Answer to reviewers

Dear editor and reviewers,

We have read with attention all the comments and suggestions. We reply to the questions raised in the following and have modified the manuscript accordingly. In particular we have added discussion with additional papers and provided more detailed analysis. We thank the editor, reviewers as well as Laurie Menviel and Axel Timmermann for these constructive comments that helped improve the manuscript.

1. References to other studies

Referee #1: *They miss out two important study on the same topic (Bozbiyik et al., 2011, Clim. Past, 7, 319–338; Obata, A. Climate–Cycle Model Response to Freshwater Discharge into the North Atlantic Journal of Climate, 2007, 20, 5962-5976), which for the first time used full GCMs, and not an EMIC as used here and in the two other previous studies.*

***Referee #2**: 6) Why are results only discussed in comparison to Menviel et al. and Schmittner and Galbraith? This focus on two studies only appears very odd. A) There is a fair number of additional paleo studies that warrant comparable attention (examples are: Köhler et al., 2005; Obata et al., 2006, Bozbiyik et al., 2011, Marchal et al., Climate Dynamics, 1999, Marchal et al., Paleoc., 1998). B) In addition, there are also publications that deal with CO2 and AMOC changes in the context of IPCC-type emission scenarios (E.g. Maier-Reimer et al., Climate Dynamics, 1994; Sarmiento and LeQuere, Sci, 1996, Joos et al., Sci, 1999, Plattner et al., Tellus, 2001, and the more recent literature on scenarios)*

Answer:

As suggested by the reviewers, we now also discuss the results in comparison to Bozbiyik et al., 2011 and Obata et al., 2007 for the Pre-industrial simulations. However they did not run glacial simulations, which hinders any comparison on the impact of fresh water flux during glacial conditions. The purpose is to discuss the impact of fresh water fluxes in coupled climate-carbon ocean-atmosphere-vegetation models, hence although Kohler et al, 2005 and Marchal et al., 1998 are discussed in the introduction they cannot directly be compared to the results. It is also beyond the scope of this study to explore the effect of fresh water fluxes in IPCC-type emission scenarios as the aim is to discuss the evolution of CO2 during glacial climates as recorded in paleo-archives. It is indeed important to study the impact of fresh water fluxes in glacial conditions as the results can depend strongly on the background climate. To make it clearer that the paper aims at studying the impact of fresh water flux in glacial conditions we have added “glacial” in the title.

2. Reference to LOVECLIM results from Menviel et al., 2008

2.1 LOVECLIM results in Menviel et al., 2008 and Kageyama et al., 2010

L. Menviel: *It looks like instead of discussing the LOVECLIM results presented in Menviel et al. 2008 the authors are referring to the LOVECLIM results presented in Kageyama et al.2010. These simulations differ in terms of their forcings and model versions employed. The authors should carefully read both papers and reference them in the right context.*

Answer:
Following L. Menviel's advice, the paragraph discussing the results presented in Kageyama et al. has been changed to make clearer that they are using another experimental setup. This study is interesting as it directly compares the results in LOVECLIM and UVic with the same fresh water forcing, although without the carbon cycle models.

"In a different study with other freshwater experiments (0.2 Sv during 500 years) but without carbon cycle models \citep{kageyama_2010}, the LOVECLIM model exhibits a smaller climate change compared to the UVic model (they were both forced by the same fresh water flux). The ``seesaw" pattern is more pronounced in the UVic results, with cooling in the North Hemisphere and warming in the southern hemisphere (\citet{kageyama_2010}, figure 6). With the LOVECLIM model the warming in the South Hemisphere is comparatively smaller. Similarly, in the UVic model the addition of this fresh water flux leads to a dryer North Hemisphere and wetter South Hemisphere, whereas it globally becomes dryer in many areas in the LOVECLIM model. The carbon cycle was not included in such simulations but these differences in the climate response should results in very different behaviors of the carbon cycle both in the terrestrial biosphere and ocean. The carbon cycle evolution is very tightly driven by the climate change. As the latter is highly model dependent, the modification of the carbon cycle vary significantly between the different models."

