Author responses to Referee #1

Comment 1)

Modelling study in the context of paleoproxy data: The motivation behind the study is to better understand variations in oceanic δ13C as measured in foraminiferas. This is discussed in the context of the two site-specific studies: Charles et al., (2010) and Ziegler et al., (2013), comparing mid-depth (400m and 1500m) to deep δ13C in the Southern Ocean as well as the global study of Oliver et al., (2010). But all the discussion stays very vague and qualitative with "increased/decreased" vertical gradients over "glacial/interglacial" timescales and mostly "globally averaged" for the numerical experiments. This induces some relatively vague conclusions such as in the abstract L. 17-18, or p12 L. 20-25. This is also true in section 3.4. In addition, in that section results of Charles et al. (2010) and Ziegler et al., (2013) are discussed in a bit more detailed but they are compared to the simulated mean vertical δ13C gradient, which is defined as δ13Csurfaceδ13Cdeep, where δ13Csurface and δ13Cdeep respectively represent mean δ13C for depths above and below 250m (please note that the "deep" ocean cannot be defined as the area below 250m depth). This is however different to Ziegler et al., who compare ∼400m depth to the deep ocean (∼3000m), and Charles et al., (2010) who compare cores at ∼1200m and ∼4600m. In general, wouldn't it make sense to show vertical profiles of globally average or basin average ∆δ13C (δ13C at depth compared to δ13C averaged over the first 250m)? Such a figure could replace Figure 4 and add a bit more information about the processes at play.

Author response to Comment 1)

Referee #1 kindly makes us aware of the too generalized and qualitative discussion throughout the manuscript. We will address this issue by 1) providing basin-averaged δ13C profiles (as a revision of Figure 4) and 2) redefining deep ocean δ13C as the volume-averaged δ13C below 2500m depth, and 3) adjusting the discussion and conclusions to be more specific and quantitative on a basin scale. In doing so, comparison with the sediment core studies will become more meaningful and the spatial differences in the sensitivity of ∆δ13C will be more visible.

Author's changes in the manuscript in response to Comment 1)

- Revision of Figure 4 by basin-mean vertical profiles of δ13C for the Southern Ocean, North Pacific, South Pacific, North Atlantic, South Atlantic and Indian ocean for the global sensitivity experiments.
- Redefining deep ocean δ13C and updating the results accordingly
- Updating discussion/abstract/conclusion to be more quantitative and specific and using the revised Figure 4 to discuss the sensitivity of ∆δ13C on a basin scale

Comment 2)

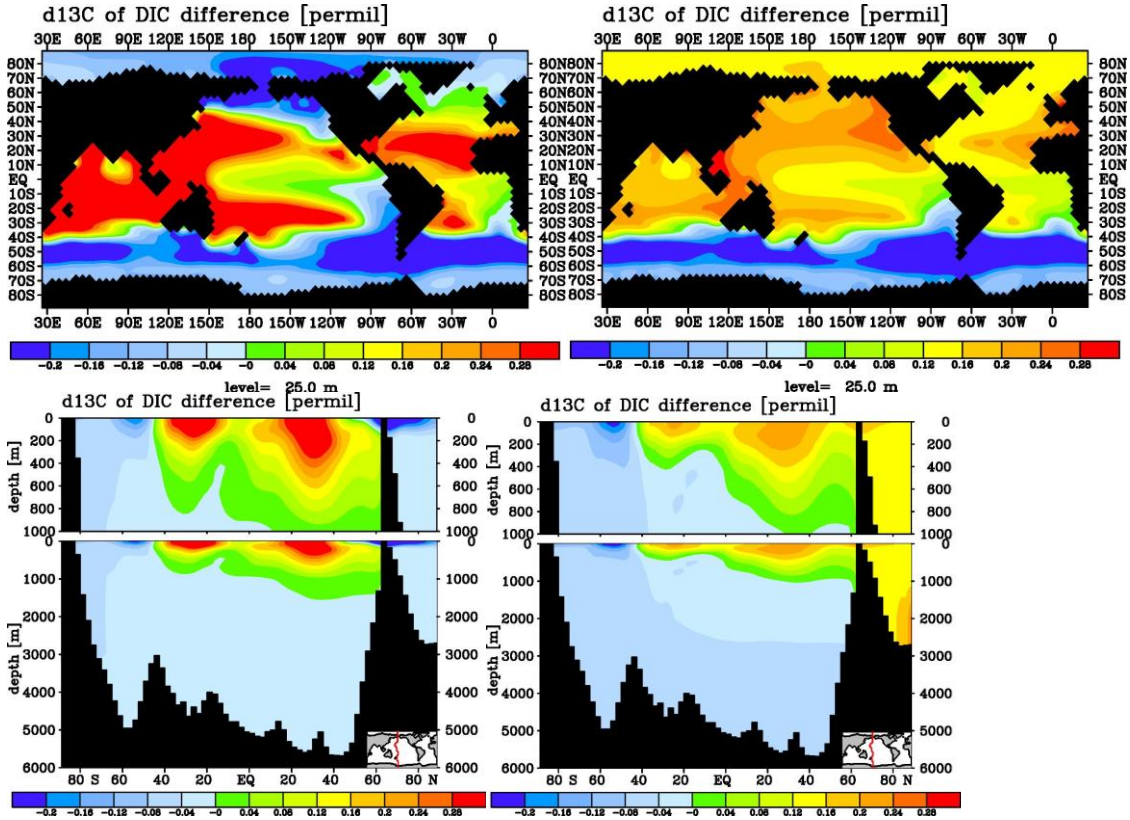
Air sea gas exchange experiments: I find the results quite surprising. A pCO2 increase and δ13CO2 decrease for fast gas exchange make sense, but a pCO2 increase for a slow gas exchange is surprising. There are no graphs shown for the slow gas exchange case, so it is hard to judge

