In their manuscript, Planchat et al. investigate the pre-industrial CO_2 outgassing in the ocean, with a particular focus on constraints from processes that affect the ocean alkalinity budget. They thereby combine a theoretical model, which budgets alkalinity from riverine source and burial sink and also accounts for a potential drift, model simulations, including a great number of sensitivity simulations, as well as a practical framework which aims to reconcile the sensitivity simulations with current river input and burial estimates. The authors have obviously put a great amount of thought and effort into the development of these tools and simulations, and the work generally seems seems and robust from a technical stand point. However, the limitations of the model and framework (and I assume there are many), are not transparently discussed. The paper is also extremely hard to follow in its current presentation, and would not be well suited for general BG readers (and arguably even experts on the topic), in its current form. I therefore recommend major revisions, which however mostly involve streamlining and improvements in the explanations (especially regarding methodology). I would also recommend potentially re-thinking the amount of frameworks and results the authors wish to present. I made some suggestions and comments, which I hope can help improve the paper.

Major Comments

- The paper and especially individual sections need a better structure and streamlining. The paper is covering a large amount of novel material: a new-ish theoretical and a new practical framework, almost uncountable amounts of sensitivity experiments, GCB results, CMIP7 results, a literature review, and then new theories in addition popping up in the results section.It would be important that the methods and results are presented in a way that the general reader can somewhat follow and understand. For individual sections, it's often not really clear what the main message of the section is (often multiple complex and only sparsely explained points, also often unconnected results). Sensitivity experiments are introduced in the results section without having been properly explained. I also believe certain aspects could be simplified (maybe inspired at how previous studies explain the alkalinity/carbon ocean budget, interhemispheric transport), but would leave it up to the authors to decide.

- I think it would be very helpful for the general reader if the paper were to introduce the "geologically-known" balance of carbonate alkalinity from river inputs to burial in the ocean (see e.g. Hartmann et al., 2013), I guess early in the methods section:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

  With the left-hand side the river transports, and the right the exports from the ocean. This is essential to understand and might make it easier to follow the equations described in section 2.1. I think this is in essence what is meant throughout the paper when referring to a "simple budget" in the results section, although it wasn't 100% clear how this differs to the theoretical framework explained in the methods. The equations (atleast to me) explain in a simpler way (atleast for me) the difference of balance of alkalinity:carbon from the river inputs and burial, and also explains why e.g. CO2 outgassing increases with CaCO3 burial (to me these explanations in the results section will be hard to follow for a general reader).

- The methods section is lacking a general overview on the strategy, which I think is needed due to the numerous frameworks/simulations and complexity of the topic. I would clearly explain from the start why there is the need to develop a a theoretical framework, then run simulations with sensitivity experiments, then another practical framework (and to which purposes the different frameworks are needed)? Why not just improve the model to perform better?

- In the methodology and even after reading the whole text, it is not really clear what the exact purposes of the individual sensitivity experiments needed. I understand they are needed for the practical framework, but why these specifically ones, would the results be different actually if you had chosen other sensitivity experiments / left out some? The results from the sensitivity experiments are brought up every now and then in the paper, but the general thinking behind these experiments, and clear explanations and reasonings behind the simulations would help a lot from the methods section.

- Regarding the strong focus of the paper on Global Carbon Budget numbers and history (and a call for potential revision?): I am not sure improving the observations to model discrepency of the Global Carbon Budget should really be a central evaluation metric for the results. There are now a few other major issues that have been identified that could explain (a large part?) of the bias between observational and model products (model biases: Terhaar et al., 2022 observation biases: Landschützer et al. 2023). In the abstract it seems like the authors are strongly calling for a revision of GCB estimates based on their numbers, but in the main text and especially in the conclusion, the authors don't seem quite as confident in these mean numbers, highlighting large uncertainties. Personally, the study does an excellent job at highlighting uncertainties in current knowledge and estimates, but the limitations in terms of the model used and the observational basis for burial/rivers are the same/similar as of previous work. I think would probably make more sense to try to motivate for better models and observations for reducing these uncertainties.

- Limitations: The limitations from the both simulations and practical should be made more transparent. For instance, the model likely very poorly represents the processes in the coastal ocean ($CaCO_3$ production there?) and its transport to the open ocean, doesn't represent terrestrial organic matter etc. . I think the practical framework doesn't distinguish between more realistic sensitivity simulation assumptions, but only aims to reduce the bias to the observations, for me this seems kind of an important caveat (so might be getting things "right-er" for wrong reasons).

