Glacial ocean cSediment fluxes dominate glacial-interglacial changes in ocean carbon inventory: results from factorial simulations over the past 780,000 years
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The authors conducted an investigation into the differences in the ocean carbon cycle response during glacial-interglacial cycles, comparing scenarios with and without sedimentation processes. By incorporating various idealized forcings based on ice core and sediment core records, they analyzed not only atmospheric CO_2 but also $\delta^{13}C$ in the atmosphere and ocean, oceanic DIC, regenerated DIC, and CO_3^{2-}, comparing these with variations reconstructed from geological records. The study identifies the dominant processes driving these changes, with the authors concluding that variations in oceanic DIC are more significant than those resulting from changes in carbon inventory driven by atmospheric CO_2, thereby highlighting sedimentation processes as the primary driver of DIC variations. These findings are robust and significant, making them well-suited for publication in Climate of the Past. However, as another reviewer has noted, the main text and supplementary materials are quite dense, often requiring the reader to refer back to the experimental setup. Additionally, it can be difficult to discern which figures correspond to specific descriptions. Enhancing the clarity of these elements would greatly benefit the overall communication of the study's results.

We thank the reviewer for the fair assessment and constructive comments. We are largely revising and restructuring the main text to shorten it and clarify the main points of our analysis.

General comments:
The supplementary material touches on changes in deep ocean circulation, but before diving into a more detailed discussion, it is useful to first introduce what happens in the BASE scenario to provide a clearer context.
In the sensitivity experiments, different forcings are applied. However, while the LGM-PI amplitudes are determined for each experiment, it would be helpful to provide a more detailed explanation of the rationale behind these choices. For example, why was an amplitude of -40 chosen for SOWI rather than -30 or -50? A clearer justification for these specific values would help readers better understand the experimental design.
It would be beneficial to clearly identify what this model successfully captures and what it may be lacking, based on the results of these experiments.
The point that simple changes in the DIC inventory do not fully explain atmospheric CO_2 variations is particularly compelling and aligns well with my understanding.
The size of the figure captions, plots of sediment core data, and the contrast in the line plots may currently lack sufficient clarity, which could affect the overall readability.

We will largely rewrite the methods, results and discussion of our manuscript to improve clarity and focus on the most relevant points. We also change the figures to improve their readability.

General Comments:
L30: It might be helpful to introduce "Last Glacial Maximum" as "LGM" when first mentioned, and then use the abbreviation in subsequent references throughout the text.

We change all instances of this as suggested.

L46: "… but not necessarily in open systems": Based on the current results s, do you have any discussions related to these previous studies? It is interesting to note that, depending on the experiment, DIC inventory either increases or decreases during glacial periods. Clarifying how these findings relate to or contrast with previous studies could provide valuable insights.

We will add the following clarification to the introduction:

"In a (hypothetical) closed atmosphere-ocean system, the combination of these processes results in increased marine carbon storage during glacials, but not necessarily in the open Earth system because the carbon removed from the surface ocean and atmosphere by these processes could have been sequestered in the water column as DIC or particulate carbon but also in marine sediments. Carbon can also be transferred to the land. Constraints on glacial atmospheric CO_2 can be reconciled with increased and decreased marine DIC inventory in an open system (Jeltsch-Thömmes et al., 2019; Kemppinen et al., 2019), though reproducing reconstructed carbon isotopic changes in atmosphere and ocean seems to require elevated DIC at the LGM (Jeltsch-Thömmes et al., 2019)."

And the following discussion:

"Some of the tested forcings also show lower glacial than inter-glacial DIC ($fPO4$, $fCO2T$) showing that CO_2 removal from the atmosphere in theory does not need to result in increased DIC in the ocean. Instead, these biogeochemical forcings cause sedimentary changes that can store large amounts of carbon in inorganic and organic sedimentary matter. Kemppinen et al. (2019) and Jeltsch-Thömmes et al. (2019) previously showed and discussed the possibility of a negative glacial DIC anomaly due to increased sedimentary storage. As found by Jeltsch-Thömmes et al. (2019), organic carbon burial extensive enough to cause a negative glacial DIC anomaly (e.g. $fPO4$) produces large $\delta^{13}C$ signals of opposite sign than reconstructed, and thus seems unlikely. In the study by Jeltsch-Thömmes et al. (2019), a negative glacial DIC anomaly due to alkalinity-driven $CaCO_3$ accumulation is also inconsistent with the proxy record of the last 25 kyr. Consistently, we find that reconstructed deep Pacific $[CO_3^{2-}]$ changes make a large-scale alkalinity-driven ($fCO2T$) glacial $CaCO_3$ accumulation, which reduces atmospheric CO_2 while also reducing DIC, unlikely because it causes larger deep Pacific $[CO_3^{2-}]$ changes than reconstructed over the last deglaciation (Table 2). The isotopic signal of such large $CaCO_3$ deposition, however, is smaller than that of POC burial changes and could more likely be overprinted by other processes (e.g. terrestrial carbon release and export production changes) to yield proxy-consistent evolutions (Table 2)."

