

Insights into exceptional freshening events in the northern Adriatic Sea throughout 2023-2024

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Response to reviewers

We thank the editor and reviewers for their constructive evaluation of our manuscript and have addressed all comments and suggestions to the best of our ability.

In addition to the language and representation improvements suggested by both reviewers, we have implemented several clarifications, particularly regarding the freshwater rate estimation methodology and the interpretation of oxygen supersaturation. As a result, the manuscript has improved in clarity, structure, and readability.

Below, we provide a point-by-point response to each comment in blue color.

Reviewer 1

Review of: “Insights into exceptional freshening events in the northern Adriatic Sea throughout 2023-2024” by Naomi Krauzig, Alessandro Coluccelli, Francesco Memmola, Pierluigi Penna, Fabrizio Moro, Enrico Zambianchi, Pierpaolo Falco Manuscript no. sp-2025-10

General comments:

This work describes the effects of heavy (and frequent) rainfall events in the Emilia-Romagna and Marche (eastern central Italy) region on the properties of the Adriatic Sea coastal waters, combining meteorological and oceanographic in situ and remote sensing data, as well as circulation model output. To my opinion, the work is interesting, scientifically sound and well highlights the environmental opportunity of combined-data coastal monitoring, especially for this kind of environmental hazards. Finally, there are just some minor (suggested) corrections that I'd like the Authors to consider (see below). I therefore recommend minor revision of the paper before publication.

Response: We thank the reviewer for the constructive assessment and helpful suggestions for improving our manuscript. We appreciate the positive evaluation, and we have revised the text accordingly in response to the points raised.

Specific comments:

One comment/question: what do the Authors think about using this multi-dataset in a predictive effort (together with model forecasts), and not only a monitoring effort during the hazardous event? Or, alternatively, what do they think about creating a "crisis monitoring unit" when an extreme event is predicted, which unit immediately starts to more thoroughly analyze this combined dataset and issues reports and warnings to the communities affected by the state of the coastal waters (e.g. to the aquaculture community)? This comment is not required but may be interesting to readers.

Response: We thank the reviewer for this forward-looking suggestion. This is indeed a highly relevant application with strong potential value for the coastal community. We agree that integrating the multi-dataset framework into a predictive or pre-event response system would significantly enhance preparedness for extreme weather events. We are currently in the final phase of publishing a high-resolution model for the entire Adriatic Sea, and this concept could naturally take shape within that framework in the future. We appreciate the reviewer for raising this important idea.

Technical corrections:

Abstract Line 20. (here or when next mentioned) please describe where Emilia-Romagna is (not everybody might know). Maybe add "see Fig. 2" in the text? Or, better, if Fig. 3 becomes Fig. 1, then highlight the region in this Figure?

Response: We agree and have now included a short geographical indication of Emilia–Romagna in the abstract which reads now: “The first freshening event in early summer 2023 was linked to consecutive heavy rainfall episodes, including Storm Minerva, which triggered catastrophic flooding across the Emilia-Romagna region in northern Italy.”

Line 27. Replace “summer-time” with “summertime”

Response: Corrected.

Keywords OK

Short summary OK

1 Introduction

Line 51. (maybe) replace "Among those" with "Among these".

Response: Revised as suggested.

Line 58. Replace "several smaller" with "several small".

Response: Corrected.

Line 59. Replace "nutrients-rich" with "nutrient-rich".

Response: Corrected based on the suggestion.

Line 61. Replace "while the plume" with "while the Po plume" or with "while the river plumes" if referred to all the rivers mentioned.

Response: Updated to "while the Po plume" for clarity.

Line 70. Replace "data near-real time" with "near-real-time data".

Response: Corrected.

Line 71. Replace "rabidity" with "rapidity".

Response: Replaced as indicated.

2 Methodology

2.1. Local meteo-marine conditions

Line 89. Replace "Senigallie" with "Senigallia".

Response: Corrected.

2.2 Precipitation and river discharge

Figure 3b. The notes on the plots are unreadable also when enlarging the document up to 200% (!): please enlarge this figure (e.g. place it underneath Fig. 3a) or enlarge the writing.

Response: We thank the reviewer for pointing this out. The figure and associated labels have been enlarged and reformatted to ensure full readability.