<u>2.2 AMOC recovery</u>
L. Menviel: *"It is stated "AMOC in LOVECLIM recovers in 200yrs ... "*

Answer: The quote is not exact and 200yrs was referring to the FWF timing not the AMOC recovering. This has been clarified: "the AMOC increases as soon as the fresh water flux stops in LOVECLIM (i.e. after 200 years) and recovers quickly in approximately 400 years, i.e. 600 years after the beginning of the fresh water flux"

<u>2.3 Seesaw pattern</u>
L. Menviel: *"P1373: Bouttes et al. state that there is no seesaw in LOVECLIM L7...This is obviously wrong."*

Answer: This section discussed the relative lower amplitude of the seesaw response in LOVECLIM compared to the UVic model. As highlighted by L. Menviel this part was not clear enough and has been erased. The discussion of the comparison of the LOVECLIM and UVic results is now only in the LGM sections as the experiments with the carbon cycle were presented only during the LGM for the UVic model. It is also now more clearly stated that the comparison of the climates obtained in both models are with the same fresh water fluxes and was done in another study (view new text above, answer 2.1)

<u>3. More details in the analysis</u>
Referee #1: *Their analysis of the detailed changes in the carbon cycle is performed on a very aggregated level, but does not go to the details.*
Referee #2: *The analysis of the simulated CLIMBER 2 results remains very superficial. There is no quantitative spatio-temporal attribution of change to mechanisms/processes neither for the ocean nor for the land. This is what I would expect given the examples provided by previous work. Considering only global and hemispheric changes is simply not enough.*

Answer:
We have added more detailed results for the atmosphere, the ocean and the vegetation following the reviewers' advice as described point by point below.

3.1. Physical changes in the atmosphere
Referee #2: *Basic questions remain unanswered. A) What are the physical changes simulated by CLIMBER 2? B) How do the temperature and precipitation fields change? C) Are there shifts in the ITCZ? D) Are there changes in light availability for photosynthesis? E) Are there changes in wind speed or is this not taken into account by the statistical atmosphere? F) Are changes in NADW and AABW the only circulation changes or are there changes in Indo-Pacific overturning? G) What about convection? H) How is the heat within the ocean redistributed and how does this affect solubility related DIC changes? I) Are there changes in intermediate water mass formation in the different basins? K) Are there changes in seasonality of T, Precip etc that affect land and ocean carbon cycling?*

Answer:
A, B, C: Changes in the temperature and precipitation fields
The figure below (new Figure 3a,b in the manuscript) shows the difference of temperature and precipitation between year 1400 (end of the FWF addition) and year 1000 (beginning of the FWF addition).The experiment considered has a fresh water flux of 0.5 Sv for 400 years in the North Hemisphere in preindustrial conditions.
The temperature change displays the bipolar seesaw pattern, with cooling in the North Hemisphere, especially with greater amplitude at high latitudes, and warming in the South Hemisphere. The precipitation pattern is more complex with generally a decrease north of 40 degrees North, a slightly increase between 15 degrees N and 40 degrees N, and a dipole closer to the equator with less precipitation around the equator and more around 25 degrees S, in link with an ITCZ shift southward.

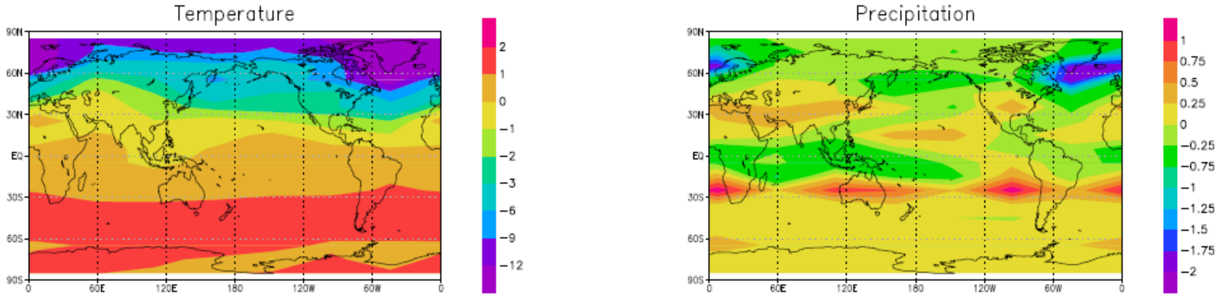

Figure R1 (new figure 3) : Difference between the average of years 990-1000 and 1390-1400 for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years for (a) air temperature (^{o}C) and (b) precipitation (mm/day).

We have added these precisions in the text:
"In agreement with past studies with CLIMBER-2 \citep{ganopolski_2001}, the alteration of the oceanic circulation leads to warming in the South Hemisphere and cooling in the North

Hemisphere, with greater amplitude at high latitudes (Figure 3a,b). The precipitation field is also modified albeit with a more complex pattern. Precipitations generally decrease north of 40 degrees N. They tend to slightly increase between 15 degrees N and 40 degrees N. As observed in other studies \citep{menviel, bozbisky}, closer to the equator a dipole forms with less precipitation around the equator and more around 25 degrees S, in link with an ITCZ shift southward."

D: Light availibility
The light availability is not considered in the terrestrial biosphere model (VECODE). It takes into account the temperature and precipitation (Brovkin et al., Ecological Modelling, 1997; Brovkin et al., Global Biogeochem. Cycles, 2002)

E: Changes in the wind field
The wind field strengthens in the North Hemisphere, especially in Asia, in the North of South America and between 60 degrees S and 40 degrees S. It tends to decrease between the equator and 15 degrees North and around 30 degrees South.

