Reply to Anonymous Referee #2

We are grateful for the comments and edits of the anonymous reviewer who invested time for the review of our manuscript. The reviewer's text is reported in Italic and our responses in roman.

Using a global ocean biogeochemical model, the authors assess the future impacts of changing riverine inputs while performing simulations with several scenarios of riverine inputs. In the paper, the authors show a slight reduction in root mean square error of primary production with respect to observations on the continental shelf and in parts of the ocean highly affected by rivers. They show that, overall, riverine nutrients may alleviate part of projected primary production decline. The topic is very relevant and potentially important for fully constraining the ocean carbon cycle. However, while the modelling work is very sound in its closed framework, I believe the author's review of literature seems to be lacking, which leads to, at times, questionable assumptions and too high confidence in a model setting not necessarily adequate for investing impacts of riverine tracers and their fate in the ocean. I do think the study should be published, but the authors should discuss the following points and, in my opinion, clearly point out uncertainties related to their framework in the abstract.

General Comments

It is debatable that the model configuration used here is actually adequate for the research question addressed in this paper. The model is limited in terms of resolution (~1 degree), and this is a strong constraint for representing fine-scale circulation features that are thought to be of particular importance in the coastal ocean. This is a topic that many studies have discussed previously, and these should be considered. Secondly, the model doesn't consider specific biogeochemical processes relevant to the coastal ocean. For instance, organic matter decomposition rates are shown to be much higher in the coastal sediment than in the open ocean (Ardnt et al., 2013), bed shear stress also re-suspend biogeochemical from the shelf seafloor. I think omitting both of these physical and biogeochemical limitations lead to the important underestimation of primary production on river-dominated continental shelves shown in this study, which seems to indicate the model is underrepresenting. This also affect exports of riverine biogeochemical compounds to the open ocean, and thus this has very important consequences for the main outcomes presented in this study. The authors do mention these limitations briefly in the limitations section, but this should be considered omni-present in attempts to interpretate the results, and at the least mentioned in the abstract.

Thank you very much for the comment. We are fully aware that in a coarse resolution model, not all physical and biogeochemical processes can be reproduced in detail and this has been already mentioned in the limitations section. However, we think that the study is useful nevertheless, in order to see the effect of an addition (or omission) of respective land-sea fluxes of chemical compounds within the coarse resolution (~1 degree) context. Especially since such models are still regularly employed in IPCC reports on projecting future ocean carbon cycle response to climate change. We will clarify that the goal of this study is not to simulate the distributions of geochemical tracers near the coast correctly, but rather to assess the large-scale impact of adding another layer of (relatively simplistic) continental margin-to-open ocean biogeochemical process. Further, to explore the best practical way of implementing the riverine inputs for modelling groups is also one of the aims of this work.

We plan to carry out two amendments, one in the abstract and one in the main text.

We will change the last sentence of the abstract to: “Simulations with high-resolution global or regional models with an adequate representation of shelf processes are required to accurately assess the impact of future riverine scenarios.”

At the end of the introduction, we will add at line 69: “Because of the coarse resolution of the model, a series of processes in the coastal zone cannot be represented in our study such as the high accumulation of organic sediment in shallow waters and respective remineralisation rates of previously deposited material (Ardnt et al., 2013; Regnier et al., 2013). These processes can only be presented in a model of much higher spatial resolution, which on the other hand cannot be integrated long enough to simulate the large scale water masses adequately and project long-term scale climatic change.”

A second, perhaps less central point, but still relevant to the study, is that the authors spin-up their model to present day fluxes, whereas these are actually more strongly perturbed over the historical time period (Beusen et al., 2016), than what is projected in terms of their future changes. Since time-scales of the ocean carbon cycle are notably long, this historical perturbation could have important legacy effects propagating into the future, potentially enhancing the primary production more than is estimated here. This should, in my opinion, also be discussed in the limitations section.

