Response to reviewer #1

We thank the reviewer for their comments. In the following we respond point by point.

Anonymous Referee #1
This is a well-conceived study about an interesting and relevant topic. The methodology is sound, and the fact that the authors' model could not reproduce the observed changes in CO2 before and after the Mid-Bruhnes event (MBE) should not prevent it from being published.

1. However, this manuscript needs a background section describing in more detail the previous studies that have addressed this question and the hypotheses that have been proposed (e.g., by Yin and Berger and Kohler).
Very few modelling studies have looked at the difference of atmospheric CO_2 before and after the MBE. Yin and Berger (2010, 2012) and Yin (2013) focused on the change of climate and ocean circulation, and Yin (2013) suggested that the change of ventilation could play a role in different CO_2 levels, but this remained to be tested. Kohler and Fischer looked at the different interglacial CO_2 values, but with a simple box model. As suggested we have expanded this section on previous work in the introduction with more details:
"To explain the different climates of interglacials before and after the MBE, modelling studies have shown that it is necessary to include the change of atmospheric CO_2 (Yin and Berger, 2010; 2012). Indeed, these numerical simulations with an intermediate complexity model have demonstrated that differences in Earth's orbital configuration, and hence seasonal and spatial distribution of insolation, cannot explain alone the colder climate recorded during pre-MBE interglacials, whereby lower atmospheric CO_2 concentration is also necessary to simulate colder climate (Yin and Berger, 2010; 2012). However, the reasons for the lower CO_2 values remain elusive and very few modelling exercises have tackled the issue of different CO_2 levels during interglacials before and after the MBE. Köhler and Fischer (2006) have produced transient simulations of the last 740,000 years using the BICYCLE box model. They used several paleoclimatic records such as ocean temperature, sea ice, sea level, ocean circulation, marine biota, terrestrial biosphere and $CaCO_3$ chemistry to force forward their model. They run a set of simulations prescribing only one forcing at a time and another with all forcings excluding one at a time, which allows them to analyse which forcings are the most important. In their simulations, they have shown that the lower CO_2 values during pre-MBE are mainly explained by the prescribed lower Southern Ocean (SO) sea surface temperature and weaker Atlantic meridional overturning circulation (low North Atlantic Deep Water formation and SO vertical mixing) compared to post-MBE interglacials. Using an intermediate complexity model, Yin (2013) conversely simulated vigorous bottom water formation and stronger ventilation in the Southern Ocean during pre-MBE interglacials and suggested this could increase deep oceanic carbon storage and lower atmospheric CO_2. However, this effect on the ocean carbon reservoir and atmospheric CO_2 has not been evaluated yet in a climate model including a carbon cycle representation."

2. At the end of the manuscript the authors should revisit these hypotheses. Do the new model results presented support either hypothesis (ie, that stronger or weaker overturning explains the change in CO2)?

In this work, we show that the modelled increase in overturning in response to the different interglacial orbital forcings and CO_2 is too small to yield much effect on the ocean carbon storage, and results in very small changes in atmospheric CO_2, with appropriate tendency as compared to observations, but an order of magnitude too small (Fig. 11). Because the ocean circulation change is small, it does not allow to decipher between the two hypotheses, which could also both be wrong, but shows that either the change of ventilation simulated by the model is not correct, or that other processes impacting the carbon cycle are missing.

In the first hypothesis, the change of CO_2 could still be due to changes in circulation, and whether it is due to stronger or weaker overturning could be tested with sensitivity experiments. Yet this would ultimately require a mechanism yielding such changes of circulation. Alternatively, the lower atmospheric CO_2 before the MBE could be due to other processes on land or in the ocean. To present these different ideas, we have added in the conclusion of the manuscript:

"Past work suggested that either a vigorous AABW (Yin, 2013) or weak Atlantic thermohaline circulation (Köhler and Fischer, 2006) during pre-MBE interglacials could increase the oceanic carbon storage and explain the lower CO_2 than during post-MBE interglacials. Other studies for different background climates have shown opposite results with respect to the effect of ocean circulation on carbon storage. A weaker AMOC could either result in more ocean carbon storage with a pre-industrial climate (Obata, 2007; Menviel et al., 2008; Bozbiyik et al., 2011) or glacial climate (Menviel et al., 2008), or it could yield less ocean carbon storage with a pre-industrial climate (Marchal et al., 1998; Swingedouw et al., 2007; Bouttes et al., 2012) or a glacial climate (Schmittner and Galbraith, 2008; Bouttes et al., 2012; Schmittner and Lund, 2015;). Menviel (2014) showed that on top of changes in NADW formation, modifications of AABW and NPDW formations could results in different oceanic carbon storage. Data indicate that the modern reduction of carbon uptake in the North Atlantic is due to a reduction in the overturning circulation (Perez et al., 2013). Because the atmospheric CO_2 change that we simulate has a low magnitude of only a few ppm, it is not yet possible to infer whether stronger or weaker overturning during pre-MBE interglacials could have significantly lowered atmospheric CO_2."

3. More background information about the ice sheet model used would also be helpful. What sea level is simulated for each interglacial?

In this study, we didn't use an ice sheet model but only the outputs from another coupled climate-ice sheet model (Ganopolski and Calov, 2011) to prescribe the ice sheets, as no reconstructed ice sheet from data exist for the nine last interglacials. We have added more details on this model:

"The prescribed ice sheet distributions are thus taken from an ice sheet simulation of the last 800,000 years (Ganopolski and Calov, 2011) using the intermediate complexity model CLIMBER-2 (Petoukhov et al., 2000; Ganopolski et al., 2001; Brovkin et al., 2002), including a 3-D polythermal ice sheet model (Greve, 1997). This ice sheet model is coupled to the climate component via surface energy and mass balance interface (Calov et al., 2005), which accounts for the effect of aeolian dust deposition on snow albedo."

We have also added the corresponding sea levels for each interglacial at the dates chosen for the snapshot experiments in Table 1.

MIS	**Date of $\delta^{18}O$ peak (ka BP)**	**Date for orbital configuration and CO_2 (ka BP)**	**CO_2 values from data (ppm)**	**Sea level changes (m) corresponding to the ice sheet configurations**
1	6	12	243.2	13.8
5.5	123	127	268.64	-0.8
7.5	239	242	269.23	5.6
9.3	329	334	280.32	-0.9
11.3	405	409	282.29	-0.8
13.13	501	506	235.92	13.1
15.1	575	579	249.36	2.3
17	696	693	234.38	-0.4
19	780	788	242.73	10.8

Table 1 Dates of orbital parameters and CO_2 used for the simulations (Luthi et al., 2008), and sea level anomalies as compared to present-day conditions (m) corresponding to the prescribed ice sheets (Ganopolski and Calov, 2011).

4. In the results section, it would be useful to have a more specific comparison of the proxy and model SST changes. The authors have a very nice table summarizing proxy SST observations, but it isn't clear how well the model agrees with the data. I can't tell in the figures how large the model SST changes are. How much beyond -0.6 C does the dark blue color go? Simply listing the global mean SST change as well as values for the North Atlantic and Southern Ocean would be helpful.

The dark blue color is for all values below -0.6°C. As suggested we have listed the global mean SST change and the values for the North Atlantic and Southern Ocean in the text. The values are summarized below (in °C):

	OC	OVC	OVIC
Global	-0.30	-0.28	-0.32
North Atlantic (30°N-65°N)	-0.36	-0.31	-0.49
Southern Ocean (south of 54°S)	-0.43	-0.44	-0.47

5. In their discussion, the authors suggest that the reason that the model did not reproduce large enough CO2 changes could be related to a shortcoming in how it simulates bottom water formation. Additionally, the authors identify mismatches between proxy and simulated vegetation changes. They should provide more information related to these potential problems. How well does the model simulate the Holocene or preindustrial with respect to atm CO2 level, overturning and vegetation? Can the authors suggest more specific solutions to address these shortcomings? Are there additional simulations, such as sensitivity tests, that the authors could propose (or run) to gain more insights?

The carbon cycle module in iLOVECLIM has been validated for the pre-industrial (Bouttes et al., 2015) but not tested for the Holocene. The overturning and vegetation have been described and validated by Goose et al. (2010)

The terrestrial biosphere module in iLOVECLIM, Vecode, is very simple with only two plant functional types. To test the impact of different vegetation responses to orbital forcings and CO_2 from the different interglacials, the vegetation distribution could be obtained from a more complex model and then prescribed in iLOVECLIM.