Author response to Comment 2)

The authors agree with Referee #1 that the discussion of *p*CO2 sensitivity to slow gas exchange rates is not explained enough in the current manuscript. As stated in the manuscript, 'pCO2 atm is governed by the transient change in the net air-sea gas exchange flux Fnet, which occurs until a new equilibrium is established'.
In order to explain the slow gas exchange experiment, we will add carbon flux figures at 100 years, when the transient response determines the new equilibrium atmospheric pCO2 (which can be seen from the atmospheric development Figure, see last page of this document). Here one can see that gas exchange is reduced as compared to the model control run for the Gas Slow experiment, and increased relative to the control for the Gas Fast experiment. Integrated globally, the net air-sea C flux is into the atmosphere during this transient phase for both experiments. Last, effects of slow gas exchange on marine δ13C will be visualised by providing Figure 3 for slow gas exchange in the SI.

Author's changes in the manuscript in response to Comment 2)

- Add a figure in the SI on the slow gas exchange experiment similar to the one in the main text for the fast gas exchange experiment (Figure 3):



- Improve text by explaining the cause for the pCO2 increase in the slow gas exchange experiment
- Provide plots of atmospheric development of δ13C and pCO2 during all experiments (see last page of this document)

- Add carbon flux figures at 100 years into the sensitivity experiments (Gas Fast and Gas Slow), in order to show the transient response that sets atmospheric pCO2:

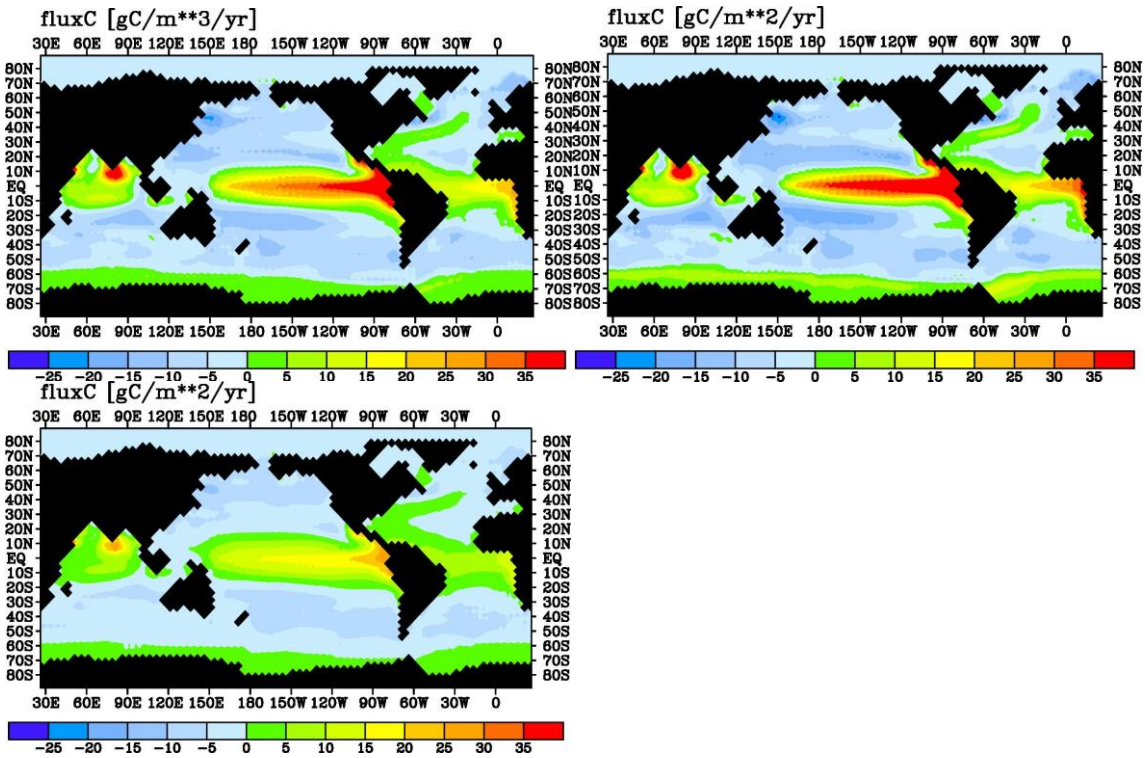


Figure of carbon flux through the air-sea interface for the model control (upper left), and global Gas Fast (upper right) and Gas Slow (lower left) sensitivity experiments at 100 years. The corresponding globally integrated flux after 100 years is 0.037 Gt C/yr flux into the atmosphere for the Gas Fast experiment and 0.026 Gt C/yr flux into the atmosphere for Gas Slow.

Comment 3)

POC sinking rate: P7, L.20-21: As POC sinking rate increases, the decrease in air-sea gas exchange is most likely due to a reduced advection/mixing of carbon rich waters into the mixed layer. P7, L.28 it is stated that marine δ13C increases overall when POC sinking rates are high. Since δ13Catm increases under high POC sinking rates, it seems surprising that marine δ13C would also overall increase. . . In fact, the limited negative δ13C anomalies shown in Figure 5 are surprising. Is there a strong increase in organic carbon burial? Would it then make sense to show the transient changes? I am not sure about L. 33-34 p7: the difference in between the global change in POC and SO only change in POC export could only be due to difference in the area to which the forcing is applied, but might not be specific to SO. When applied globally, there is a significant impact on global export production as well as marine and atmospheric δ13C. The SO is a relatively small area of the ocean, so changes applied to that region only can be easily compensated. Results could be discussed with respect to previous experiments performed with the Bern3D and looking at the influence of the remineralization depth on atmospheric CO2 and δ13C (e.g. Roth et al., 2014 Earth system dynamics and Menviel et al., 2012, Quaternary Science Reviews).

Author response to Comment 3)

We thank Referee #1 for several detailed comments on our analysis of the POC sinking rate experiments. Here we try to respond to each point:
P7, L.20-21: The reduced air-sea gas exchange rate in response to high POC sinking rates is due to the almost complete export of surface ocean carbon to depth – thus not permitting escape to the atmosphere. Net upward advection/mixing of carbon and nutrients is thus reduced.
P7, L.28: Both marine (+0.15 permil) and atmospheric δ13C (+0.23 permil) increase because there is indeed a relatively higher loss of 12C than 13C (in POC) to the sediments in our experiment. The results presented are thus a transient response (as can be seen as well in the new SI Figure on atmospheric development during the experiments, see last page of this document). We have added an additional 10 000 years to the POC fast experiment to show the effects of a continued experiment, but argue not to go beyond that due a.o. extremely long equilibration times (as stated in Roth (2014), δ13C changes for over 200 000 years): See response to Referee #2, comment 2.2.3.
P7, L. 33-34: The relatively minor effect of the SO-only POC experiment is indeed compensated for outside of the SO, thank you for this improved explanation of our results.
Discussion on context of previous studies: We agree with Referee #1 (and Referee #2) that a comparison to more previous studies are valuable for the reader and will improve the manuscript.

Author's changes in the manuscript in response to Comment 3)

- Updating the discussed sentences on Page 7
- Putting our results into the perspective of additional previous studies, as suggested by both Referee #1 and #2.