Thank you for the comment. In the revised manuscript, we will be more clear about using the recent-past riverine fluxes, i.e., constant fluxes at 1970’s level, to spin-up the model, rather than present day fluxes. Beusen et al. (2016) have shown in their Figure 3 that the nutrient fluxes did not vary much before 1970. However, using constant riverine fluxes rather than transient fluxes to spin-up the model can potentially have legacy effects on the results. We will discuss this in the limitations section.

Specific Comments:

Abstract

- *L16 “With four riverine configurations: deactivated, fixed at a contemporary level, coupled to simulated freshwater runoff, and following four plausible future scenarios.” Are only the nutrients (and if yes which ones) changing, or also carbon and alkalinity? This should be stated here.*

We will change it to “...with four riverine transport configurations for nutrients (nitrogen, phosphorus, silicon and iron), carbon and total alkalinity: deactivated, fixed at a contemporary level, coupled to simulated freshwater runoff, and following four plausible future scenarios.”

- *L17 “The inclusion of riverine nutrients and carbon…” Those numbers are valid for contemporary I guess?*

  We will change it to “The inclusion of riverine nutrients and carbon at 1970’s level improves the modelled contemporary spatial distribution relative to the observations…”

- *L20 “Riverine nutrient inputs alleviate nutrient limitation,…“ Should be reformulated, since riverine nutrient inputs are unlikely alleviated nutrient limitation in general, but reduce (?) it in some regions (?).*

  We will change it to “Riverine nutrient inputs lessen nutrient limitation under future warmer conditions as stratification increases, and thus lessen the projected future decline in PP…”. It is not feasible to put detailed regions in the abstract due to word limit, but we have explained the regions in detail in section 3.2.

  Introduction

- *In general, there are very little citations in the introduction, and often the same ones are used repeatedly. There are some recent modeling studies of implications of riverine inputs in the ocean that would be very relevant for this study. These should, in my opinion, be considered in the introduction:*

  Lacroix, F., Ilyina, T., Mathis, M., Laruelle, G. G., & Regnier, P. (2021). Historical increases in land-derived nutrient inputs may alleviate effects of a changing physical climate on the oceanic carbon cycle. Global Change Biology, 27, 5491– 5513. https://doi.org/10.1111/gcb.15822

  Liu, X., Stock, C. A., Dunne, J. P., Lee, M., Shevliakova, E., Malyshev, S., & Milly, P. C. D. (2021). Simulated global coastal ecosystem responses to a half-century increase in river nitrogen loads. Geophysical Research Letters, 48, e2021GL094367. https://doi.org/10.1029/2021GL094367

  I would furthermore suggest citing some regional-scale studies that investigate implications of riverine inputs on biogeochemistry of specific shelves, literature is abundant here. In addition, I would read and refer to the last 2-3 Global Carbon Budget studies for potential importance of riverine carbon fluxes for the ocean.

  Thank you very much for the suggestion and the references. We will include the above mentioned literature as well as some other ones (e.g. Tivig et al., 2021), and will also add more references on regional studies, e.g. Arctic (Siberia's river basin) and Amazon river estuary (Drake et al., 2021).

- *L25 “The large range of the riverine input across our four riverine 26 configurations does not transfer to a large uncertainty of the projected global PP and ocean C uptake…“ In terms of global PP, one could argue this could be due to the representation of continental shelf in the model, which leads to heavily underestimated continental shelf PP.*

We agree completely with the reviewer on this point and we will change this sentence to "Simulations with high-resolution global or regional models with an adequate representation of shelf processes are required to accurately assess the impact of future riverine scenarios."

We are fully aware of the underrepresented shelf process issue and the underestimated coastal PP in coarse-resolution models. We have discussed those issues in section 4.3 (Firstly, poorly represented physical shelf processes, as well as uncertainties in biogeochemical dynamic. For example, conversion of organic to inorganic carbon occurs rapidly via remineralization in estuaries before they are transported to the open ocean. Secondly, coarse-resolution models tend to underestimate primary production along the coast. Such well-known model issues may limit the impact induced by riverine inputs). We have pointed out in section 4.2 that "However, the scenario differences might be of importance in regional projections, such as in seas surrounded by highly populated nations and/or near river estuaries. Simulations with high-resolution global or regional models with an adequate representation of shelf processes are required to accurately assess the local impact of riverine inputs."