Fig. 3 in general. Since it is the first figure to be cited and this is done at line 106, why is it placed at line 243, and why is it not named Fig. 1? Maybe figures should be reorganized and placed better. Line 106. Therefore, if Fig. 3 is re-located, then replace "(see Figure 3 for river mouth locations and characteristic circulation patterns)" with (simply) "(Figure 3)" or, better "(Figure 1)".

Response: We appreciate the reviewer's observation regarding figure order. Our intention was to begin the Results section by presenting the time series (Figure 1), as this provides a clear and direct depiction of the freshening events before introducing the atmospheric drivers and river inputs shown in subsequent figures. The current sequence follows the narrative structure of the manuscript: (1) description of the oceanographic response, (2) the precipitation events that triggered it, (3) the associated river discharge patterns, and (4) the resulting biogeochemical impacts.

We do indeed refer to Figure 3 earlier in the text to aid reader understanding by showing river locations, but this reference is only intended as supporting contextual information. If preferred, we can remove the optional parenthetical remark (“see Figure 3 for river mouth locations and characteristic circulation patterns”) to avoid confusion.

2.3 Freshwater rate estimation

Line 113. "and the estimated area of the affected region, as determined from satellite observations". This sentence could be a bit more detailed (even though you cite product refs): e.g. "and the estimated affected region, i.e. via the width of the coastal current turbid band (Fig. 3), determined from satellite observations".

Response: We expanded this sentence accordingly to clarify how the affected region was estimated from satellite observations. It now reads “This method was based on in-situ salinity data from the Fortunae buoy (product ref. 1; Table 1) and the estimated area of the affected region, derived from satellite SST and ocean-colour observations (product refs. 5 and 6; Table 1) capturing the cold and turbid coastal plume.”

2.4 Complementary satellite and model-based datasets

Line 134. "These included daily fields...". Could you pls include the spatial resolution too (in brackets, maybe), please? This way the reader has "right away" a more complete grip on the basic specs of the data/model used, while further details can be acquired in the cited ancillary documentation.

Response: The spatial resolution of the satellite and model products has been added in parentheses and reads as follows: “These included daily fields of sea surface temperature (SST; $0.01^\circ \times 0.01^\circ$), chlorophyll-a concentration (Chl-a, 1km x 1 km), light attenuation coefficient at 490 nm (KD490; 1km x 1 km), surface salinity (SSS; $0.042^\circ \times 0.042^\circ$), and horizontal current components (u and v; $0.042^\circ \times 0.042^\circ$).”

Line 145. Replace "while the model outputs" with "while model output".

Response: Replaced as indicated.

2.5 Statistical analysis

Line 159 (Table 1). Maybe it could be useful to add a word in column "Product ID & type" for the Copernicus products, better describing them, e.g. "ERA5, numerical models - precipitation", "CEMS EFAS, numerical models - ocean circulation", etc.

Response: We appreciate the reviewer’s suggestion. The structure of Table 1 follows the standard format required by the Ocean State Report, which specifies the layout for product identification. For this reason, we maintained the prescribed format without adding additional descriptors in the “Product ID & type” column. However, the nature of each product (e.g., numerical model, satellite observation, in-situ data) is indicated within the table and further detailed in the accompanying documentation references.

3 Results

3.1 Surface freshening

Fig. 1. Why do you use similar colors in each panel? In this way it is difficult to distinguish between curves (also because the fig. is quite small). Would it not be better to use contrasting colors (e.g. blue and red) for all curve pairs?

Response: We thank the reviewer for highlighting this issue. We chose the colour scheme based on standard physical interpretation (blue for temperature, red for salinity, and orange for density) to ensure intuitive readability across the manuscript. To improve visual clarity, we have now increased the contrast between the curves and enhanced the font size and figure resolution.

3.2 Environmental connections

Line 208. " During this period, the Po River remained well below the climatological average discharge". This is interesting. Can you comment on why? Maybe the Po was already so low that rainfall didn't manage to raise it above average?

Response: Indeed, despite these extreme rainfall episodes, the Po River remained well below its climatological average discharge and this behaviour is consistent with the fact that the most intense precipitation was concentrated over the eastern Apennine catchments rather than over the Po basin itself, which had also previously experienced prolonged drought conditions. As a result, local rivers such as the Lamone, Savio, and Reno exceeded historical flood levels, while the Po showed only a limited hydrological response.