L117: How are the dissolution processes of organic matter and calcium carbonate in the sediment model formulated? Specifically, regarding the burial dissolution of organic matter, since it is also mentioned later when explaining changes in oxygen concentration, it would be helpful to explicitly describe the dependence of these processes on oxygen concentration.

We will add the following to the model description:

"$CaCO_3$ dissolution rates in the sediments are determined from the pore water saturation state, and POC remineralisation is parameterised by a linear dependence on porewater O_2 (Heinze et al., 1999; Tschumi et al., 2011). "

L125: "balance...kept constant thereafter,": Does this mean that during initialization the river input is set to balance the burial rate and this value is used consistently throughout? If so, could you also clarify the specific values of these rates?

That is correct, we diagnosed the burial fluxes at the end of the spin-up and kept the compensating continental inputs constant throughout the transient simulations. We will add a table with the specific fluxes to the SI.

L142: Could the results be largely different depending on which variation (δD or δ 18 O) each experiment is concerned with?

The only difference would be the timings of environmental shift due to lags between δD and $\delta^{18}O$ during deglaciations. The amplitudes would be similar because both forcings were normed.

L153: Is there a specific assumption or basis for the 30%?

There is no specific reason for the exact maximum magnitude of the forcings we apply, they were chosen to cause noticeable CO_2 or circulation shifts, informed by previous studies.

We will add the following to the description of the experiment design:

"Data constraints on carbon cycle forcings are too sparse to know exact magnitudes and timings of the forcings that might have varied spatially and temporarily over the last eight glacial cycles. An inverse estimation of the forcings from the resulting proxy signals requires a different simulation ensemble and is beyond the scope of our study. Rather than trying to guess the most proxy consistent forcing amplitudes and patterns, we designed seven simplified forcings, each with one exemplary magnitude, to simulate the generic effects of processes that have been identified as glacial-interglacial carbon cycle drivers. Except for the orbital changes, which were calculated following Berger (1978); Berger and Loutre (1991) and the reconstructed CO_2, N_2O and CH_4 curves (Loulergue et al., 2008; Joos and Spahni, 2008; Bereiter et al., 2015; Etminan et al., 2016), which we used to calculate the radiative forcing of greenhouse gas changes, the amplitudes of the forcings were set to cause noticeable CO_2 or circulation shifts, informed by previous studies (e.g. Tschumi et al., 2011; Menviel and Joos, 2012; Menviel et al., 2012; Jeltsch-Thömmes et al., 2019; Pöppelmeier et al., 2020)."

L159: How was the alkalinity adjustment carried out?

We will add the following explanation to the description of our experiment design:

"In addition we performed one run in which we let the model dynamically apply external alkalinity fluxes (in addition to the constant terrestrial solute supply applied in each simulation, see spin-up methodology) to restore the reconstructed atmospheric CO_2 curve

(CO2T). In this simulation, the model evaluates the difference between the simulated and reconstructed CO_2 at each time step and adds or removes the marine alkalinity required to cause the necessary compensatory air-sea carbon flux from the surface ocean. Alkalinity changes, e.g. due to changes in shallow carbonate deposition or terrestrial weathering, are an effective lever for atmospheric CO_2 change (e.g. Brovkin et al., 2007), and this additional run shows the long-term changes in marine biochemistry if this was the dominant driver of glacial-interglacial atmospheric CO_2 change."

L228: "However, … constant.": Which figure does this description correspond to?
This statement was meant in relation to the δD record shown in Fig. 1. We will clarify this passage.

L284: "40°CS" is a typo and should be corrected to "40°S."

Will be amended.

L355: What is happening in the case of SOWI? Is the weakening of the AMOC leading to an increased accumulation of DIC in the deep ocean?