Comment 4)

Vmax: It is quite surprising that ∆δ13Catm decreases when nutrient utilization increases. P8, L. 27: I doubt the correct reason for the surface negative δ13C anomaly is put forward. Maps of changes in export production and nutrients could be added to better understand the model response. If the nutrient advection to the surface of regions outside of SO is reduced, then so should be the advection of carbon rich - 13C depleted waters. This is also consistent with the significant atmospheric CO2 reduction, but the δ13CO2 is more surprising. The change in nutrient utilization in the Southern Ocean should be given, as well as control and perturbed surface nutrient content.

Author response to Comment 4)

It is indeed surprising that δ13Catm decreases, and we see an explanation should be in place. We will provide the reader with a selection of maps of export production, nutrients, air-sea pCO2 difference and carbon flux through the air-sea interface, such that the marine and atmospheric changes in response to the experiment are visualized. We also consider exploring alternative formulations of the experiment with a smaller perturbation of Vmax to check whether qualitatively the same changes occur then.

Author's changes in the manuscript in response to Comment 4)

- Explain δ13Catm decrease, while providing the reader with more maps/information on the effects of the experiment on air-sea gas exchange, pCO2 difference and nutrients.

Comment 5)

Sea-ice: Legend of Figure S4 needs additional information

Author response to Comment 5)

The caption of Figure S4 is indeed incomplete. We hope adding units and additional text on how the figure should be understood should provide the reader with enough information to interpret Figure S4.

Author’s changes in the manuscript in response to Comment 5)

- Caption of Figure S4 adjusted to ‘The pCO2 difference [ppm] between the surface ocean and the atmosphere for the model control run, based on an atmospheric value of 279 ppm. Negative values indicate a potential carbon flux into the ocean.’

Comment 6)

Hasted conclusions: The vertical gradient of δ13C is stated to vary by no more than 0.5 permil. But it should be noted that this includes the full range of anomalies obtained: from much lower to much higher than the control state. For example, the maximum changes in vertical δ13C gradient are obtained for Vmax (∼+0.2 permil) and a fast gas exchange (∼-0.25 permil), thus leading to ∼0.5 permil change. It would be more appropriate to say that the maximum variation of each parameter leads to a ∼0.25 permil change in vertical δ13C gradient, as the pre-industrial control state is an interglacial state.
Section 3.4., p10: very broad statements are made with respect to the impact of changes in ocean circulation on δ13C L. 17-18 and L. 20-27. These statements do not rely on any quantitative work on the impact of changes in ocean circulation on oceanic δ13C. The authors could for example consider looking at Menviel et al., 2015 (Global Biogeochemical Cycles) to have a better estimate of the impact of ocean circulation changes on δ13C. L. 21 to 23 are particularly unjustified because the rate of change of δ13C resulting from both biogeochemical changes and oceanic circulation are not studied here.
L. 14-15, p 12: I don't think that the results shown here indicate that the changes in pCO2 and δ13Catm are dependent on the location of the sea-ice edge, nor that sea-ice has a strong impact on atmospheric or oceanic δ13C.

Author response to Comment 6)

The generalization of 0.5 permil is something we want to make more specific. We will do this in two ways: 1) make the discussion and conclusion region-specific (revising Figure 4 with basin vertical gradients of δ13C) and 2) follow the reviewers advice to describe the effect of the individual sensitivity studies, instead of generalizing to a global average and a total effect.
Section 3.4: Regarding our statements on the effects of ocean circulation, we will extend our literature study in order to make more specific statements on the potential effects of ocean circulation on δ13C.
L. 14-15, p 12: We would like to rephrase this sentence to 'The effect of sea ice cover on pCO2atm and δ13Catm as well as marine δ13C depends on whether the sea ice covers a source or sink region for carbon.' We will also update P9, L20 accordingly, as it describes the same idea.

Author's changes in the manuscript in response to Comment 6)

- Replace the general statement on 0.5 permil throughout the manuscript with a basin region-specific description of the results and describing the isolated effect of the sensitivity experiments
- Update P12 L14-15 and P9, L20 to describe that the effect of sea ice cover depends on whether the ice covers a source or sink region for carbon.
- Extend our literature study on the effects of ocean circulation on δ13C to make more specific statements on this topic.

