RESPONSE TO REVIEWER #2'S COMMENTS

TITLE - The Role of Rivers in Ocean Forecasting

RECOMMENDATION: Major revisions

This paper aims at providing a review of the river release representation in ocean modeling, spanning from global to coastal scales.

It offers a valuable contribution to ocean modeling developers and practitioners, as it assesses current advancements and offers recommendations for the next generation modeling of the global coastal ocean to more accurately account for riverine inputs.

I encourage the authors to make additional efforts to deliver a comprehensive and detailed overview of the current state of the field, ensuring it serves as a valuable reference for the community.

As it stands, the manuscript is lacking in several key topics. It would greatly benefit from incorporating a broader range of relevant studies and addressing open issues that deserve reporting and discussion.

Response: We thank the reviewer for these valuable comments. A detailed response to specific comments is provided below, using italic text in blue.

Major comments:

Title: I suggest to modify the title to clarify the the paper aims at providing a review of the state of art of river release representation within OOFS

Response: We modified the title as follows: "The representation of rivers in operational ocean forecasting systems: A review".

Line 52-53: The "point source input" here mentioned is not a rigorous definition. More precise, the river release entering as surface point sources affects the vertical velocity surface boundary condition of the free surface equation (i.e. the vertically integrated continuity equation, not the continuity equation itself) and the surface boundary conditions for the diffusive heat and salt fluxes (Beron Vera 1999)

Response: We made the following changes to the text (underlined): "A first approach, referred to as a point source input, adds a term of freshwater flux, <u>entering as surface point sources</u> into one or more layers of the model, <u>to the divergence of flow in the vertically integrated</u> continuity equation, with no associated velocity profile. <u>It affects the vertical velocity surface boundary condition of the free surface equation, and the surface boundary conditions for the diffusive heat and salt fluxes.</u>"

Line 70: "to account for baroclinic flow", I'd suggest to replace with "to account for baroclinic and barotropic flows"

Response: Corrected.

Line 75: Figure 1 caption. Which EBM does the caption refer to? Please include a reference to the model

Response: The reference was already included as a footnote. We also added this information in the caption: "Schematic diagram of the estuary box model (EBM<u>) implemented in the Community Earth System Model (CESM) (Sun et al., 2017)</u>."

Line 97-98: please detail more the relevant result found out by Bao et al 2022 by comparing 2way versus linked approach.

Response: We added the following sentence: "In a case study of Hurricane Florence, Bao et al. (2022) achieved significant improvement in simulated water levels (20%-40% at the head of Cape Fear River Estuary) during the post-hurricane period by using a two-way coupled model, compared to a stand-alone and linked (one-way coupled) approach. This higher performance can be largely explained by the momentum exchanges at the model interfaces, capturing the nonlinear effects between runoff and residual water level from the ocean."

Line 98-99: this sentence is too concise. Moreover the seamless river-sea continuum modeling deserves a specific additional section, e.g. Section 2.4

Response: We decided to move this sentence (and additional related content) to Section 2.3 (Freshwater input in high resolution models) instead, as it relates more closely to the development of high resolution models than to model coupling.

See also response below.

Add discussion and references on the topics below:

- **The Influence of Seasonal and Non-Seasonal River Release on Stratification and Sea Level Variability:** It is important to discuss how variations in river release can impact both stratification and sea level changes. Relevant studies include in addition to the already mentioned Chandanpurker et al 2022:
  - Zhang, Y. J., Ye, F., Stanev, E. V., & Grashorn, S. (2016). Seamless cross-scale modeling with SCHISM. Ocean Modelling, 102, 64-81.
  - Giffard, P., Llovel, W., Jouanno, J., Morvan, G., & Decharme, B. (2019). Contribution of the Amazon River discharge to regional sea level in the tropical Atlantic ocean. Water, 11, 2348. https://doi.org/10.3390/w11112348
  - Piecuch, C. G., Bittermann, K., Kemp, A. C., Ponte, R. M., Little, C. M., Engelhart, S. E., & Lentz, S. J. (2018). River-discharge effects on United States Atlantic and Gulf coast sea-level changes. Proceedings of the National Academy of Sciences, 115(30), 7729-7734.
  - Piecuch, C. G., & Wadehra, R. (2020). Dynamic sea level variability due to seasonal river discharge: A preliminary global ocean model study. Geophysical Research Letters, 47(4), e2020GL086984.
  - Verri, G., Pinardi, N., Oddo, P., Ciliberti, S. A., & Coppini, G. (2018). River runoff influences on the Central Mediterranean overturning circulation. Climate dynamics, 50(5-6), 1675-1703