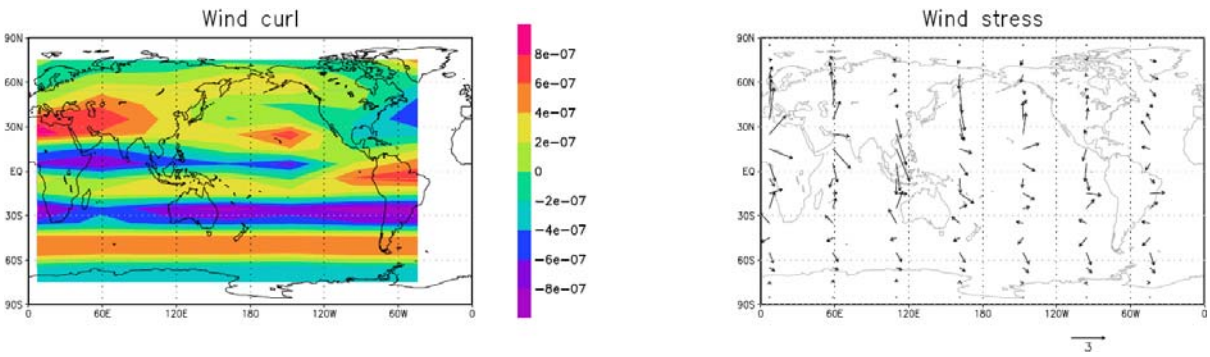

Figure R2: Difference between the average of years 990-1000 and 1390-1400 for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years for the wind curl and wind stress.

We look in more details at the changes in the ocean and the terrestrial biosphere in the following (including questions raised in F to I).

3.2. Changes in the vegetation
Referee #1: *For example, the studies which investigates changes in the terrestrial carbon cycle in most details were a study using the dynamical global vegetation model LPJ-DGVM (Köhler et al., 2005, Climate Dynamics, cited in the Bouttes paper, which includes dynamic vegetation, but no feedback from vegetation changes to climate physics) and the Bozbiyik et al. paper, with prescribed vegetation, but with feedbacks to the climate physics, see discussion in that paper). Both papers give very detailed analysis, why terrestrial carbon storage changed. In the Köhler paper the response was an interplay of a southwards shift in the northern treeline with the temperature dependent change in the soil respiration fluxes. Depending on the background climate (amount of land ice sheets) the combination of both processes led to either a CO2 peak (for present-day) or drop (LGM). The Bozbiyik paper finds more dynamics in the tropics connected with the ITCZ. This depth of analysis is missing in the Bouttes paper. It argues more on the phenomenal level, but is not going to the details.*

Concerning the differences to Schmittner and Menviel (the two other papers on the same topic) it need to be said, that Menviel uses the same vegetation model as Bouttes (VECODE) and this should be mentioned and discussed. In the description of the different scenarios the reader is sometimes confused if it is talked about "Menviel" or "Schmittner", if the authors means the other papers or the own scenarios which are labelled similarly.
From my understanding the paper needs to improve to fulfil its targets. It needs to go beyond showing time series of changes in typical variables (such as temperature, precipitation, CO2, terrestrial and marine C inventories) to a deeper understanding, what is really happening in the model. VECODE is much simpler than LPJ, (contains only three classes (trees, grass, nothing)) so maybe the changes in the terrestrial part are based on different issues (precipitation as mentioned?).
Referee #2*: 4) A) How do NPP, soil respiration rate, heterotrophic respiration, and the distribution of plant functional type change in different regions and how are these changes related to underlying drivers such as air and soil temperature, precipitation and soil moisture, or available radiation. B) How do negative and positive influences on total carbon storage balance in different regions? C) Köhler et al., find substantial changes in total carbon storage in northern mid-latitudes, whereas Bozbiyik et al., find largest total changes in the tropics. How does the response of VECODE compare to these results?*

Answer:
C: Contrary to Kohler et al., 2005 but similarly to Bozbiyik et al., 2011, in CLIMBER-2 most changes in the terrestrial biosphere happen at low latitudes, i.e. between 30° S and 30° N (new figure 7 and below). However, the changes are different (see new text below).

A, B: Overall the terrestrial biosphere looses carbon. The changes are mainly in the low latitudes where the change in NPP is mostly driven by precipitation. In the high latitudes where temperature is important the relative change of vegetation is small. The soil carbon content usually follows the change in vegetation. The more vegetation there is the more carbon is transferred to the litter and soil. However this is mitigated by the change of temperature and humidity which modify the decomposition process. The latter is increased where the climate becomes warmer and wetter, such as between 20°S and 30°S. However the effect of the increase input of carbon from the vegetation dominates.