- *L35 "Although riverine carbon only plays a minor role in the global carbon cycle, …" Recent Global Carbon Budget publications disagree with this (Friedlingstein et al., 2021). If the higher estimates of outgassing of riverine carbon are true (up to 0.8 Pg C yr-1), they could potentially play a large role in explaining discrepancies between CO2 estimates arising observation-based products and model-based results.*

  We will change this sentence to "Despite our limited understanding on the riverine carbon fluxes, they could play an important role in closing the global carbon budget (Friedlingstein et al., 2021) and could be very sensitive to regional and global changes such as weathering, land cover and climate (Meybeck and Vörösmarty, 1999)."

- *L44 Maybe add the more recent Beusen et al. (2016) estimates to this for the historical time period?*

  We will add the following sentence in the revised version: "Beusen et al. (2016) estimated that river nutrient transport to the ocean increased from 19 to 37 Tg N yr^{-1} and from 2 to 4 Tg P yr^{-1} over the 20th century, taking into account of both increased nutrient input to rivers and intensified retention/removal of nutrients in freshwater systems."

Methods

- *L118 "The riverine influx includes carbon, nitrogen and phosphorus, each in dissolved inorganic, dissolved organic, and particulate forms, as well as alkalinity (ALK), dissolved silicon and iron (Fe)." Are there specific ocean variables for terrestrial dissolved and particulate organic matter? If not how does not model deal with organic P-N-C ratios that differ from those of the Redfield ratio? This is an important point to clarify because high C-to-nutrient ratios are thought to be largely responsible for ocean outgassing.*

In the model there is one dissolved organic pool (DOC) and one particulate organic pool (DET, detritus). First, we calculate the riverine organic P-N-C ratios for both dissolved and particulate forms, then add the least abundant species (scaled by the open ocean Redfield ratio) to the DOC and DET pools, respectively. The excess budget from the remaining two species both in dissolved and in particulate forms are assumed to be directly remineralized into inorganic form and added to the corresponding dissolved inorganic pools (i.e., PO4, NO3, and DIC) in the ocean. We will elaborate on this, based on the text in line 137-140, in the revised version.

- *L140 "Any remaining riverine organic matter is then added to its inorganic pool" This is not really clear. Is excess organic carbon is added to the DIC pool? If not I think this might be the reason why river inputs cause a net sink in the model, and not source as is relatively well acknowledged (see e.g., Global Carbon Budget, 2021). Also keep in mind that organic carbon mineralization has a small effect on alkalinity (which I don't think would have a huge impact here).*

  Please see the response to the last point. Excess DOC is indeed added to the DIC pool, but yet the riverine fluxes in the model lead to a net C sink, which might be potentially due to the overestimation of the organic-to-inorganic conversion of excess nutrients.

  Also, maybe more important here: are you assuming the large particulate fluxes (particulate P and N) from NEWS2 are organic? Because from my understanding, these can be inorganic (for P bedrock erosion, occluded etc..), and this would not at all be bio-available in the coastal ocean.

  Although the Global NEWS2 data provide the total particulate N and P rather than differentiated inorganic and organic particulate forms, particulate N occurs largely as organic matter while particulate P is typically dominated by inorganic forms (Mayorga et al., 2010). The reviewer is completely correct in stating that particulate P is mostly inorganic and not directly bio-available. Thus, adding the remaining particulate P (after calculating the least abundant species according to the Redfield ratio) into dissolved inorganic P pool may lead to bias in the enhanced primary production. Along the same line, adding the remaining riverine dissolved organic matter into the corresponding dissolved inorganic pool may also partly lead to bias in the enhanced primary production. Therefore, we have calculated the upper range of the impact of the directly remineralized dissolved organic and particulate matter on the enhanced primary production, by comparing with the corresponding riverine dissolved nutrients [X/(X+DIXriv)*100%] (X is the directly remineralized dissolved organic and particulate matter). Assuming that all coastal regions are nutrient limited, this direct remineralization is responsible for approximately 33.3-80.5% of the enhanced primary production.