- Regarding the impacts of an alkalinity imbalance: The paper really lays a large focus on the potential impacts of an alkalinity imbalance, and largely motivates a major part of the frameworks introduced. But if I understand correctly, this imbalance is only a possibility and its even uncertain in which direction this imbalance would be?

- Regarding the spatial variability of the preindustrial outgassing: The authors acknowledge that the fate of terrestrial organic matter plays a major role in explaining spatial patterns of river-induced outgassing in the ocean. However, since this paper doesn't really investigate constraints or uncertainties regarding the fate of terrestrial organic carbon in the ocean I wouldn't really be particularly confident in the spatial distribution derived from the framework presented here. While this seems to reduce biases in the Southern Ocean between model and observational means, I would argue this is a region that is both one of lacking observational data, and complex region for models to simulate. Recent estimates of OM lability generally seem to suggest rapid degradation, even already in the coastal ocean, which would go against significant transport to and outgassing in the Southern Ocean (Aarnos et al., 2019; Lacroix et al., 2021; Powley et al., 2024).

Specific Comments

Abstract

L1 "The disparities in estimates of the ocean carbon sink, whether derived from observations or models…"

Did the authors not mean: "The disparities in the estimates of the ocean carbon sink between observations and models ..

"raise questions about our ability to accurately assess its magnitude and trend over recent decades. "

For me this is too strong of a statement.

L17 "Addressing the current inconsistencies between the combined carbon and alkalinity budgets.." What these inconsistencies are hasn't been mentioned yet, so I would tend to leave this out here (or briefly explain what is meant beforehand).

L19 "… and intermodel comparisons are required to constrain its regional distribution." I would argue that improving the models regarding the fate of terrestrial carbon in the ocean would also be needed (maybe even as a more urgent priority).

Introduction

L21-L26 As mentioned, I'm not sure I would make the discrepency between observations and model estimates the central motivation here, since many other factors have been put forward recently that may also explain the difference.

L40 "The spatial distribution of this riverine/burial-driven air-sea carbon flux is also highly uncertain and depends on the assumptions and methods used for its assessment (see Table B2). "

I would expand on which important assumptions are referred to here.

L41 “The historical value..”

This term is kind of confusing here, historical=pre-industrial ?

L48 “These disparities have emerged and disappeared without apparent reason..“

L49-L54 I believe these strategic changes were made using the best and most recent science (and not with the primary goal of reducing the discrepency). I don’t think this qualifies as “without apparent reason”.

L57-L60 I would maybe add information whether the CMIP6 models even consider riverine fluxes. I would guess not, and in a probably very simplified manner.

Methods

2.1 -> I guess this section describes the theoretical framework mentioned previously? I would make this more clear (not really sure overview and definitions is really a fitting subtitle).

L140 “this conceptual tool only permits estimates of a potential air-sea carbon flux resulting from a local/regional carbon:Alk imbalance”

Please clarify what is meant by “potential air-sea carbon flux”.

L142-143 “There is indeed no guarantee of its local/regional applicability due to the transport of the induced carbon:Alk local/regional imbalance. “

Could you maybe explain its applicability then, or how exactly you are dealing with this uncertainty?

L208 “The inorganic fraction is supposed to be in the form of bicarbonate ions and thus affects both DIC and Alk in a similar manner. “

Is it supposed to be or is it added as such?

L210 This simulation also includes the burial of OM and $CaCO_3$ produced by pelagic organisms, which is exported to the ocean interior and only partially remineralized or dissolved in the water column and at the seafloor.

Since this paper focusses on alkalinity fluxes and its burial, I would recommend giving a brief overview of how these processes affect the alkalinity balance (and especially how the burial is parametrized).

L231-244 The sensitivity experiments are described here, but it is not really clear why they are (individually) needed.

L248 “For instance, the gap in the $CaCO_3$ burial (0.24 versus 0.35 PgC yr^{-1}) would drive a 0.22 PgC yr^{-1} difference in the Alk budget. “

Isn't this a difference in the carbon budget? (0.22 Pg ***C*** yr-1)

Figure 4: "The negative impact of OM burial on Alk is attributed to the release of ammonium when OM is remineralized at the seafloor rather than buried."

I am not sure this information belongs in the caption, but in the text.

L302 "This residual component is attributed to a residual carbon budget imbalance due to internal ocean processes."

I guess this would be a model drift?