Besides, the names of the experiments have been changed as discussed later.

In the manuscript the following paragraph discusses the change of terrestrial biosphere:
"The terrestrial biosphere reacts to both to the air temperature and precipitation changes. The main changes take place at low latitudes (Figure 7), contrary to \citet{kohler_2005b}, but as in \citet{bozbiyik_2011}. However the changes of vegetation are different in CLIMBER-2. In Africa there is an decrease of carbon in the vegetation around the equator, but an increase North of 10 degrees N and South of 10 degrees S, while in \citet{bozbiyik_2011} there is an increase between the equator and 20 degrees South. In South America there is a decrease between 10 degrees South and 30 degrees South but an increase everywhere else while in \citet{bozbiyik_2011} there is an increase between the equator and 20 degrees South on the West and a decrease in the North. Overall, the vegetation decreases in the colder and dryer North and decreases in the warmer and globally wetter South (Figure 8). However, the carbon content in the soil increases in both hemispheres. In the North the colder and dryer climate leads to less decomposition. In the South, because the vegetation increases the stock of carbon in the soils also becomes larger. Overall it results in an increase of carbon in the terrestrial

biosphere. Hence the carbon content increase is mostly driven by the soil carbon changes from the climate response."

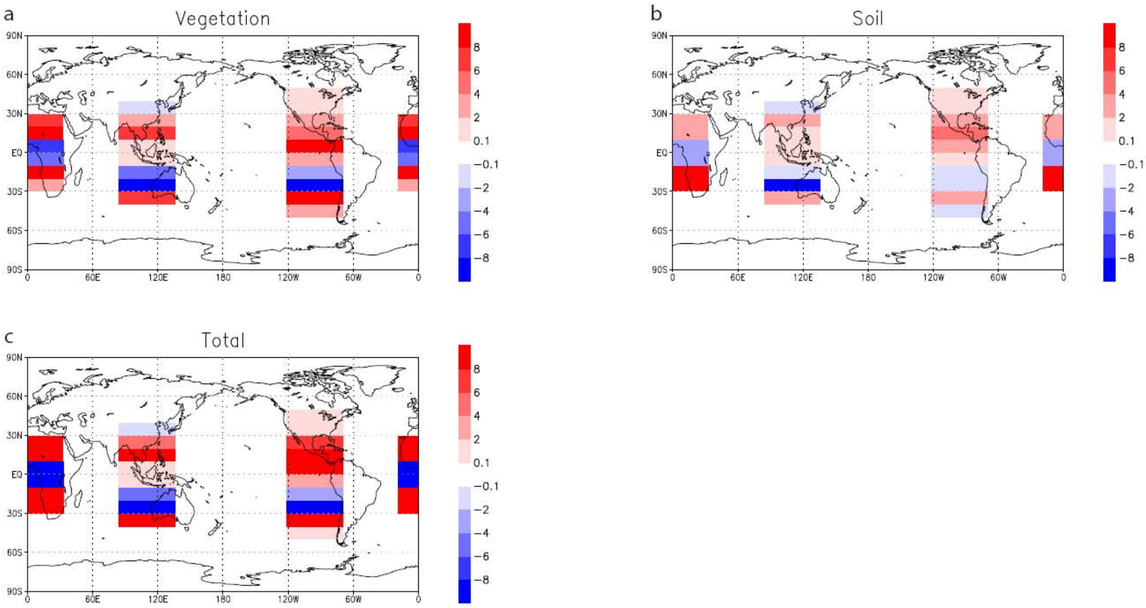

Figure R3 (new figure 7). Change of carbon content (GtC) in (a) the vegetation, (b) soil and (c) total for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years.

LGM

With LGM conditions the change of temperature and precipitation is similar, although the initial state is different. Consequently, the terrestrial biosphere also changes similarly (see figure below).