  We will add a paragraph in the discussion on this point in the revised version.

- *L156 "REF: Reference run. Riverine nutrient and carbon supply is deactivated." Are there other sources of nutrients and carbon in the model? If riverine nutrients and carbon were the only inputs to the ocean model and their sediment loss is non-zero, I would expect all related variables to thrive to zero, which does not make a very* *interesting reference run. In the case there are other inputs, they should be given in numbers and explained.*

The only external inputs of nutrients are from aerial dust (iron) deposition and nitrogen fixation.

The REF simulates primary production and ocean CO_2 uptake evolution under climate change, without riverine input. It is interesting to see that the effect of riverine inputs on primary production is different between the historical and future time period (due to a different nutrient depletion level). This assessment is only possible to make by subtracting the climate effect on primary production in REF.

- *L179-L185 In my opinion the authors don't need to specifically defend themselves on this particular point, at least not to this extent. I would consider shortening or removing.*

  We prefer to keep it unshortened, but will separate it from the other content of the section. Following the suggestion of the other reviewer to add more information on the statistical significance of our results, we plan to add a new sub-section on statistical robustness, where we will include this part and additional signal-to-noise assessment that measures the riverine impact against the magnitude of simulated inter-annual ocean biogeochemistry variability. For more details, please see our response to the other reviewer's comments on the significance of the results.

Results

- *L198 "Although the total PP in FIX is still considerably lower than the satellite-based estimates, the inclusion of riverine nutrients and carbon does slightly improve the distribution of PP especially on continental margins (Figure 3), according to our area-weighted root mean square error (RMSE) analysis. „*

  Figure 3 really shows that a large part of the underestimation of PP is originating from the continental shelf, in particular regions of riverine inputs. The improvement is minor compared to the actual bias. In my opinion, this actually shows that the model underestimates the impacts of rivers on PP, which does have a strong implication for the conclusions of this paper, and should be assessed somehow.

  We agree with the reviewer that the riverine nutrient input (at 1970's level) does not significantly improve the simulated contemporary primary production along the continental shelf. The reasons could be:

  1) The underestimation of primary production on continental margins due to coarse model resolution and unresolved shelf processes is larger than the impact of riverine nutrient input. Therefore, it could not be compensated.

  2) The time period of contemporary primary production that we look into is 2003-2012, but the riverine nutrient input in the model is at 1970's level. Beusen et al. (2016) have shown that the riverine nitrogen and phosphorus has increased by ~40.0% and 28.6% from 1970 to 2000. Therefore, the riverine impact might be higher.

We will add this into discussion.

Figure 4: It's a bit concerning to me that considering riverine inputs lead to a sink of carbon in the ocean. It is relatively well acknowledged that river inputs are thought to cause a source of carbon (e.g., Regnier et al., 2013; Resplandy et al., 2018). The reason for this is that carbon to nutrient ratio of the (bio-available) terrestrial inputs is larger than the Redfield ratio. I guess the fact that most particulate P and N is thrown in as dissolved inorganic species might be the explanation for this. How is the alkalinity to DIC ratio of riverine inputs constrained? Either way, either explain the reason for this or I would consider not discussing the CO2 flux for the "unperturbed" river simulation.

Firstly, the riverine DIC to alkalinity ratio that we have applied is 1:1.

Our model shows the ocean as a weak carbon sink when including riverine, which can be partly due to our assumption that the excess dissolved organic and particulate matter immediately becomes remineralized bioavailable inorganic nutrients from rivers. This is because we have only one dissolved organic pool (DOC) and one particulate organic pool (DET) in the model, and the Redfield ratio needs to be kept. We have assessed the impact of this approach on our results (please see the response to the comments in the Method section).

