positive chl bias at the Po River mouth?

Response: *We thank the reviewer to pointing out the missing justification and the imprecise link. The northern Adriatic Sea in general is an advection-dominated system, in which wind and river forcing govern the along-shelf transport and spread of phytoplankton biomass (Zavattarelli et al., 2000; Polimene et al., 2007). It is in this context that we considered the first-order upwind advection scheme potentially suboptimal: although robust and monotone, it is only first-order accurate, and its diffusive truncation error can damp the sharp cross-shelf and plume gradients that characterize the region.*
We initially attempted to run the model with a higher order TVD advection scheme, but we encountered stability issues with biogeochemical tracers and therefore we adopted the upwind scheme. We now specified this in the simulation set-up in lines 210-212:

"A higher order total variation diminishing (TVD) scheme was also tested but proved insufficiently robust due to instabilities in the biogeochemical tracers."

The implementation of a higher-order advection scheme that remains robust for steep biogeochemical gradients is left for future work (lines 503-504; 539-542).

"Nevertheless, a higher-order advection scheme would be expected to improve the simulated spatial patterns and is left for future work."

"Future developments should incorporate higher-order advection schemes, the inclusion of ISM and CDOM for light absorption and more mechanistic sediment diagenetic modules, building on the unstructured framework, which already resolves the complex coastal geometry and cross-shelf gradients at variable resolution."

We do not have clear evidence of numerical diffusion, because we didn't carry out sensitivity experiments. A signal of numerical diffusion could be the lower spatial variability of SB (lower IQR) compared to NB (Fig. 9), but this is not supported by the comparison with EMODnet since SB shows IQR values closer to EMODnet. We have clarified in the revised manuscript that the present experiments do not isolate the effect of the advection scheme from boundary conditions, river loads influences or the choice of biogeochemical parameters. We have revised the discussion accordingly and added new comments in the discussion in lines 497-504 clarifying the rationale for the advection scheme and why we expect it to be suboptimal:

"The northern Adriatic coastal zone is an advection-dominated system, in which wind and river forcing govern the along-shelf transport and spread of phytoplankton biomass (Polimene et al., 2006; Zavatarelli et al., 2000). In such a regime the first-order upwind scheme adopted for horizontal advection, although robust, monotone and positivity-preserving, properties that are desirable for biogeochemical tracers, is only first-order accurate, and its diffusive truncation error tends to smooth the sharp cross-shelf and plume gradients that characterise the region, although no sensitivity experiments were carried out to isolate it from the effects of the boundary conditions, river loads or the specific choice of biogeochemical parameters. Nevertheless, a higher-order advection scheme would be expected to improve the simulated spatial patterns and is left for future work."

We have corrected the link between the advection scheme and the positive Chl-a bias at the Po river mouth. Numerical diffusion would tend to reduce and spread a concentration maximum rather than enhance it. The localized overestimation is instead attributable to uncertainty in river nutrient loads (lines 431-434):

"The surface comparison of chl-a with EMODnet (Fig. 5) shows similar patterns for spring, summer and autumn with a positive bias around the Po mouth and a negative bias along the coast. This pattern can be observed also in other variables of Fig. 5 and may result from uncertainties in the river nutrient loads."

Technical Corrections

RC2.6: line 77: I think this is the first time "ADR" is used- please define it (advection-diffusion-reaction, I assume)

Response: *Yes, it is the first time that ADR appears in the text. We corrected the text adding the definition:*

"The present work offers a full description of the advection-diffusion-reaction (ADR) equation formalism and of..."

RC2.7: line 108: The word "quotes" does not make sense. Do you mean fractions perhaps?

Response: *Yes, it was fraction, but we decided to rephrase the whole sentence as follows, after corrections from comment RC2.2 (lines 108-110):*

"The bottom boundary conditions for tracers use a benthic return parameterization. The settling flux, $w_s|_{z=-H}C|_{z=-H}$, deposits particulate organic matter (POM) into the benthic compartment, where the sedimented POM is remineralized using constant rates and returned to the water column as a nutrient flux, $F_b(C)$"

RC2.8: line 135: "The carbon, nitrogen, and silicon cycles are solved independently across their inorganic form and the organic content within each FG." I am not sure what this sentence means- I find the structure ambiguous.

Response: *We understand that this sentence can be ambiguous, we rephrase it as follows (lines 136-137):*

"The cycles of carbon, nitrogen, phosphorus and silicon are solved separately, with the inorganic (dissolved nutrient) pool and the organic content within each FG treated as distinct state variable."

RC2.9: line 165: what does "synthetically" mean here?

Response: *This is an error. We removed the term "synthetically" that has no meaning here (line 166).*

RC2.10: line 330: Table 3 shows a slightly higher IQR for SB compared to NB

Response: *This was an error. We corrected changing "much lower" with "slightly higher" (Line 369).*