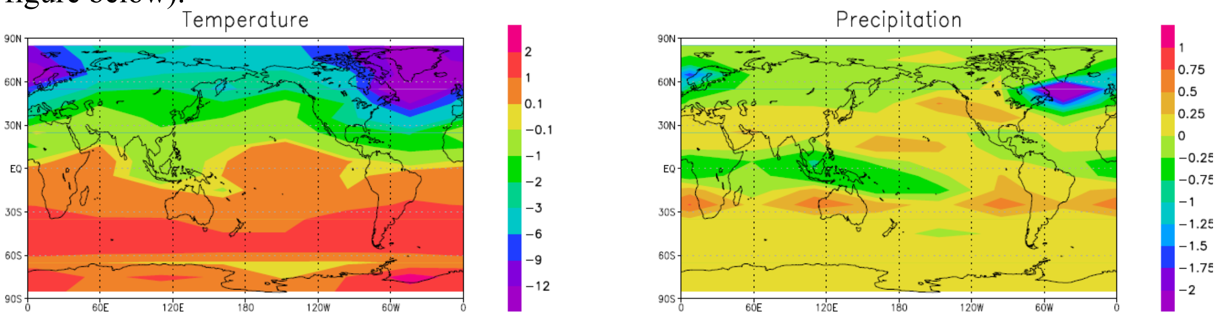

Figure R4. Difference between the average of years 990-1000 and 1390-1400 for the simulation during the LGM with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years for (a) air temperature (^{o}C) and (b) precipitation (mm/day).

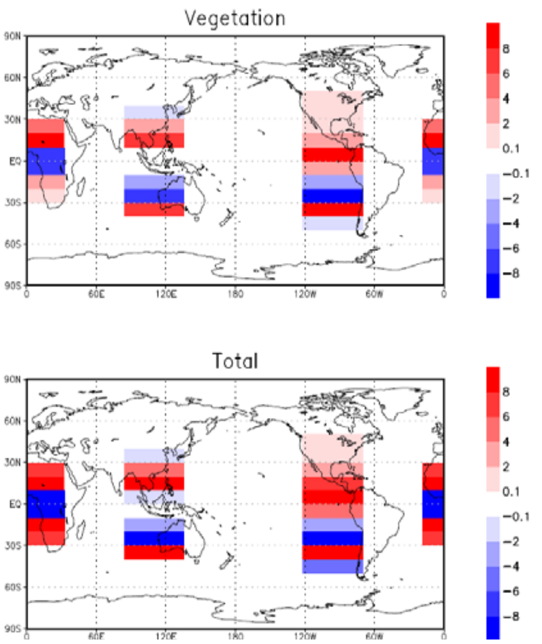

Figure R5. Change of carbon content (GtC) in (a) the vegetation, (b) soil and (c) total for the simulation during the LGM with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years.

<u>3.3 Changes in the ocean</u>

Referee #1: *For the ocean my understanding of the text so far is, that the argument of changes in the C cycle is mainly based on the solubility effect (colder ocean stores more C). Is this really explaining all? What about regional changes in NPP (biological pump). Furthermore, the authors need to tackle the results of the Bozbiyik paper. Bozbiyik for example finds, that the ocean C cycle comes to a new equilibrium, thus the ocean is not acting as passive sink to the atmospheric CO2 anomalies. What is new there and is it in (dis)agreement with the own results?*

Referee #2: *3) A) How are changes in ocean carbon storage related to changes in SSS, SST, alkalinity, organic matter, calcite, opal, iron, export productivity, dissolved organic material? B) How do the cycles of organic matter and calcite change in response to freshwater input? C) Are there changes in wind speed and air-sea gas exchange rates? D) What is the role of ocean-sediment fluxes? E) Are the changes in DIC restricted to the Atlantic or are there also changes in the SO, Pacific or Indian Ocean? F) Are there changes in oxygen concentrations?*

Answer:

A: "*SSS, SST, alkalinity, organic matter, calcite, opal, iron, export productivity, dissolved organic material*". **B**: organic matter, calcite. **C**: wind speed and air-sea exchanges. **D**: ocean-sediments fluxes.

A thorough discussion of all these variables would probably be very tedious and would distract the reader from the main physical points discussed in the manuscript, which relates mainly to ocean circulation changes and surface properties, as developed below.

E, F: see below.

- Oceanic meridional circulation, questions raised by reviewer number 2 (3.1): F (NADW), G (convection), I (intermediate waters)

The circulation changes significantly in the Atlantic with an important reduction of deep water formation in the North Hemisphere (figure below and new figure 5). There is also an increase in the subsurface between the equator and 45 degrees S. The changes are smaller in the other two basins. The Pacific displays a dipole with a slight decrease in the subsurface North Pacific and increase in the subsurface South Pacific.