The text now reads: "During this period, the Po River remained well below the climatological average discharge, with values around 2000 m³/s, as the most intense rainfall did not affect its main basin, whereas local rivers like the Lamone, Savio, and Reno exceeded historical flood levels (Figure 3c)."

Line 228. Replace "Marche region" with "Marche region, just south of Emilia-Romagna,".

Response: Replaced as indicated.

Line 229. "Replace "Discharges increase" with "Discharge increases... were reported" or "and increase in the discharges... were reported".

Response: Revised to: "An increase in the discharge of the Adige and Po was reported"

Line 233. Replace "Parma Apennines" with "inland, in the Parma Apennines".

Response: Replaced as indicated.

Line 259. Replace "provide spatial" with "provide a spatial".

Response: Corrected as suggested.

3.3 Ecological implications

Fig. 4. Same as comment on Fig. 1 curve colors... e.g. never mind the "psychological affinity" of the curve color to the color of the parameter when visually observed at sea (e.g. green for chl, brown for turbidity, etc.).

Response: We agree with the reviewer's observation on the readability. The colour scheme in Figure 4 was originally chosen to follow standard physical interpretation (e.g., green for chlorophyll-a and brown for turbidity) to support intuitive reading across the manuscript. However, we agree that the similarity between some curves reduced readability. To improve visual clarity, we have increased the contrast between the plotted lines and enhanced both the font size and figure resolution, while keeping the same intuitive selection. These adjustments ensure that the figure is more easily interpretable while maintaining a physically meaningful colour scheme.

4 Discussion and conclusions

Line 360. Replace "Mediterranean is particularly vulnerable" with "Mediterranean, it is particularly vulnerable".

Response: Corrected as suggested.

Line 375. Replace "Such integration" with "Such an integration".

Response: Corrected as suggested.

Appendix Line 403. "waves characteristic" with "wave characteristics".

Response: Corrected.

Line 404. Replace "informations are" with "information is".

Response: Replaced as indicated.

Line 431. Replace "information are available under" with "information is available in".

Response: Corrected as indicated.

Line 492. Replace "Assuming x and y are" with "Assuming that x and y are".

Response: Revised accordingly.

Reviewer 2

General comments:

This is a very interesting and well-structured article that delivers what promises in its title. It is concise, to the point, and succeeds in compiling and integrating data from various sources and platforms to provide a quantitative view into the complex dynamic interactions between extreme atmospheric phenomena (rainfall events), land processes, and coastal ocean response in a vulnerable domain of the Mediterranean Sea, the coastal northwestern Adriatic. The study proposes a methodology that can be implemented to quickly assess the impact of extreme storms on water quality and coastal ecosystems, provided that high-frequency measurements from autonomous met-ocean monitoring platforms are available. The manuscript is well-written, with very few mistakes, if any, and I recommend it for publication after minor revisions: two points are raised in the 'Specific comments' section for the authors to address.

Response: We appreciate the reviewer's detailed and constructive feedback. The manuscript has been revised accordingly to address the points raised.

Specific comments:

Section "2.3 Freshwater rate estimation" and Appendix A2 describe the estimation of the freshwater rate required to result in the observed decrease in the surface seawater salinity due to consecutive rainfall events over a period of $\Delta t = 13$ days. This freshwater rate is estimated $Q_f \approx 42.5 \text{ m}^3 \text{ h}^{-1}$. However, the rationale behind the dimensions of the 'control volume' (box) where the mass balance equation (1) is applied needs further clarification I think: 15000 m offshore (based on satellite imagery) $\times$ 1.5 m depth (where the buoy CTD lies) $\times$ 1 m width. Unless explicitly justified, the choice of 1 m alongshore width, that determines linearly the value of Q_f , seems arbitrary. As I understand it, this value of $Q_f \approx 42.5 \text{ m}^3 \text{ h}^{-1}$ represents the freshwater inflow per meter of coastline (alongshore, in the vicinity of the buoy) necessary to achieve the observed salinity drop. It should not be assumed as constant along the entire coastline north of the buoy, as many rivers of various discharge capacities contribute freshwater. Moreover, this value does not represent the total freshwater input for the entire coastal segment (e.g. from the Adige River mouth to Fano buoy, Fig 3b for river contribution). Some clarifying remarks on these points would help the readers better understand the authors' assumptions and interpretation of their findings (note, the abstract should then be rephrased accordingly).