Borges and Frankignoulle (2005) stated that "marginal seas act as a strong sink of CO_2 of about −0.45 Pg C yr^{-1}. This sink could be almost fully compensated by the emission of CO_2 from the ensemble of near-shore coastal ecosystems of about 0.40 Pg C yr^{-1}. Although this value is subject to large uncertainty, it stresses the importance of the diversity of ecosystems, in particular near-shore systems, when integrating CO2 fluxes at global scale in the coastal ocean." Chen and Borges (2009) demonstrated that " the available data of pCO2 measurements in about 60 continental shelves of the world allows the conclusion that continental shelves are indeed sinks for atmospheric carbon….The concept of marginal seas as sinks and near-shore coastal ecosystems as sources of atmospheric CO2 allows reconciling diverging views on carbon cycling in the coastal ocean. The fact that the inputs of terrestrial/riverine organic carbon would be in excess of carbon burial in marine sediments does not necessarily imply a net heterotrophy of marginal seas that is in contradiction with the high offshore export rates of POC and DOC consistently reported across continental margins. …Hence, inner estuaries and near-shore ecosystems are effective filters for terrestrial/riverine organic inputs and impose a by-pass of carbon towards the atmosphere for the global carbon cycle."

In our model, the shelf processes are not well represented due to model resolution. However, the processes that the riverine input of nutrients and carbon causes CO2 outgassing near coastal regions and CO2 ingassing on continental shelves lead to an globally integrated overall net weak carbon sink in the continental margins in the model. Simulations with high-resolution global or regional models with a good representation of shelf processes are required to accurately assess impact of riverine inputs on carbon cycling in the coastal ocean.

We will summarise this into a paragraph and add it to discussion.

- *L305 "Our experiments show that riverine nutrient inputs have a dominant role over the organic matter inputs in FIX, enhancing CO2 uptake along continental margins via sustaining PP in both historical and future time periods." This is however purely a consequence of the ratio of (bio-available) nutrients to organic matter that is added to the ocean, which as mentioned, I don't think is completely correct from a process-based perspective. In fact, I think most river-dominated shelves show C outgassing, see regional CO2 fluxes from Chen and Borges (2009) or regional-based studies.*

  Please see the response to the last comment.

- *L337 "…do not transfer to large uncertainties in future global marine biogeochemistry projections in NorESM." Yes, but if you would have taken uncertainties related to the coastal ocean into account, through e.g. sensitivity analysis of sediment degradation, I wonder if the conclusions would be different here, I would assume so.*

  We will change the sentence to "A large range of the riverine inputs in GNS, e.g., temporal changes in DIN fluxes across scenarios ranging 24.8-63.0% of the annual flux in FIX, do not transfer to large uncertainties in future projections of global marine primary production in our model, which can be primarily attributed to unresolved shelf processes due to coarse model resolution."

  Minor edits

- *L22 "and thus lessen the projected future decline in PP by up to 0.6 PgC yr-1 22 (27.3%) globally depending on the riverine configuration." -> , globally,*

  We will change it accordingly.

- *L55 "Taking the advantage of the latest improvement of global" Remove "the".*

  We will change it accordingly.

- *L171 "By comparing FIX versus REF…" Add comma here.*

  We will change it accordingly.

- *L332 ". Therefore, it is worth exploring the merits of using GNS in future projections of marine biogeochemistry." Not really sure what is meant here.*

  This sentence was to express that using future scenarios of transient riverine fluxes can be explored by future modelling studies on projection of marine biogeochemistry, especially on high-resolution regional scales. We will remove this sentence in the revised version, since it has been explained at the end of this paragraph (Line 338-340).

Reference

Arndt S., B.B. Jørgensen, D.E. LaRowe, J.J. Middelburg, R.D. Pancost, P. Regnier,Quantifying the degradation of organic matter in marine sediments: A review and synthesis,Earth-Science Reviews, Volume 123, 2013, Pages 53-86, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2013.02.008.

Beusen, A. H. W., Bouwman, A. F., Van Beek, L. P. H., Mogollón, J. M., and Middelburg, J. J.: Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum, Biogeosciences, 13, 2441–2451, https://doi.org/10.5194/bg-13-2441-2016, 2016.