The increased isolation of the deep Pacific in SOWI causes increased preservation of POC and $CaCO_3$ in the sediments, and thus less DIC accumulation in the deep ocean than under the BASE forcing. AMOC weakening without wind stress changes (simulation AERO) leads to increased DIC in the deep Atlantic. We reworded the sentence for clarity.

L370: As mentioned earlier, to clarify the relationship between oxygen depletion and the increase in organic carbon burial, could you provide the specific formulation used?

We will extend the model description as stated above. For the specific equations, we refer to Appendix A of Tschumi et al., 2011 (equation A3).

L393: "However … during the deglaciation." Which figure should be referenced to understand this description?

This section was discussing the old Fig. 9. We will revise the section with clearer figure references.

L433: "which may be linked to changes in weathering fluxes not considered here.": Does this mean that changes in weathering could lead to increased inputs of DIC with lower carbon values?

This is a speculation but one possibility is that the mean δ^{13}C of continental DIC reaching the ocean was different during the Eemian, i.e. because of different weathered lithologies or different DIC transport/transformations in terrestrial water ways.

L457: "the reconstructions show…": Where can I find information on the changes in POC burial by region?

We will add a map of POC burial to Fig. 10.

L484: "… better simulated in REMI": Can this be understood from Figure 11c (BGC)?

We will improve the figure and clarify the text, such that this point is now better understandable.

L494: Does this imply that alkalinity is being removed too quickly in order to reproduce CO 2 levels?

Yes, the alkalinity forcing required to drive the whole deglacial CO_2 change by ALK changes is too strong for sedimentary $CaCO_3$.

L497: Which region's sediment core does Qin et al. (2018) refer to? There appear to be other reconstructions of [CO 32-] as well. Could you clarify why the comparison was made exclusively with this particular study?

Qin et al. (2018) present a record of the western tropical Pacific. Here, we are not focussing on site-specific details of the record but the general pattern of glacial-interglacial changes and their amplitudes. The most important question for us is the glacial-interglacial [CO_3^{2-}] amplitude and how it compares across the last eight glacial cycles. Over the last glacial cycle, the low glacial-interglacial amplitude shown in Qin et al. (2018) is similar in other Pacific records (e.g. Yu et al., 2013, Kerr et al., 2017). We chose the Qin et al. (2018) record for Fig. 12 because it is the best resolved record we could find covering almost the entire simulation period. The resolution of a later and longer record (Qin et al., 2020) has a lower resolution over 800 ka. Over the deglaciation (Fig. 13), we also compared the simulation results to Yu et al. (2013).

L498: Why is it that, in Experiment BASE, CO 2 shows a significant change, yet there is little to no change in CO 32- ?

In BASE, the DIC increase is accompanied by acidification and reduced $CaCO_3$ accumulation, which means that DIC increases while [CO_3^{2-}] stays almost constant.

L539: "… increased remieneralization of sedimentary organic matter …": Does this contribute to the rise in CO 2 by the slow decomposition of organic matter once it has accumulated in the sediment?

In addition, the re-ventilation of the ocean increases oxygen supply to the previously dysoxic sediments, which raises remineralization rates. We will clarify this in the text.

L592: How does the change in AMOC affect atmospheric CO 2 in this model? Based on this description, does a weakening of the AMOC lead to an increase in CO 2 ?

We agree, our formulation was unclear. In most cases, a strengthening of AMOC causes a CO_2 increase in our model. However, AMOC is only pushed into a stronger circulation state during this time interval if it had already transitioned into a weaker state previously. Otherwise the orbital forcing during the time window does not cause a shift in AMOC strength.

We will revise the sentence accordingly.

L598: Does "increased Southern Ocean wind forcing" refer to a weakening of the wind Forcing?

Yes, we will correct this.

L608: typo: it should be "Menviel et al. (2011)" rather than "(Menviel et al., 2011)."

Will be amended.

L686: typo: it should be "CO 32- " rather than "CO 3-- ."

Will be changed.

Table2: Since only CO 2 reflects the difference between the Holocene and the glacial period, it might be worth considering aligning the other variables as well for Consistency.

We will change the table to show deglacial changes for all metrics.

Figure 9: Does Δδ 13 C represent the difference from the modern value? It would be helpful to clarify this in the footnote, as it is not currently specified.

Apologies for the missing information, we will add it to the figure caption. The anomalies are with reference to 20 ka, or the closest available value.

Figure 15: It might also be helpful to change the color of the lines to make them easier to distinguish at a glance.

We will choose different line colours.