Response: We agree with the reviewer's interpretation. The 1 m alongshore width was chosen to express the required freshwater input per metre, providing an easily interpretable quantity while ensuring dimensional consistency in the mass-balance calculation. This approach yields of course only an indicative value that reflects the local freshwater signal at the buoy site. It is not intended to represent the total freshwater discharge along the broader coastline, nor to imply uniform contributions from the various river systems in the

region. We acknowledge that this required clearer explanation. We have now added clarifying remarks in Section 2.3 and Appendix A2, and we have adjusted the abstract accordingly to avoid potential misinterpretation.

The following section has been added for clarification:

“Note that the control volume is defined by an offshore distance of 15×10^3 m, consistent with the observed plume extent, a depth of 1.5 m corresponding to the buoy sensor level, and an alongshore width of 1 m. This width is intentionally chosen to express the freshwater requirement per meter of coastline. The resulting freshwater rate therefore represents the required freshwater inflow per meter of coastline near the buoy location, rather than the total discharge integrated along the entire coastal segment.”

Lines 301-302: “...and oxygen supersaturation...”.

Here, oxygen supersaturation appears to be inferred from dissolved oxygen (DO) concentration and high chlorophyll-a values shown in the figures. Since DO concentration alone does not demonstrate supersaturation, I suggest either including the corresponding %DO saturation data or rephrasing this statement accordingly (e.g., “...and oxygen supersaturation, as indicated by %DO saturation calculations (not shown) ...”).

Response: We agree with the reviewer. It was an oversight on our part, as we originally intended to include indicative %DO saturation values in the text. We have now added these values in parentheses to support the statement and improve clarity. The sentence now reads:

“While turbidity remained low, the biogeochemical response included a marked increase in chlorophyll-a concentration and oxygen supersaturation reaching approximately 150 percent, indicating a nutrient rich but low sediment freshwater input.”

Lastly, since wave information is not utilized in the analysis of data and synthesis of the findings, consider removing any reference to it all together (for the observational capabilities of the buoy, the reader can refer to the bibliography the authors provide).

Response: We thank the reviewer for this comment. Although the buoy is equipped to measure wave parameters, these data were not used in the present analysis. To avoid potential confusion, we have clarified in the Appendix that wave measurements are available from the platform but were not considered in this study. Readers interested in the full observational capabilities of the buoy are referred to the cited references.

Technical corrections

Line 24: "A key distinction between the two years was the marked recovery of Po River discharge in 2024 after a prolonged drought, significantly amplifying freshwater inputs."

Suggestion: "A key distinction between the two years was the significant recovery of Po River discharge in 2024 after a prolonged drought, which significantly amplified freshwater inputs."

Response: We thank the reviewer for the suggested improvement. The sentence has been revised as recommended.

Line 69: "The need for coastal observations and monitoring efforts is therefore progressively being recognized in order to guide policy and progress towards public safety needs."

Suggestion: "The need for coastal observations and monitoring efforts is increasingly recognized as essential for guiding policy and public safety needs."

Response: We agree with the proposed phrasing. The text has been updated accordingly.

Line 245: "Figure 3: (a) Overview of (a) the study area..." change to "Figure 3: (a) Overview of the study area..."

Response: This correction has been implemented.

Lines 281-282: "... (Figure2b-e), an extreme turbidity increase (~100 NTU average) was recorded for ...".

Aren't these high turbidity values on average more like ~70-75 NTU? (Fig 4, mid panel).

Response: We thank the reviewer for noticing this discrepancy. The turbidity values were rechecked, and the correct indicative range is indeed ~70 NTU. The text has been corrected accordingly.

Line 370: "These events compromise water quality, threaten aquaculture viability, and impact tourism, posing socio-ecological risks."

Suggestion: "These events compromise water quality, threaten aquaculture viability, and negatively impact tourism, posing socio-ecological risks."

Response: We agree with the reviewer's suggestion, and the sentence has been revised as recommended.