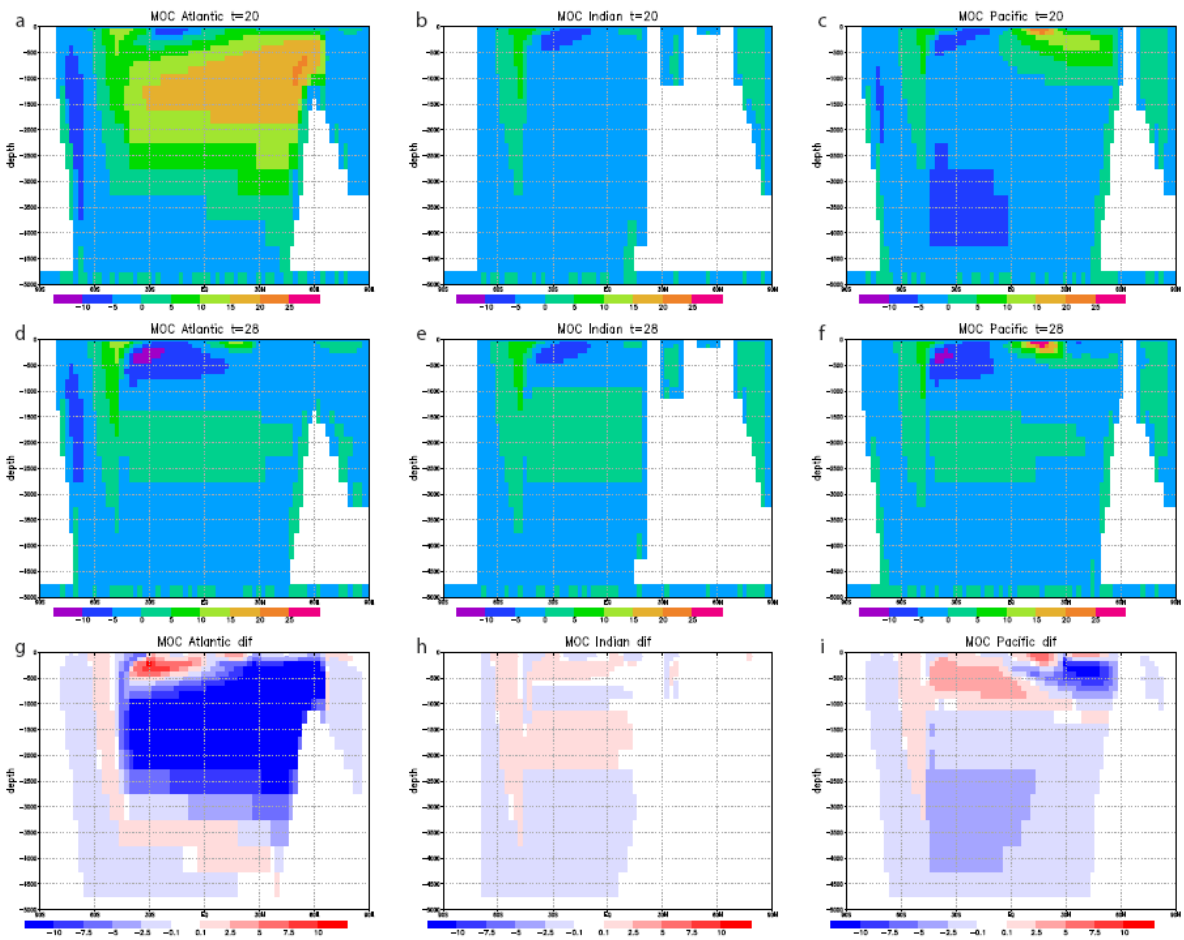

Figure R6 (new figure 5). Meridional overturning streamfunction (Sv) for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years at (a, b and c) the average of years 990-1000, (d, e and f) the average of years 1390-1400 and (g, h and i) the difference between the two for the three basins: (a, d and g) Atlantic, (b, e and h) Indian and (c, f and i) Pacific.

-Temperature, salinity and DIC, questions raised by reviewer number 2(3.1): H (T and CO2 solubility) and A, E

In the Southern Ocean, the heat penetrates down to -2000 m deep in the three basins (figure below and new figure 4). The change of temperature (cooler in the North and warmer in the South) which impacts the solubility of CO2, in association with the change of circulation, results in more DIC in the North Atlantic and at depth (figure below and new figure 6), and a relatively small area in the upper North Pacific. Because of the warming in the South there is less DIC in most of the upper part (above -2000 m) of the three basins (excepting northern parts of the Atlantic and Pacific).