  Response: The effect of variable river release and how it impacts coastal processes was already evoked throughout the manuscript, but we now have added more discussion in a new Section 2.1, titled "Capturing seasonal and non-seasonal river variability", as follows:

  "Realistic (model- or observation-derived) river discharges and ancillary variables (e.g. salinity, temperature) are necessary for capturing seasonal and non-seasonal effects in the coastal ocean. The Bay of Bengal is one example where the inclusion of seasonal river discharges and salinity in regional model simulations significantly improved the representation of sea surface temperatures,

near-surface salinity, stratification, mixed-layer depth and barrier-layer thickness, leading to a better simulation of the formation, progression and dispersion of the freshwater plume (Jana et al., 2015).

Seasonal variability in river discharge not only impacts coastal salinity and temperature, but also contributes to the sea level changes both locally and remotely, mostly via a halosteric sea level contribution. This effect was observed, for example, between the mouth of the Amazon River and the continental shelves of the Gulf of Mexico and Caribbean Sea (Giffard et al., 2019). Similarly, in the U.S. Atlantic and Gulf coasts, river discharge and sea level changes were found to be significantly correlated (Piecuch et al. 2018). Such dynamic SSH signals driven by river discharge can explain 10-20% of the regional-scale seasonal variance around major rivers, such as the Amazon, Ganges, Brahmaputra, Irrawaddy, Ob, Lena, and Yenisei (Piecuch and Wadehra, 2020).

However, non-seasonal effects of river runoff on sea level changes remain largely unexplored over the global ocean and across a wider range of time scales, mainly due to the lack of consolidated discharge databases (Durand et al., 2019). Furthermore, river forcing must be considered jointly with wind work and heat flux, as they constitute major contributors to the energy budget in some basins (Verri et al., 2018).”

Further discussion on this topic was added as follows:

- *Section 3.1.1: “Although use of climatological data is still commonly accepted, even when the estuarine dynamics is not resolved, more realistic and less subjective estimates of volume fluxes and salinity inputs would produce a more accurate representation of <u>coastal (e.g. river plumes) to basin-wide circulation and dynamics (e.g. dense water formation, overturning circulation cells, water exchange at straits) (Verri et al., 2018)</u>, especially during non-seasonal (e.g. storm induced) events (Chandanpurkar et al., 2022).”*
- *Section 4: “Global systems tend to opt for climatologies in comparison with regional or coastal systems that favour observed data when available, which allows to capture the non-seasonal events and their potential local or regional impacts.”*
- *Section 5: “Sotillo et al. (2021b) highlighted that service evolution roadmaps, such as the CMEMS guidelines, need to include a better characterization of the land boundary, especially of the coastal freshwater exchanges, to improve forecasts particularly under severe weather conditions. This includes real-time updated time series (past, present, forecasts) of river inputs for both major and minor or ephemeral streams as a progressive replacement of static climatologies.”*

- **Unstructured Modeling of the River-Sea Continuum:** This approach offers various advantages, including alleviating the challenges associated with prescribing river salinity because it can be set equal to zero at the head of an estuary solved by an unstructured grid. A dedicated section discussing this topic is warranted. Key references for this discussion include, in addition to the already mentioned Zhang et al 2016: Le Bars et al 2016, Maicu et al (2021), Bellafiore et al (2021), Vallaeys et al. (2018), Vallaeys et al. (2021), and Verri et al. (2023), Bonamano et al (2024), among many others.