L309 "Role of sediment burial fluxes"

This section was really tough to read and understand, it has a lot of unconnected (complex and not really explained) information put together, it is really unclear in terms of streamlining -> maybe try to revise?

L310 "At global scale, the riverine carbon flux in the standard simulation (+0.52 PgC yr^{-1}) is insufficient to fully account for the air-sea carbon outgassing (0.27 PgC yr^{-1}) alone (Fig. 4d and 5a). "

I think most readers will not understand what is meant here (actually I am also not sure), since 0.52 PgC yr-1 is larger than 0.27 PgC yr-1.

L315 "Increasing the river input by a factor of 1.5 (riv1p5)"

Increasing all species of carbon? Wasn't clear to me from the methods, and would be quite important to know to understand the increase in carbon outgassing?

L324 "This underscores the significance of considering $CaCO_3$ burial when constructing the ocean carbon budget, especially when evaluating the net air-sea carbon flux. "

Yes but I would argue understanding the fate of terrestrial OM and its burial is equally important, in terms of magnitudes atleast?

L325 "The total carbon outgassing obtained from a simple carbon budget only holds however for our simulations in which the global Alk inventory is in equilibrium"

I think you should explain which of these fluxes above are the simple carbon budget? To me they seem coming from the simulation.

L334 Why are the regional burial fluxes actually discussed in the "imbalanced" alkalinity section? Is it not possible that these large regional burial fluxes are actually in quasi-equilibrium with the river fluxes? If you are removing alkalinity in these places artificially, would you not have less alkalinity burial in other places as a result in the model?

L373 "Part of this discrepancy arises because atmospheric carbon uptake by continental shelves (0.10 PgC yr^{-1} Regnier et al., 2022) is fully integrated into our net pre- industrial

riverine/burial-driven air-sea carbon flux as we also consider OM and $CaCO_3$ burial in these regions, reducing this flux by 0.10 PgC yr^{-1}."

The OM and CaCO3 burial on continental shelves will likely not be well resolved at the applied model resolution (+ not taking into account coastal specific processes such as benthic CO3 producers etc.).

L426-L440 This section was really heavy and hard to understand.

L485 "Additionally, a better understanding of the intrinsic properties of these external fluxes is needed, such as whether the organic carbon brought by rivers is refractory or not (Aumont et al., 2001; Jacobson et al., 2007; Gruber et al., 2009)."

Improving the understanding on the fate of the terrestrial organic carbon is probably equally important. I don't think its impacts are resolved by degrading the organic matter at the river mouths as in such models.

References:

Aarnos, H., Gélinas, Y., Kasurinen, V., Gu, Y., Puupponen, V.-M., & Vähätalo, A. V. (2018). Photochemical mineralization of terrigenous DOC to dissolved inorganic carbon in ocean. Global Biogeochemical Cycles, 32, 250–266. https://doi.org/10.1002/2017GB005698

Hartmann, J., A. J. West, P. Renforth, P. Köhler, C. L. De La Rocha, D. A. Wolf-Gladrow, H. H. Dürr, and J. Scheffran (2013), Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification, Rev. Geophys., 51, 113–149, doi:10.1002/rog.20004.

Hauck, J., Nissen, C., Landschützer, P., Rödenbeck, C., Bushinsky, S., & Olsen, A. (2023). Sparse observations induce large biases in estimates of the global ocean CO2 sink: An ocean model subsampling experiment.

Lacroix, F., Ilyina, T., Laruelle, G. G., & Regnier, P. (2021). Reconstructing the preindustrial coastal carbon cycle through a global ocean circulation model: was the global continental shelf already both autotrophic and a CO2 sink?. Global Biogeochemical Cycles, 35, e2020GB006603. https://doi.org/10.1029/2020GB006603

Powley, H. R., Polimene, L., Torres, R., Al Azhar, M., Bell, V. A., Cooper, D., ... & Artioli, Y. (2023). Modelling terrigenous DOC across the north west European Shelf: Fate of riverine input and impact on air-sea CO2 fluxes. Science of The Total Environment, 912, 168938.

Terhaar, J., Goris, N., Müller, J. D., DeVries, T., Gruber, N., Hauck, J., et al. (2024). Assessment of global ocean biogeochemistry models for ocean carbon sink estimates in RECCAP2 and recommendations for future studies. Journal of Advances in Modeling Earth Systems, 16, e2023MS003840. https://doi.org/10.1029/2023MS003840