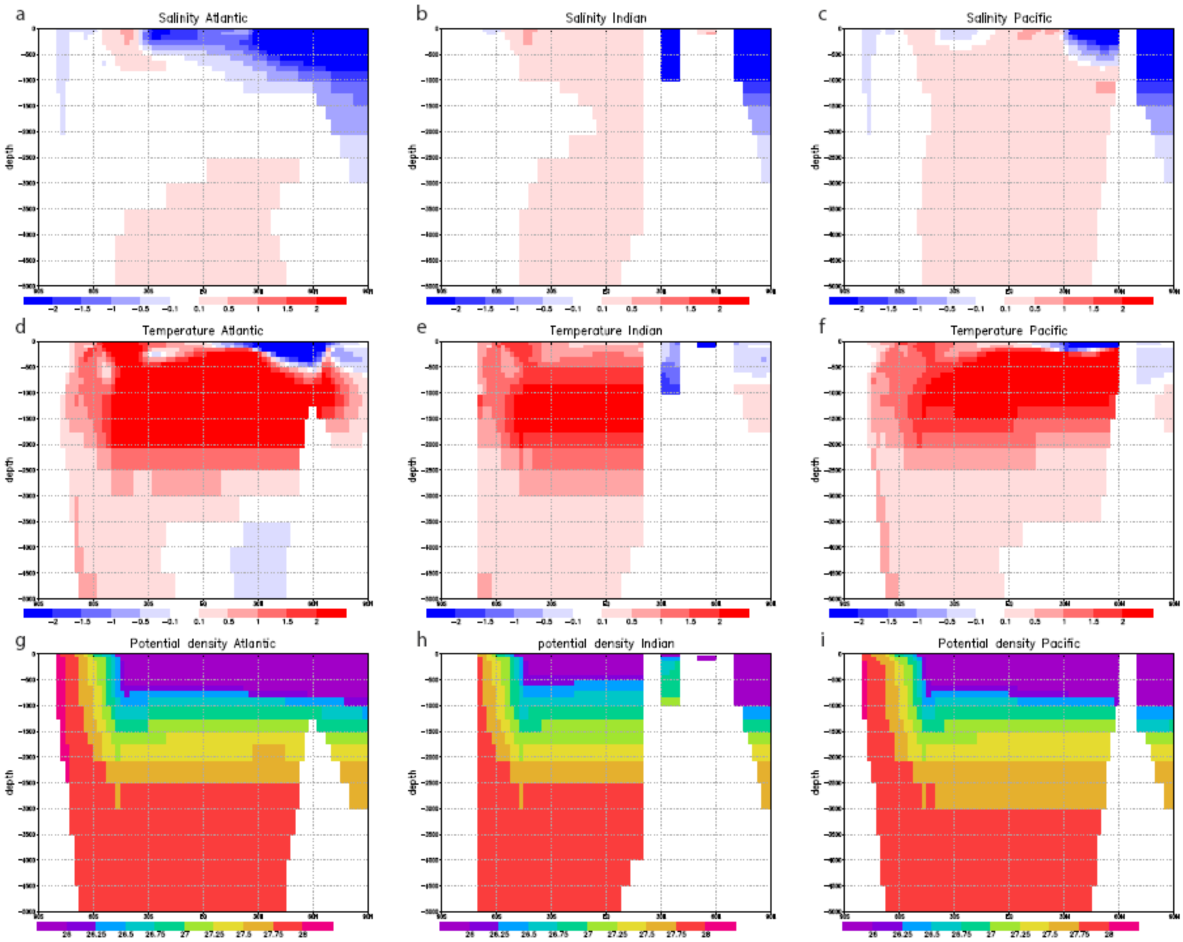

Figure R7 (new figure 4). Zonally averaged salinity, temperature and density for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years: (a, b and c) salinity difference between the average of years 990-1000 and years 1390-1400; (d, e and f)temperature difference between the average of years 990-1000 and years 1390-1400; (g, h and i) density at the average of years 1390-1400. The three basins are: (a, d and g) Atlantic, (b, e and h) Indian and (c, f and i) Pacific.