Concerning the overturning, it could be artificially modified by adding fresh water or using a scheme for the sinking of brines from sea ice as in Bouttes et al. (2009).

Finally, another test concerns the ice sheets, which are not well constrained at all for these periods of time. Sensitivity experiments could be run with prescribed ice sheets designed to be very different and idealized to evaluate their impact.

We have added a discussion on these potential additional sensitivity tests, which remain far too extensive for this already long paper (lots of figures as already noticed by the reviewers), but should constitute an interesting follow up to be done later on.

In part 3.3: "In addition, the model-based reconstruction that we used shows relatively small changes of sea level equivalent between interglacials. Data reconstructions seem to indicate possible larger differences between interglacials (Spratt and Lisiecki, 2016), whose effect on the size of the land surface and the carbon cycle remains to be tested. Sensitivity experiments with prescribed idealised ice sheets designed to be very different would help to evaluate their impact."

In the conclusion:

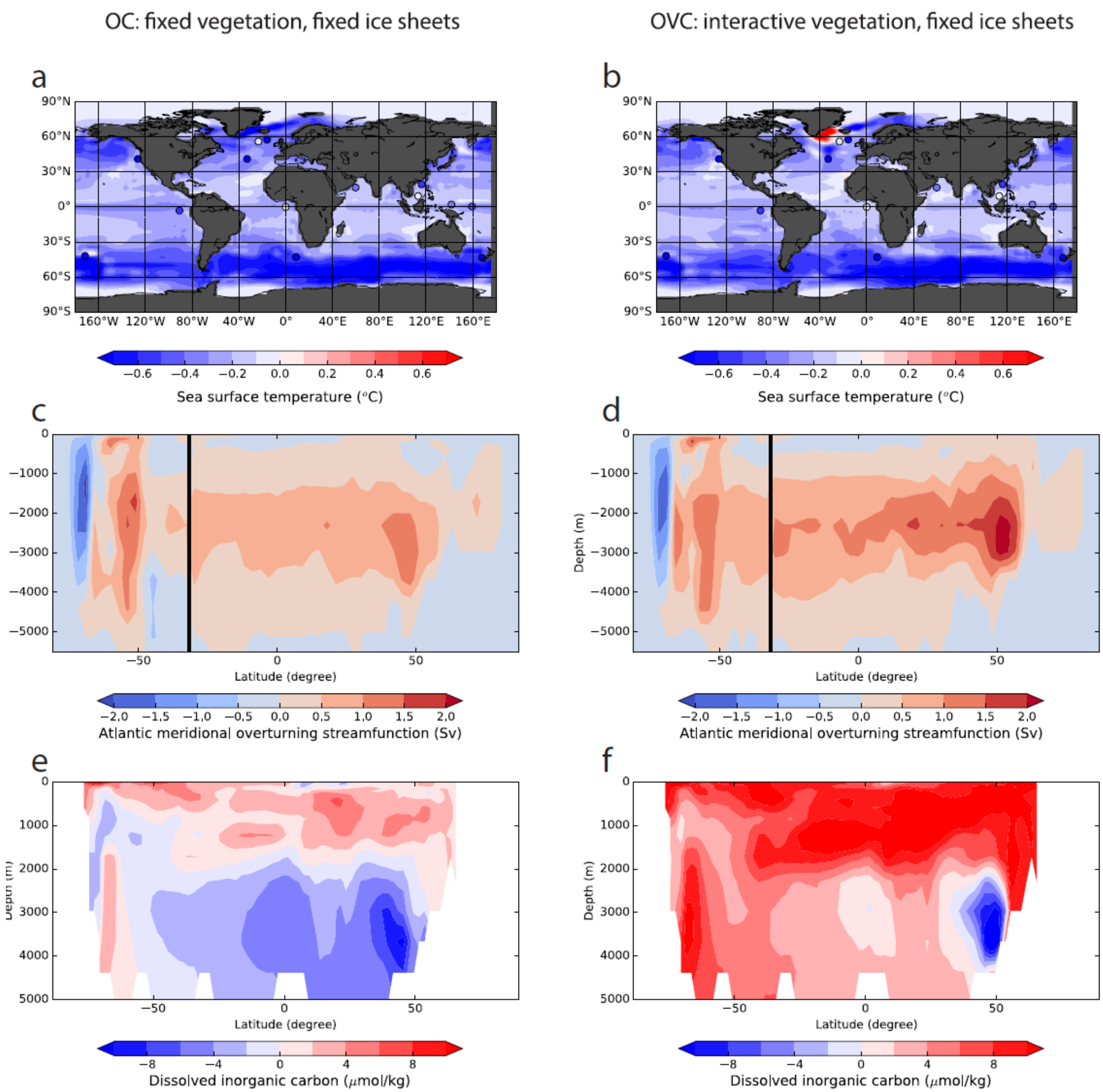
"The vegetation model in iLOVECLIM only simulates grass and trees, to better evaluate the different vegetation response to orbital and CO_2 forcings it would be useful to use a more complex terrestrial biosphere model. "

