Author's response

We thank both referees for the time they dedicated to reviewing our manuscript and their valuable comments. Below is a point-by-point response to the referee comments with:

black text = reviewer comment
blue text = our response
red text = changes in manuscript

Anonymous referee #1

In their revised manuscript, Savelli et al. complement the description of their implementation of river fluxes in the ECCO-Darwin assimilation model with a more comprehensive description of the model itself, a more thorough regional analysis investigating both regional stoichiometries and coastal residence times, and an improved perspective on the global ocean impact of river fluxes for the ocean FCO2. They have also included a thorough discussion of important limitations still present in the model. The revised manuscript is well written, clear and I would now therefore recommend the article for publication.

Minor Comments:
L1 I would state «to the ocean » since the manuscript focuses on the ocean more than coastal regions?

We replaced "to coastal regions" with "to the ocean" on the first line of the Introduction.

L28 "and contribute to an estimated coastal-ocean carbon sink from 0.2 to 0.7 Pg C yr−1" . There is, to my knowledge, as of now no consensus whether lateral inputs lead to a sink or source in coastal regions, I would state "may contribute" or "influences the coastal ocean carbon sink".

We replaced "contribute" with "may contribute" on L32.

Anonymous referee #2

The authors have responded to all points raised in the first review round, and they have added clarifying text and figures. While these help to better understand their approach and its limitations, they confirm my assessment of this manuscript as a technical report describing an interim step towards a new version of the ECCO-Darwin model. The new version aims at a substantial improvement by consistently taking into account the effects of terrestrial runoff. This will be exciting material for a publication in GMD.

As the reviewer correctly states, the objective of this study is not to improve the existing calibrated version of ECCO-Darwin but to (1) carefully document a key new modeling building block and (2) evaluate its impact through a set of sensitivity experiments. A new, optimized ECCO-Darwin solution is ongoing work but is a much more ambitious and long-term objective than what we set out to do in this study. We revised the manuscript carefully to make the focused intent of this study clearer:

Abstract:
"Terrestrial sources of carbon and nutrients drive biogeochemical cycles in coastal regions and in the global ocean. Quantifying their impact on the spatiotemporal variability of the ocean carbon cycle is pivotal to understanding the distinctive characteristics of ocean basins dominated by riverine inflow. ECCO-Darwin is a data-constrained, global-ocean biogeochemistry model that has heretofore lacked lateral inputs of carbon and nutrients. The objective of this study is to add this new capability to ECCO-Darwin and to carry out a suite of sensitivity experiments in order to quantify the impact of these lateral fluxes on coastal- and open-ocean biogeochemistry. We generate riverine inputs by combining daily point-source freshwater discharge from JRA55-do with the Global NEWS 2 watershed model, accounting for lateral inputs from 5171 watersheds worldwide. The addition of riverine inputs drives a small CO_2 outgassing (+0.02 Pg C yr^{-1}) due to compensating processes at regional scales. In basins dominated by carbon runoff, such as the Tropical Atlantic and Arctic Oceans, the addition of riverine inputs increases CO_2 outgassing (+13 and +9%, respectively). In contrast, runoff in nutrient-dominated Southeast Asia leads to increased CO_2 uptake (+9%). This new riverine biogeochemical input capability will enable future ECCO-Darwin solutions to better capture key processes that occur along coastal margins in global oceans."

L40: "Here, we add the capability to represent lateral fluxes of carbon and nutrients in the ECCO-Darwin global-ocean biogeochemistry model and we examine the impact of these fluxes on the model's sea-air CO_2 flux and Net Primary Production (NPP)."

L49: "The sensitivity analysis described herein will allow for further understanding of the contribution of riverine inputs in future ECCO-Darwin solutions and ocean modeling studies that aim to represent processes occurring along coastal margins."

L351: "This study presents a set of sensitivity experiments that quantify the contribution of riverine inputs in the ocean sea-air CO_2 flux and NPP; this was made possible following necessary and consequential simplifications that we elaborate in the following section."