Comment minor points and typos)

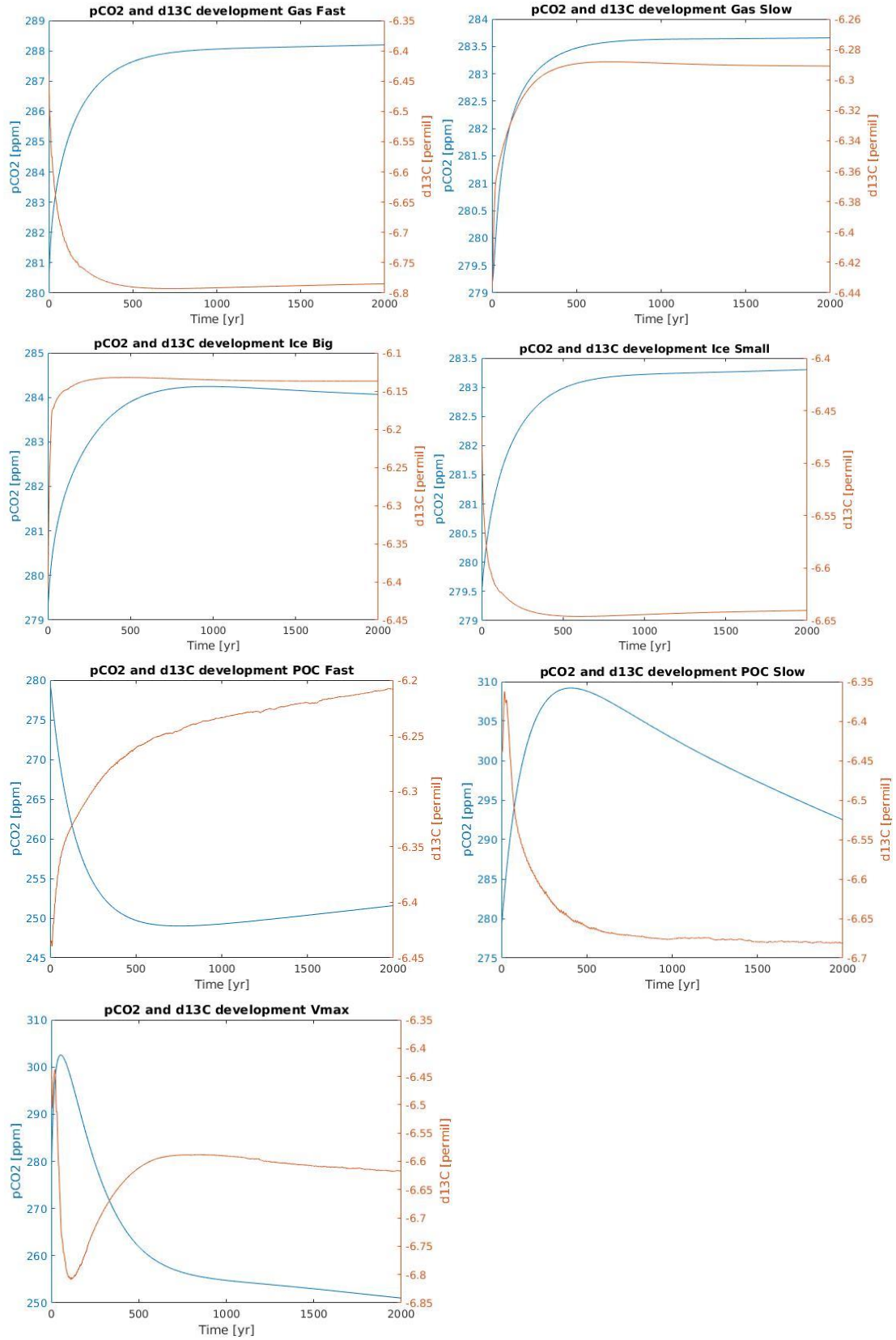
Throughout the text, please write "biogeochemical" without parentheses. P2, L. 3: "Air-sea" P6- L.2, please rephrase P6, L. 29: Please remove "In the ocean," Figure 8: y axis of second plot should read "pCO2 (ppm)"

Author response to minor points and typos)

Our apologies for these mistakes, and thank you for pointing them out.

Author's changes in the manuscript in response to minor points and typos)

- We will replace (bio)geochemical with biogeochemical
- We will replace air-se with air-sea on P2, L. 3
- Removing P6, L. 29 'In the ocean'
- We will replace the Figure 8 y-axis units with [ppm]



Draft version of New SI Figure showing atmospheric development of pCO2 and δ13C during the sensitivity experiments (global experiments for POC sinking and gas exchange)