"The impact of ventilation changes could be tested by artificially modifying the buoyancy forcing in the areas of bottom water formation."

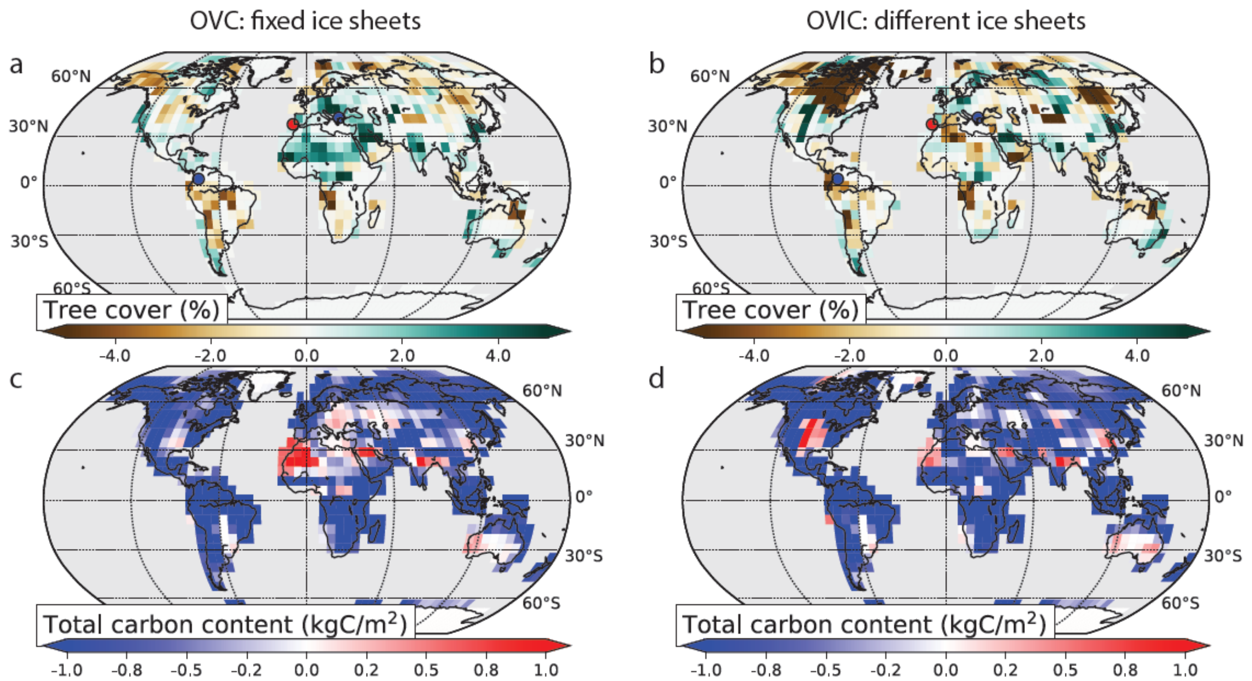
Bouttes, N., D. Paillard and D. M. Roche, Impact of brine-induced stratification on the glacial carbon cycle, Clim. Past, 6, 575-589, doi: 10.5194/cp-6-575-2010, 2010

6. Lastly, I think the manuscript has too many figures. Several figures could be combined to make it easier to compare the different simulation scenarios. For example, Figure 4 could have 3 columns, one each for the OC, OVC, and OVIC simulations (thus, combining figures 4, 13, and 16). Similarly, results from figures 12 and 15 could be placed side-by-side.

