RESPONSE TO REVIEWER #1'S COMMENTS

General comments

The authors provide an overview of the role of river forcing in ocean models, with an emphasis on current status of Operational Ocean Forecasting Systems (OOFS). This offers an accessible introduction and status update. providing a valuable reference to those working on OOFS and to a wider community for whom the inner-workings of OOFS will be less familiar. The review paper provides a fair reflection of the current state.

Response: We thank the Reviewer for this positive and constructive feedback on our manuscript. A detailed response to specific comments is provided below, using italic text in blue.

Specific comments

1. Paper title: Given the emphasis on OOFS, consider a more specific title e.g. "The Representation of Rivers in Operational Ocean Forecasting Systems". This better represents the paper content in my view. Consider also updating the Abstract to be clear on scope. or example in Line 13, the authors suggest that *"This paper provides an overview of recent advances in river modelling"* which might suggest a detailed review of hydrological process representation, whereas I think the paper rather more provides "an overview in recent approaches to representing coastal river discharges and processes in ocean models".

Response: We agree with the Reviewer. The title was modified to better reflect the paper content as suggested: "The Representation of Rivers in Operational Ocean Forecasting Systems: A Review". The abstract was also modified as suggested. The sentence now reads: "This paper provides an overview of recent approaches to representing coastal river discharges and processes in ocean models, with a particular focus on estuaries."

2. In general review of freshwater impacts on ocean prediction in opening paragraph, it would be worth including example references from Bay of Bengal, as an area with significant sensitivity to freshwater influence (e.g. Jana et al 2015 - https://doi.org/10.1016/j.csr.2015.05.001), and a body of literature on resulting influence of BoB freshwater and barrier layers effects on TC and broader monsoon development.

Response: We thank the reviewer for this suggestion. We added the following text in a new Section 2.1 (Capturing seasonal and non-seasonal river variability) rather than in the Introduction: "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)."

In the introduction, only minor additions were made, for example (underlined):
"At coarse scales that cannot resolve the estuarine dynamics, but even at finer scales in some cases, river outlets are often represented in a simplistic way, with climatological runoff and zero or constant salinity values, implicitly neglecting estuarine mixing and exchange as well as seasonal and non-seasonal variability (Sun et al., 2017; Verri et al., 2020; Verri et al., 2021)."

3. Paper structure:

- In describing paper contents on line 40, please sign-post later sections more precisely - i.e. "Section 2 reviews...." etc.

  Response: We agree. The structure of the paper is now described precisely in the last paragraph of the Introduction.

- I would recommend addition of a brief Section 4: Discussion & Conclusions section that highlights some recommendations for the community, and highlights gaps in capabilities and knowledge to address (see also comment below).

  Response: A new Section 5 (Summary and recommendations) was added, discussing current limitations in OOFS and providing recommendations on ways forward, as follows:

  "The description of the status of implementation of river forcing in OOFS revealed the complexity and limitations associated with appropriately treating riverine freshwater discharges into ocean models. Despite a growing demand for operational oceanographic products and services, especially in coastal areas (Ciliberti et al., 2023), OOFS still suffer from limitations with respect to (1) the representation of the physical processes and (2) data availability and quality. How river forcing inputs are defined or parameterized and how model components interact, often non-linearly, remain challenging questions, as they point to a lack in the definition of standard practices regarding river forcing. An enhanced representation of rivers in OOFS must go through improvements in model physics, appropriate spatial and temporal resolutions, and coupling between land, ocean and atmosphere. The difficulty in incorporating river flow also varies by geographic region, especially with respect to the availability and quality of river discharge, salinity and bathymetric datasets. It is further modulated as a function of model scale and resolution (whether one deals with a global, regional, or coastal model configuration).

  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. Recommendations towards standardized inputs of freshwater (and associated river inputs of nutrients and sediment loading), homogenized river forcing approaches, and a more integrated watershed-ocean strategy are being made (Campuzano et al., 2016; Capet et al., 2020; Sobrinho et al., 2021). Validated observational error estimates must also be a priority to ensure accurate estuary-mouth forcing (De Mey-Frémaux et al., 2019; Polton et al., 2023), for river discharge as well as auxiliary variables, such as coastal salinity. As such, improved interfaces between coastal monitoring and modelling systems are required. The FOCCUS project exemplifies efforts to address these challenges, particularly through its advancements in hydrological and estuarine modelling, dynamic freshwater inputs, and integration of AI-driven tools to enhance river discharge estimations and coastal system forecasts.