Borges, A. V., Delille, B., and Frankignoulle, M.: Budgeting sinks and sources of CO2 in the coastal ocean: Diversity of ecosystems counts, Geophysical Research Letters, 32, https://doi.org/10.1029/2005GL023053, 2005.

Chen C.-T. A., Borges A.V., Reconciling opposing views on carbon cycling in the coastal ocean: Continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO2, Deep Sea Research Part II: Topical Studies in Oceanography, Volume 56, Issues 8–10, 2009, Pages 578-590, https://doi.org/10.1016/j.dsr2.2009.01.001.

Drake, T. W., Hemingway, J. D., Kurek, M. R., Peucker-Ehrenbrink, B., Brown, K. A., Holmes, R. M., Galy, V., Moura, J. M. S., Mitsuya, M., Wassenaar, L. I., Six, J., and Spencer, R. G. M.: The Pulse of the Amazon: Fluxes of Dissolved Organic Carbon, Nutrients, and Ions From the World's Largest River, Global Biogeochemical Cycles, 35, e2020GB006895, https://doi.org/10.1029/2020GB006895, 2021.

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C. E., Hauck, J., Le Quéré, C., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., Bates, N. R., Becker, M., Bellouin, N., Bopp, L., Chau, T. T. T., Chevallier, F., Chini, L. P., Cronin, M., Currie, K. I., Decharme, B., Djeutchouang, L., Dou, X., Evans, W., Feely, R. A., Feng, L., Gasser, T., Gilfillan, D., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, Ö., Harris, I., Houghton, R. A., Hurtt, G. C., Iida, Y., Ilyina, T., Luijkx, I. T., Jain, A. K., Jones, S. D., Kato, E., Kennedy, D., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Körtzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lienert, S., Liu, J., Marland, G., McGuire, P. C., Melton, J. R., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S. I., Niwa, Y., Ono, T., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rödenbeck, C., Rosan, T. M., Schwinger, J., Schwingshackl, C., Séférian, R., Sutton, A. J., Sweeney, C., Tanhua, T., Tans, P. P., Tian, H., Tilbrook, B., Tubiello, F., van der Werf, G., Vuichard, N., Wada, C., Wanninkhof, R., Watson, A., Willis, D., Wiltshire, A. J., Yuan, W., Yue, C., Yue, X., Zaehle, S., and Zeng, J.: Global Carbon Budget 2021, Earth Syst. Sci. Data Discuss., 2021, 1-191, 10.5194/essd-2021-386, 2021.

Mayorga, E., Seitzinger, S. P., Harrison, J. A., Dumont, E., Beusen, A. H. W., Bouwman, A. F., Fekete, B. M., Kroeze, C., and Van Drecht, G.: Global Nutrient

Export from WaterSheds 2 (NEWS 2): Model development and implementation, Environmental Modelling & Software, 25, 837-853, https://doi.org/10.1016/j.envsoft.2010.01.007, 2010.

Meybeck, M. and Vörösmarty, C.: Global transfer of carbon by rivers, Global Change Newsletter, 37, 18-19, 1999.

Regnier, P., P. Friedlingstein, P. Ciais, F.T. Mackenzie, N. Gruber, I.A. Janssens, G.G. Laruelle, R. Lauerwald, S. Luyssaert, A.J. Andersson, S. Arndt, C. Arnosti, A.V. Borges, A.W. Dale, A. Gallego-Sala, Y. Goddéris, N. Goossens, J. Hartmann, C. Heinze, T. Ilyina18, F. Joos, D.E. LaRowe, J. Leifeld, F.J. R. Meysman, G. Munhoven, P. A. Raymond, R. Spahni, P. Suntharalingam, and M. Thullner, 2013, Anthropogenic perturbation of the carbon fluxes from land to ocean, *Nature Geoscience*, 6(8), 597-607. DOI: 10.1038/NGEO1830

Tivig, M., Keller, D. P., and Oschlies, A.: Riverine nitrogen supply to the global ocean and its limited impact on global marine primary production: a feedback study using an Earth system model, Biogeosciences, 18, 5327-5350, 10.5194/bg-18-5327-2021, 2021.