As suggested we have combined figures 4 and 13 together but we have left figure 16 alone as it has only one panel and it would have made the space taken by figures larger.



We have also combined figures 12 and 15 together.



References

Bouttes, N., Roche, D. M., and Paillard, D.: Systematic study of the impact of fresh water fluxes on the glacial carbon cycle, Clim. Past, 8, 589-607, 2012.

Bozbiyik, A., Steinacher, M., Joos, F., Stocker, T. F., and Menviel, L.: Fingerprints of changes in the terrestrial carbon cycle in response to large reorganizations in ocean circulation, Clim. Past, 7, 319–338, doi:10.5194/cp-7-319-2011, 2011.

Brovkin, V., Bendtsen, J., Claussen, M., Ganopolski, A., Kubatzki, C., Petoukhov, V., and Andreev, A.: Carbon cycle, vegeta-

tion and climate dynamics in the Holocene: experiments with the CLIMBER-2 model, Global Biogeochem. Cyc., 16, 1139, doi:10.1029/2001GB001662, 2002.

Calov, R., Ganopolski, A., Claussen, M., Petoukhov, V., and Greve. R.: Transient simulation of the last glacial inception, Part I: Glacial inception as a bifurcation of the climate system, Clim. Dynam., 24, 545–561, doi:10.1007/s00382-005-0007-6, 2005.

Ganopolski, A., Petoukhov, V., Rahmstorf, S., Brovkin, V., Claussen, M., Eliseev, A., and Kubatzki, C.: CLIMBER-2: a

climate system model of intermediate complexity, Part II: Model sensitivity, Clim. Dynam., 17, 735–751, 2001.

Greve, R.: A continuum-mechanical formulation for shallow poly- thermal ice sheets, Philos. T. Roy. Soc. Lond. A, 355, 921–974, 1997.

Marchal, O., Stocker, T. F., and Joos, F.: Impact of oceanic reor- ganizations on the ocean carbon cycle and atmospheric carbon dioxide content, Paleoceanography, 13, 225–244, 1998.

Menviel, L., Timmermann, A., Mouchet, A., and Timm, O.: Meridional reorganizations of marine and terrestrial productivity during Heinrich events, Paleoceanography, 23, PA1203, doi:10.1029/2007PA001445, 2008.

Menviel, L., England, M.H., Meissner, K., Mouchet, A., Yu, J.: Atlantic-Pacific seesaw and its role in outgassing CO_2 during Heinrich events, Paleoceanography, 29, doi:10.1002/2013PA002542, 2014.

Obata, A.: Climate-Carbon Cycle Model Response to Freshwater Discharge into the North Atlantic, J. Climate, 20, 5962–5976, doi:10.1175/2007JCLI1808.1, 2007.

Pérez, F. F., Mercier, H., Vázquez-Rodríguez, M., Lherminier, P., Velo, A., Pardo, P. C., Rosón, G. and Ríos, A. F.: Atlantic Ocean CO_2 uptake reduced by weakening of the meridional overturning circulation, Nature Geoscience, 6, 146–152, doi: 10.1038/NGEO1680, 2013.

Petoukhov, V., Ganopolski, A., Brovkin, V., Claussen, M., Eliseev, A., Kubatzki, C., and Rahmstorf, S.: CLIMBER-2: A climate system model of intermediate complexity, Part I: Model description and performance for present climate, Clim. Dynam., 16, 1– 17, 2000.

Schmittner, A. and Galbraith, E. D.: Glacial greenhouse-gas fluctuations controlled by ocean circulation changes, Nature, 456, 373–376, doi:10.1038/nature07531, 2008.

Schmittner, A., and Lund, D. C.: Early deglacial Atlantic overturning decline and its role in atmospheric CO_2 rise inferred from carbon isotopes ($\delta^{13}C$) Climate of the Past, 11, 135-152, 2015.

Swingedouw D., Bopp L., Matras A. and Braconnot P.: Effect of land-ice melting and associated changes in the AMOC result in little overall impact on oceanic CO_2 uptake, Geophysical Research Letters 34, L23706, 2007b.