  This study underscores the complexity and importance of accurately representing riverine freshwater discharges in OOFS. The challenges lie not only in the variability of river forcing *methods but also in the diversity and quality of data sources available across different geographical and temporal scales. Advancing the representation of riverine processes requires improvements in model physics, resolution, and coupling strategies to better integrate the land-ocean continuum. As the demand for reliable coastal forecasts grows, the need for real-time, high-quality river discharge data becomes increasingly pressing. Standardized methodologies and enhanced integration of riverine parameters, including salinity, temperature, and other biogeochemical components, will support seamless coupling between watershed and ocean models. Such efforts are critical for improving predictions of coastal dynamics, particularly under extreme weather conditions, and for fostering a deeper understanding of their implications on global climate and ecosystem functioning."*

- Recommend to move the detailed Tables 1-4 into Appendix materials, but draw out any key themes/similarities/differences in the main manuscript as shorter (more digestible) Section 3.3.

  Response: We agree. Tables 1-4 were moved to a new Appendix A and section 3.3 was moved to a new Section 4 and expanded as follows:

  "Figure 3 provides a graphical summary of the 6 river forcing methods and 4 data sources used in the OOFS listed in Appendix A. In terms of river forcing methods, most systems specify vertical or lateral freshwater fluxes to account for riverine inputs. Only a few of them rely on more sophisticated approaches that use channel extensions within the ocean model or routing schemes from hydrological models to transport the water from the watershed to the coast. Furthermore, global systems inventoried in the survey do not use lateral boundary conditions, possibly due to a lack of spatial resolution near river mouths.

  In terms of the data sources used in OOFS, what stands out from the survey is the use of in situ data as a primary source in most systems, and climatology either as a primary or fallback source of freshwater discharge. 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. Data from hydrological models or reanalyses were only given as primary data sources in a few regional and inland systems.

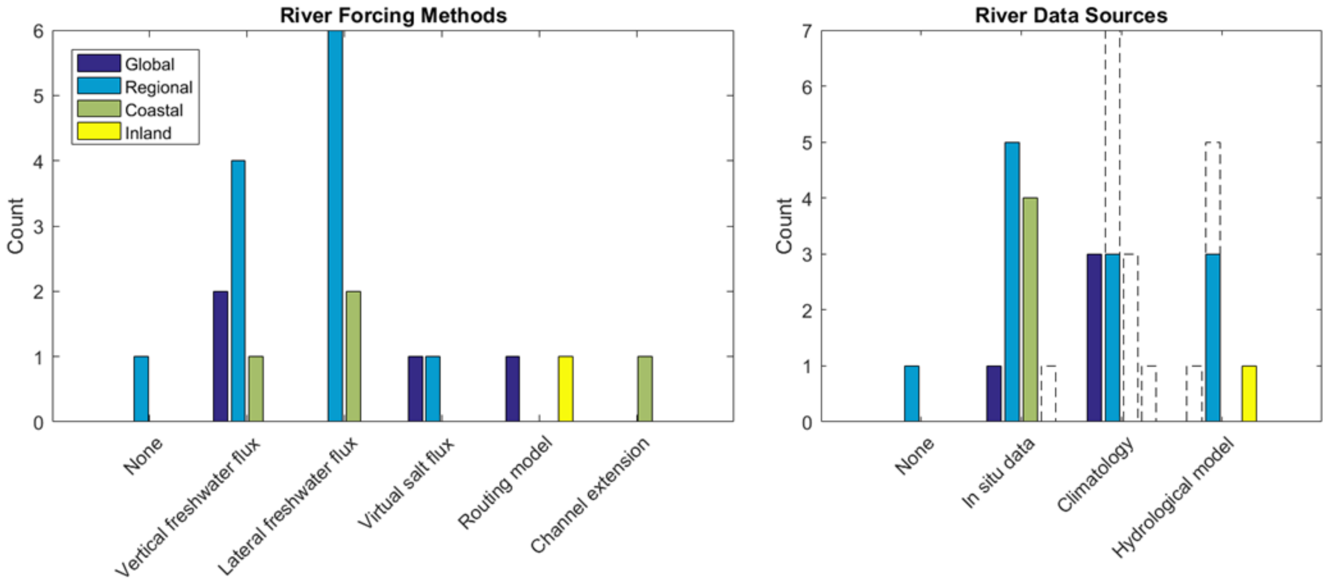

Figure 3: Graphical summary from a survey on river forcing methods (left panel) and data sources (right panel) used in global, regional, coastal and inland OOFS listed in Appendix A. Coloured bars indicate the primary data sources or methods, whereas dashed bars represent secondary data sources used as a fallback when primary sources are unavailable.