Response: We agree that this topic warrants a dedicated section; however, it was chosen to include this discussion to Section 2.3 (Freshwater input in high resolution models) instead of a new section, and to modify the subtitle as "Freshwater input in high resolution models: unstructured modelling of the river-sea continuum", since this section already had some elements suggested by the reviewers. However, this paper is not meant to provide a review on unstructured modeling, but rather on river forcing methods. Therefore, our choice is to keep this discussion as brief as possible, while highlighting the necessary key points. This is also justified by the fact that a manuscript coauthored by two of the same authors as this paper was submitted in the same collection of papers in State of the Planet. This new manuscript addresses this topic in detail and is entitled "Solving Coastal Dynamics: Introduction to High Resolution Ocean Forecasting Services", by Staneva, J., Melet, A., Veitch, J. and Matte, P.

We added details on unstructured modeling that relate to river forcing, in new paragraphs as follows:

"The use of unstructured grids offers various advantages, including a more accurate treatment of the freshwater inputs from rivers, a realistic representation of river-sea interactions and estuarine processes at spatial and temporal scales usually not resolved in the ocean, and an improved interface between estuaries and the open ocean, sometimes with higher-order spatial discretizations (Staneva et al., 2024). The unstructured grid modelling combined with an efficient vertical coordinate system can better solve the coastal sea dynamics (Verri et al., 2023).

"With seamless grid transitions between models or domains, flexibility and cross-scale capabilities are augmented (Zhang et al., 2016). As examples, a river-coastal-ocean continuum model has been developed for the Tiber River delta, reproducing the coastal dynamic processes better than the classic coastal–ocean representation, including the salt wedge intrusion, and revealing new features near the river mouth induced by river discharge and coastal morphology (Bonamano et al., 2024). In the Columbia River estuary, where both shelf and estuarine circulations are coupled, a multi-scale model has proved to reproduce key processes driving the river plume dynamics in a region characterized by complex bathymetry and marked gradients in density and velocity (Vallaeys et al., 2018). Likewise, Vallaeys et al. (2021) used a similar model in a topographically challenging area of the Congo River estuary, characterized by high river discharge, strong stratification and large depth. Similarly, Maicu et al. (2021) simulated the circulation in the Goro Lagoon and Po River Delta branches using downscaling and a seamless chain of models integrating local forcings and dynamics into a coarser OOFS based on a cascading approach.

"While these examples were successful in representing dynamical processes across temporal and spatial scales, in some contexts, the large inward tidal extent and/or complex bathymetries and coastlines, often featuring coastal infrastructures, pose significant challenges for explicitly resolving estuaries, making it impractical in many coastal models. As a result, this approach has yet to become standard practice in OOFS."

- **Machine Learning Approaches to Estimate Riverine Release.** Key references to consider include studies that highlight successful machine learning applications in hydrology and oceanography. Regarding the salinity at river mouths some references are provided below:

- Fang, Y., wei Chen, X., Cheng, N.-S., 2017. Estuary salinity prediction using a coupled GA-SVM model: A case study of the Min River Estuary, China. Water Sci. Technol.: Water Supply 17, 52–60.
- Qiu, C., Wan, Y., 2013. Time series modeling and prediction of salinity in the Caloosahatchee River Estuary. Water Resour. Res. 49 (9), 5804–5816. http: //dx.doi.org/10.1002/wrcr.20415, arXiv:https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/wrcr.20415, URL: https://agupubs.onlinelibrary.wiley.com/doi/ abs/10.1002/wrcr.20415.
- Guillou, N., Chapalain, G., Petton, S., 2023. Predicting sea surface salinity in a tidal estuary with machine learning. Oceanologia 65 (2), 318–332. http://dx.doi.org/10. 1016/j.oceano.2022.07.007, URL: https://www.sciencedirect.com/science/article/ pii/S0078323422000835.
- Qi, S., He, M., Bai, Z., Ding, Z., Sandhu, P., Zhou, Y., Namadi, P., Tom, B., Hoang, R., Anderson, J., 2022b. Multi-location emulation of a processbased salinity model using machine learning. Water 14 (13), http://dx.doi.org/10.3390/w14132030, URL: https://www.mdpi.com/2073-4441/14/13/2030
- Saccotelli, L., Verri, G., De Lorenzis, A., Cherubini, C., Caccioppoli, R., Coppini, G., Maglietta, R., 2024. Enhancing estuary salinity prediction: a Machine Learning and Deep Learning based approach. Applied Computing and Geosciences
- Maglietta, R., Verri, G., Saccotelli, L., De Lorenzis, A., Cherubini, C. Caccioppoli, R., Dimauro, G., Pinardi, N., Coppini, G. (2024) Advancing Estuarine Box Modeling: a Novel Hybrid Machine Learning and Physics-Based Approach. Environmental Modelling and Software