Conclusion and Perspectives:

"In this study, we added the capability to represent lateral fluxes of carbon and nutrients in the data-constrained ECCO-Darwin global-ocean biogeochemistry model and we carried out a suite of sensitivity experiments in order to quantify the impact of these lateral fluxes on coastal- and open-ocean biogeochemistry. Globally, the role of present-day riverine inputs in ECCO-Darwin

results in substantial, compensating regional responses in ocean carbon uptake and outgassing. In carbon-dominated margins, such as the Arctic and Tropical Atlantic Oceans, rivers drive a large source of CO_2 from the ocean to the atmosphere. In nutrient-dominated margins such as Southeast Asia, however, rivers drive a large ocean carbon uptake. While our experiments reveal clear regional responses, we identify limitations related to missing estuarine and benthic processing and incomplete equilibration over multi-decadal timescales in the Arctic Ocean. Our methodology combines Global NEWS 2 and JRA55-do to implement biogeochemical river discharge on top of point-source freshwater discharge, globally, and at a daily frequency. These fields can be used (and are already being used) for many regional-to-global ocean model applications. Documenting such methodology is essential, given the lack of accurate representation of land-to-ocean and coastal processes in global ocean and Earth System Models (ESMs). This work is part of an open-science/open-source initiative available for everyone on the ECCO-Darwin GitHub repository (https://github.com/MITgcm-contrib/ecco_darwin/tree/master). The quantification of the perturbation pertaining to the addition of terrestrial runoff in an ocean model over 20 years in the modern period is an interim, but significant step towards the development of new optimized ECCO-Darwin solutions that will integrate riverine inputs together with improved estuarine, sediment, and benthic parameterizations."

The current manuscript describes a technical interim step, namely results of a sensitivity study that shows that the degree of realism of the model mostly deteriorates when terrestrial runoff fluxes are added.

We removed the previous Figure 3 and accompanying discussion that pertained to model-data comparisons following the addition of riverine inputs to avoid any confusion related to the objective of this study, which is not to improve the current solution but to explore its sensitivity as a stepping stone towards a future, more-optimized solution.

This may to some extent be related to the use of a calibrated version of the ECCO-Darwin model that already implicitly accounts for the effects of terrestrial runoff. Explicitly adding terrestrial runoff to such a model presents some form of double counting and it may not be surprising that model results deteriorate. This will not happen in the final version when terrestrial runoff is included prior to the calibration.

Double-counting is indeed possible given that the previously optimized ECCO-Darwin solution did not include biogeochemical river discharge. We added the following sentence in the revised manuscript to qualify this:

L160: "Given that the previously optimized ECCO-Darwin solution did not include biogeochemical river discharge, the sensitivity experiments may contain some double-counting that will lead to deterioration of the model results relative to observed pCO_2 and sea-air CO_2 flux data products. Therefore, the analysis herein is restricted to examining the perturbation response rather than quantifying possible improvement or degradation of the simulation vs. observations."

The presentation is mostly clear and the new title correctly reflects the status of the manuscript. One awkward exception is the consistent use of ‘air-sea flux’ when meaning ‘sea-air flux’ in the text and at axis labels on some figures. The sign of the fluxes is thus opposite to what the wording pretends, making it difficult to read and difficult to understand.

We agree with the referee and have replaced “air-sea” with “sea-air” CO_2 flux wherever needed in the text, tables, and figures.

Also newly added are supplementary figures that show the limitations of the short duration of the model integration, which precludes a definite assessment of the results at least in some areas. Apart from this, I find the revised manuscript technically correct.

The absence of equilibration following the addition of riverine inputs in the Arctic Ocean over the model period is acknowledged in the following paragraph:

L251: “The 28-year model period (1992–2019) does not allow the system to fully equilibrate with the addition of riverine inputs. However, time series of change in air–sea CO_2 flux and NPP with the addition of river carbon and nutrients (Supporting Information Figures S2–S9) indicate that most regions approach quasi-equilibrium by the year 2000, consistent with the global response. In contrast, the change in air–sea CO_2 flux and NPP with the addition of river carbon and nutrients in the Arctic do not stabilize over the model period (Supporting Information Figures S3 and S7).”