Additional considerations were also highlighted by the respondents, essential for appropriately representing river inflow in ocean models and addressing challenges such as numerical instabilities and data limitations. For example, spatial smoothing around the river source, or equivalently, optimizing the integration distance for equivalent coastal precipitation may be required to prevent numerical instabilities. Similarly, an increased diffusivity within the surface mixing layer can be implemented to simulate the effects of river inflow. Salinity and temperature of the input freshwater can either be set to zero and to the local SST, respectively, or derived from a combination of real-time gauge data and monthly averages when available. To account for ungauged areas, river gauge data can be scaled, or additional coastal runoff can be included. In contrast, some systems directly convert precipitation data into river discharges, disregarding hydrological processes and assuming an instantaneous response.

In sum, the representation of rivers in OOFS requires careful consideration of various numerical methods, data sources, and modelling approaches. However, certain choices or simplifications may pose limitations for applications demanding high accuracy in specific regions."

4. Recommendations and additional commentary

- While the paper compiles a list of various potential data sources and products, I am missing a particular narrative on relative strengths/weaknesses/limitations of the various approaches.

  Response: See response above and to next comment.

- This could partly be mitigated by slightly more expansion where relevant and available on reference discussions of data quality. As a specific, but not limited, example, GloFAS-ERA5 is highlighted as an operational discharge product in Section 3.1.3, but without discussion of its quality, or recommendation of its value for OOFS.

Response: Our objective in this paper is not to assess the quality or value of a given product or dataset, but rather to make an inventory of existing current approaches and available datasets. A detailed gap analysis and identification of ways forward will be the topic of a follow-up contribution. However, in this paper we document what are the preferred options adopted in many studies for inputting river discharge in OOFS. We also modified the manuscript as follows:

We added in Section 3.1.2 on River Databases: "Furthermore, a detailed comparative assessment of these various data sources is still lacking."

We added in Section 3.1.3 on Operational river discharge products: "The FOCCUS project (Forecasting and Observing the Open-to-Coastal Ocean for Copernicus Users, foccus-project.eu) further enhances operational hydrological models by addressing the land-ocean continuum through improved river runoff estimations and the development of advanced coupling between hydrological and coastal ocean models. FOCCUS builds on existing pan-European hydrological frameworks, such as E-HYPE and LISFLOOD, to provide dynamic freshwater inputs, including nutrient and inorganic matter transport. Additionally, the project integrates novel AI techniques to optimize estuarine modeling and freshwater forcing for coastal systems. These innovations directly contribute to refining CMEMS and supporting all European coastal services with more accurate and seamless coastal monitoring and forecasting capabilities.

In some instances, the regional products may appear to be the preferred option for some regional or local studies, as they were designed to specifically represent the hydrological characteristics of a given area, sometimes with higher resolution and accuracy. However, a global solution is attractive in data scarce areas and where consistency between discharge products and across all forcing variables is required over large domains (Polton et al., 2023)."

Finally, we included a new Section 5 (Summary and recommendations) where a summary of challenges and limitations is provided, followed by a few recommendations on ways forward.

- While Section 3.3 provides useful reference detail on OceanPredict community approaches, the authors could help synthesise the details from the Table to better reflect in qualitative discussion the various approaches - e.g. numbers using climatologies, river models etc.

  Response: The Section 4 (formerly Section 3.3) now includes a qualitative discussion and a new Figure 3 synthetizing results from the survey (also copied in a response above).

4. Authors might also consider referencing Polton et al 2022 (https://doi.org/10.5194/gmd-16-1481-2023) as additional example of practical guide on implementing freshwater OBC inputs to ocean models (see their Section 3.7).

Response: We thank the reviewer for this suggestion. Reference from Polton et al. (2023) was added. More specific details found in this review paper were also added, as follows:

- *In Section 2.2, we added: "Additional subtleties arise for large rivers or deltas, where the coastal source points need to be spread laterally to avoid numerical instabilities if inflow values are locally too large (Polton et al. 2023)."*
- *In section 3.1.2, we added a reference to the river database found in the CORE.v2 dataset (Large and Yeager, 2009): "A global freshwater budget is included in the CORE.v2 datasets that have an accompanying database for continental runoff from rivers, groundwater and icebergs, estimated from continental imbalances between precipitation, evaporation and storage, then distributed between bordering ocean basins based on river routing schemes and flow estimates (Large and Yeager, 2009)."*
- *In Section 3.1.3 we added: "In some instances, the regional products may appear to be the preferred option for some regional or local studies, as they were designed to specifically represent the hydrological characteristics of a given region, sometimes with higher resolution and accuracy. However, a global solution is attractive in data scarce areas and where consistency between discharge products and across all forcing variables is required over large domains (Polton et al., 2023)."*
- *In Section 5 we added a citation to Polton et al.: "Validated observational error estimates must also be a priority to ensure accurate estuary-mouth forcing (De Mey-Frémaux et al., 2019; Polton et al., 2023), for river discharge as well as auxiliary variables, such as coastal salinity."*