Regarding the water level along estuaries:

- Sampurno, J., Vallaeys, V., Ardianto, R., and Hanert, E.: Integrated hydrodynamic and machine learning models for compound flooding prediction in a data-scarce estuarine delta, Nonlin. Processes Geophys., 29, 301–315, https://doi.org/10.5194/npg-29-301-2022, 2022.

Response: There is a vast literature on machine learning applications in hydrology and oceanography. Since our focus is on the treatment of rivers in OOFS, and indirectly on salinity, we added discussion and references, but limiting ourselves only to applications on this topic, as follows:

- *In Section 2.2 (Freshwater input in coarse resolution models), we added the following paragraph: "New hybrid approaches, such as the Hybrid-EBM (Maglietta et al., 2025; Saccotelli et al., 2024), combine physics-based models with machine learning techniques to predict the salt-wedge intrusion length and salinity at river mouths. Hybrid-EBM outperforms the classical EBM and addresses the shortcomings of the dimensional equations in the physics-based EBM, which rely on several tunable coefficients and require site-specific calibration, by substituting them with machine learning algorithms (Maglietta et al., 2025)."*
- *In Section 2.4 (One-way and two-way coupling): "Alternative approaches for assessing the risk of compound flooding have been proposed, including integrated hydrodynamic and machine learning methods to predict water level dynamics (Sampurno et al. 2022). Such*

approaches are particularly valuable in data-scarce regions, where developing fully calibrated, computationally intensive models can be impractical or infeasible."

- *We added a new section 3.1.5 (Machine learning-derived discharge estimates): "Modern data-driven techniques based on machine learning are becoming increasingly used in hydrology for rainfall-runoff modelling. In particular, Long Short-Term Memory (LSTM) neural networks (Greff et al., 2016; Hochreiter and Schmidhuber, 1997) are highly effective in capturing both periodic and chaotic patterns in time-series data while accurately learning long-term dependencies (Fang et al., 2017; Hu et al., 2019; Mouatadid et al., 2019). In numerous hydrological studies, LSTM has demonstrated superior performance over traditional process-based models in simulating runoff, primarily in data-rich regions (Feng et al., 2020, 2021; Frame et al., 2022; Gauch et al., 2021; Hunt et al., 2022; Konapala et al., 2020; Kratzert et al., 2019; Lees et al., 2021; Li et al., 2023; Luppichini et al., 2024; Nearing et al., 2021; Reichstein et al., 2019). However, limited efforts have explored the transferability of LSTM models to data-scarce regions (e.g. Akpoti et al., 2024), with Ma et al., (2021) and Muhebwa et al. (2024) (and references therein) being a few such exceptions. Recent global-scale implementations (Rasiva Koya and Roy, 2024; Tang et al., 2023; Yang et al. 2023; Zhao et al. 2021) highlight the potential of LSTM models to serve as a reliable tool for global river discharge estimations. However, extensive validation outside the training basins is still required to fully assess their applicability."*
- *In Section 3.2 (Salinity and temperature): "Alternatively, salinity predictions in estuaries and at river mouths have been successfully estimated using machine learning approaches. A few examples can be found in the recent literature: Qiu and Wan (2013) developed an autoregressive model relating salinity at a given time to past observations of salinity and physical drivers (freshwater inflow, rainfall, tidal elevation) in the Caloosahatchee River Estuary; Fang et al. (2017) used a genetic algorithm coupled with support vector machine to predict salinity in the Min River Estuary; Qi et al. (2022) applied four neural network models to emulate salinity simulations in the Sacramento-San Joaquin Delta from a process-based river, estuary and land modelling system; Guillou et al. (2023) were able to reproduce the seasonal and semi-diurnal variations of sea surface salinity at the mouth of the Elorn estuary (bay of Brest), with support vector regression performing best among all tested algorithms."*