We further mention this limitation in the discussion as follows:

L282: “We note that our multi-decadal estimates do not reach equilibrium in the Arctic Ocean following the addition of riverine inputs (Figures S2–S9) and do not have a realistic representation of blue carbon, bottom-sediment processes, and fine-resolution coastal ecosystems that drive the coastal-ocean sink and transformation of elements.”

We also mention this limitation in the conclusions as follows:

L394: “While our experiments reveal clear regional responses, we identify limitations related to missing estuarine and benthic processing and incomplete equilibration over multi-decadal timescales in the Arctic Ocean.”

My main concern is that I do not see why people outside the ECCO-Darwin world should read a report about an interim step.

Even if our audience were to be limited to existing ECCO users, this is not a small club. ECCO users form a large, vibrant, and diverse open-science/open-source community that has contributed to upwards of 2,000 publications in more than 200 journals and books since 1996 (https://ecco-group.org/publications.htm). Because of this large community adoption, it is critical

that every building block of this modeling framework be thoroughly described, evaluated, and documented. As one recent user adoption example, the ECCO-Darwin modeling framework was adapted (without our knowledge nor involvement) for mCDR MRV carbon credit work: https://www.carbontosea.org/2025/11/25/an-independent-mrv-review-of-the-first-oae-credits/ This community adoption should suffice to justify and motivate publication of this study. But beyond the ECCO community, we believe that the combined Global NEWS 2 and JRA55-do BGC river discharge product together with the contrasting regional responses of the sensitivity experiments and their connection to the nature of riverine inputs and upstream land use depicted in our manuscript could be of wider interest for the ocean modeling and Earth Science communities at large.

There are some technical aspects that some researchers currently working towards addition of terrestrial runoff may be interested in.

We agree with the referee and have added the following in the revised manuscript to emphasize this point:

L396: “Our methodology combines Global NEWS 2 and JRA55-do to implement biogeochemical river discharge on top of point-source freshwater discharge, globally, and at a daily frequency. These fields can be used (and are already being used) for many regional-to-global ocean model applications. Documenting such methodology is essential, given the lack of accurate representation of land-to-ocean and coastal processes in global ocean and Earth System Models (ESMs). This work is part of an open-science/open-source initiative available for everyone on the ECCO-Darwin GitHub repository (https://github.com/MITgcm-contrib/ecco_darwin/tree/master).”

But scientifically, I do not see a key message here and suggest that the manuscript become an appendix or supplementary material to the publication that will describe the fully consistent model. I look forward to seeing such a paper, which should be a major scientific achievement for which GMD would be a suitable outlet.

Indeed, a fully optimized global simulation that assimilates all available observations with the best possible numerical representation of physical and biogeochemical processes is our long-term goal. But this objective is way beyond the limited scope of the present study. Realistically, this is probably a ~10+ year objective for our group. There are many interim steps that are still needed and under active development, e.g., estuarine model, bottom sediment model, and improved representation and estimation methods for ocean ecology. We want to ensure that each one of these steps is properly developed, described, and evaluated before we put all these pieces together.

As the present study pertains to the development, description, and evaluation through model sensitivity experiments of a “lateral BGC flux module” within a global-ocean biogeochemistry model, we believe that it is a good fit for GMD’s call for studies that include (1) “development and technical papers, describing developments such as new parameterizations or technical

aspects of running models, such as the reproducibility of results” and (2) “model experiment descriptions, including experimental details and project protocols”.

Finally, we emphasize that based on your previous suggestions, we have significantly improved the manuscript. We have addressed every major and minor comment while explicitly acknowledging and describing the limited scope of our study. We would be grateful if these changes might lead you to reconsider your assessment and view the manuscript as a meaningful contribution suitable for publication in GMD.