- **Estimation of River Temperature and Its Minor Role:** The estimation of river temperature should be acknowledged in the context of riverine release even if it is not the primary factor influencing oceanographic processes

Response: In Section 3.2 (Salinity and Temperature), the following sentence was added: "Moreover, integrating salinity, temperature, and other parameters such as nutrients or sediments directly into river outflows could improve model performance (Verri et al., 2018). While these factors play a secondary role in influencing oceanographic processes, their inclusion could advance research on coastal hypoxia, carbon cycling, and regional weather and climate, ultimately supporting seamless predictions of land–ocean–atmosphere feedbacks in next-generation Earth system models (Feng et al. 2021)."

Minor comments:

Line 10: I'd mention also the subsurface water discharge

Response: We instead added in the second sentence of the abstract the following text (underlined): "They govern the hydrological and biogeochemical contributions to the coastal ocean through surface and subsurface water discharge and influence local circulation and the distribution of water masses, modulating processes such as upwelling and mixing."

Line 40: The first time the acronym OOFS is mentioned, it should be spelled out in full.

Response: Done.

Line 48-49: the prescribed salinity values at river mouths are typically based on constant annual/monthly values which are the result of sensitivity tests and/or in situ campaigns (*Verri, G., Pinardi, N., Oddo, P., Ciliberti, S. A., & Coppini, G., 2018. River runoff influences on the Central Mediterranean overturning circulation. Climate dynamics, 50(5-6), 1675-1703*)

Response: We thank the reviewer for this suggestion. This was added to the text as follows (changes are underlined): "However, although water properties at the head differ from those at the mouth, in models too coarse to resolve the estuaries, river discharge observed far from the river outlet is typically inputted at the coast with zero salinity (Verri et al., 2021; Herzfeld, 2015). Alternatively, salinity values can be prescribed based on constant annual or monthly values derived from sensitivity tests and/or in situ campaigns, when available (Verri et al., 2018)."

Line 75: Figure 1 caption. Which EBM does the caption refer to? Please include a reference to the model

Response: The reference was already included as a footnote. We also added this information in the caption: "Schematic diagram of the estuary box model (EBM) implemented in the Community Earth System Model (CESM) (Sun et al., 2017)."

Line 111-112: I believe here you should refer to Verri et al 2018 rather than Verri et al 2021. Sensitivity tests by Verri et al 2018 demonstrate that a more realistic estimates of riverine inputs would produce a more accurate representation of coastal (plume) to basin wide circulation and dynamics (dense water formation, overturing circulation cells, water exchange at the straits …)

Response: The change was made from Verri et al. (2021) to Verri et al. (2018). We also added more details as given by the reviewer, as follows: "more realistic and less subjective estimates of volume fluxes and salinity inputs would produce a more accurate representation of coastal (e.g. river plumes) to basin-wide circulation and dynamics (e.g. dense water formation, overturning circulation cells, water exchange at straits) (Verri et al., 2018)"

Line 192: "However, strong land-sea differences in microwave emissivity make satellite observations unreliable within some 70 km of the coast" I believe the water turbidity is the main limit to be mentioned here

Response: The article by Vazquez-Cuervo et al. (2018) describes land contamination as the primary factor for degraded quality in the satellite salinity products near the coast. In addition, Menezes (2020) showed *that there can be seasonal sensitivity in SMAP's skill, notably in the Bay of Bengal. This was also stressed by Grodsky et al. (2018) in an application in the Gulf of Maine, showing that SSS retrievals over cold coastal seas are subject to an SST-dependent bias due to microwave sensor sensitivity, on top of a land contamination bias.*

The sentence was modified as follows (changes are underlined): "However, seasonal variability in the skill of SSS retrievals can be associated with SST-dependent bias and strong land-sea differences in microwave emissivity, making satellite observations unreliable within some 70 km of the coast (Grodsky et al., 2018; Menezes, 2020; Vazquez-Cuervo et al., 2018)."

Menezes, V. v. (2020). Statistical assessment of sea-surface salinity from SMAP: Arabian sea, bay of Bengal and a promising red sea application. Remote Sensing, 12(3). https://doi.org/10.3390/rs12030447

Grodsky, S. A., Vandemark, D., & Feng, H. (2018). Assessing coastal SMAP surface salinity accuracy and its application to monitoring Gulf of Maine circulation dynamics. Remote Sensing, 10(8). https://doi.org/10.3390/rs10081232

Line 194-195: The satellite retrieved salinity close to the river mouth is a crucial challenge and more recent studies should be mentioned and briefly discussed *e.g. Medina et al 2020; Sakai et al 2021, Chen et al 2017*

Response: We thank the reviewer for the suggestions. The following additions were made to the text and references: "Higher resolution coastal satellite products have been demonstrated based on empirical relationships between local salinity and ocean color observations (Geiger et al, 2011; Chen et al., 2017), using deep neural networks trained on Sentinel-2 Level 1-C Top of Atmosphere (TOA) reflectance data (Medina-Lopez and Ureña-Fuentes, 2019; Medina-Lopez, 2020), or by relating the reflectance of the visible bands from Sentinel-2 imagery with electrical conductivity, influenced by the concentration and composition of dissolved salts (Sakai et al., 2021), although these are not applied globally"

Furthermore, we added the following paragraph: "A recent study in the German Bight (Thao et al., 2024) demonstrated the critical role of high-resolution salinity inputs at estuarine mouths in improving the predictive capabilities of coupled wave-ocean models. Using the GCOAST model system, which seamlessly integrates estuarine and coastal dynamics with regional ocean models, researchers validated salinity and temperature fields against in-situ observations. The results highlighted that estuarine inflows significantly enhance the accuracy of coastal ocean models."

Chen, S., & Hu, C. Estimating sea surface salinity in the northern Gulf of Mexico from satellite ocean color measurements. Remote Sensing of Environment, 201, 115–132. https://doi.org/https://doi.org/10.1016/j.rse.2017.09.004, 2017.

Medina-Lopez, E. Machine learning and the end of atmospheric corrections: A comparison between high-resolution sea surface salinity in coastal areas from top and bottom of atmosphere Sentinel-2 imagery. Remote Sensing, 12(18). https://doi.org/10.3390/RS12182924, 2020.

Medina-Lopez, E., & Ureña-Fuentes, L. High-resolution sea surface temperature and salinity in coastal areas worldwide from raw satellite data. Remote Sensing, 11(19). https://doi.org/10.3390/rs11192191, 2019.

Sakai, T., Omori, K., Oo, A. N., & Zaw, Y. N. Monitoring saline intrusion in the Ayeyarwady Delta, Myanmar, using data from the Sentinel-2 satellite mission. Paddy and Water Environment, 19(2), 283–294. https://doi.org/10.1007/s10333-020-00837-0, 2021.

Thao, N.T., Staneva, J., Grayek, S., Bonaduce, A., Hagemann, S., Nam, T.P., Kumar, R., & Rakovec, O. (2024): Impacts of extreme river discharge on coastal dynamics and environment: Insights from high-resolution modeling in the German Bight. Regional Studies in Marine Science, Vol 73, 103476, doi:10.1016/j.rsma.2024.103476

Section 3.1.2: a missing reference in the list is the recent database of climatological runoff for the Adriatic rivers provided by *Aragão, L., Mentaschi, L., Pinardi, N., Verri, G., Senatore, A., & Di Sabatino, S. (2024). The freshwater discharge into the Adriatic Sea revisited. Frontiers in Climate*

Response: We thank the reviewer for this suggestion. The following text was added to the list of regional databases in Section 3.1.2:

• A river discharge climatology and corresponding historical time series for all rivers flowing into the Adriatic Sea with an average climatological daily discharge exceeding 1 m^3s^{-1} (Aragão et al., 2024).

As well as this reference:

• Long-term (1993-2011) satellite-derived estimates of continental freshwater discharge into the Bay of Bengal (Papa et al., 2012).

Section 3.3 all the OOFS should be references through links to their web pages /publications

Response: Links to websites or publications were added for each OOFS.