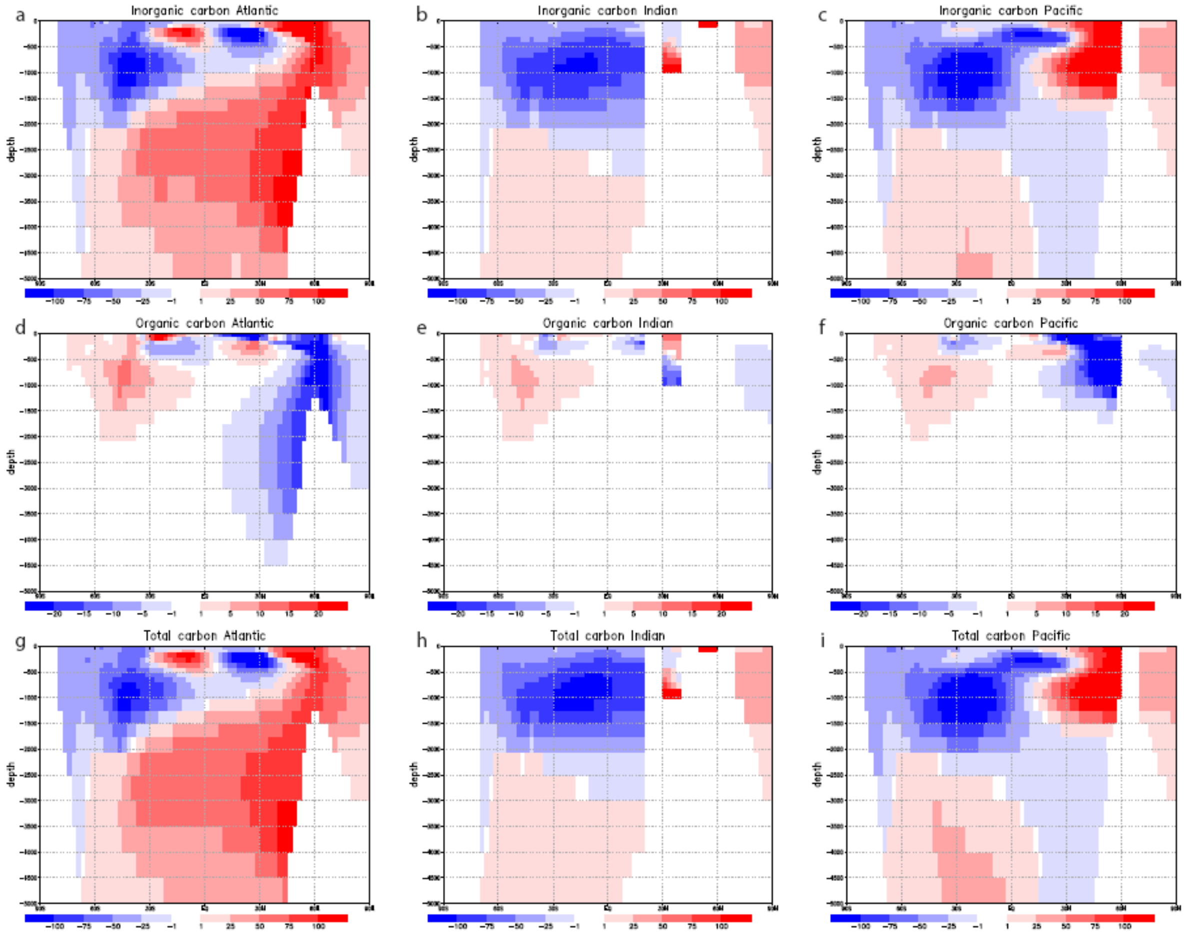

Figure R8 (new figure 6). Change of zonally averaged inorganic, organic and total carbon for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years: (a, b and c) inorganic carbon difference between the average of years 990-1000 and years 1390-1400; (d, e and f) organic carbon difference between the average of years 990-1000 and years 1390-1400; (g, h and i) total carbon difference between the average of years 990-1000 and years 1390-1400. The three basins are: (a, d and g) Atlantic, (b, e and h) Indian and (c, f and i) Pacific.

- Sea ice

The sea ice cover greatly increases in the high latitudes North (see figure below), especially in the Atlantic and to a less extent in the Pacific. It thus prevents the air-sea gas exchange on a greater area.

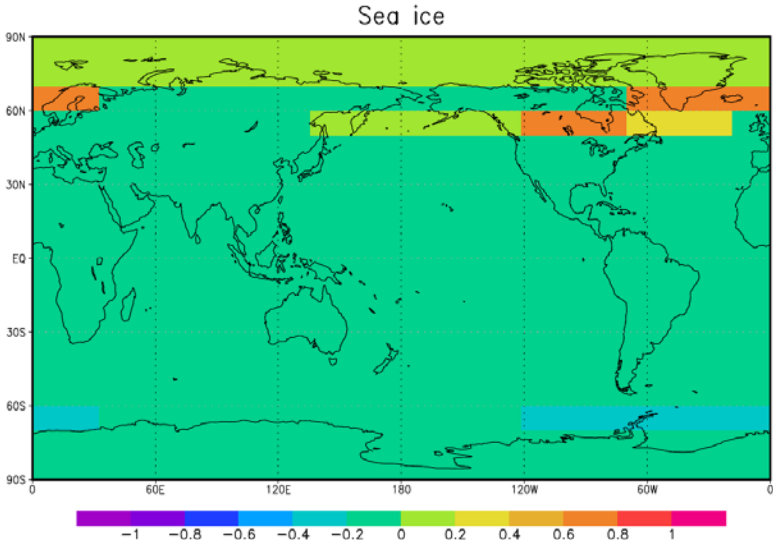

Figure R8. Change of the fraction of the cell covered by sea ice in the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years. The difference is between the average of years 990-1000 and years 1390-1400.

- Oxygen (F)

Similarly to the DIC, the oxygen concentration tends to mostly decrease in the North Atlantic due to the shut-down of the AMOC. It also decreases in the subsurface of the North Pacific where the circulation has decreased. It increases in the subsurface (mostly between -1500 and -250 m) in the South Atlantic (between 30 and 60 degrees South), the Indian and the South Pacific.

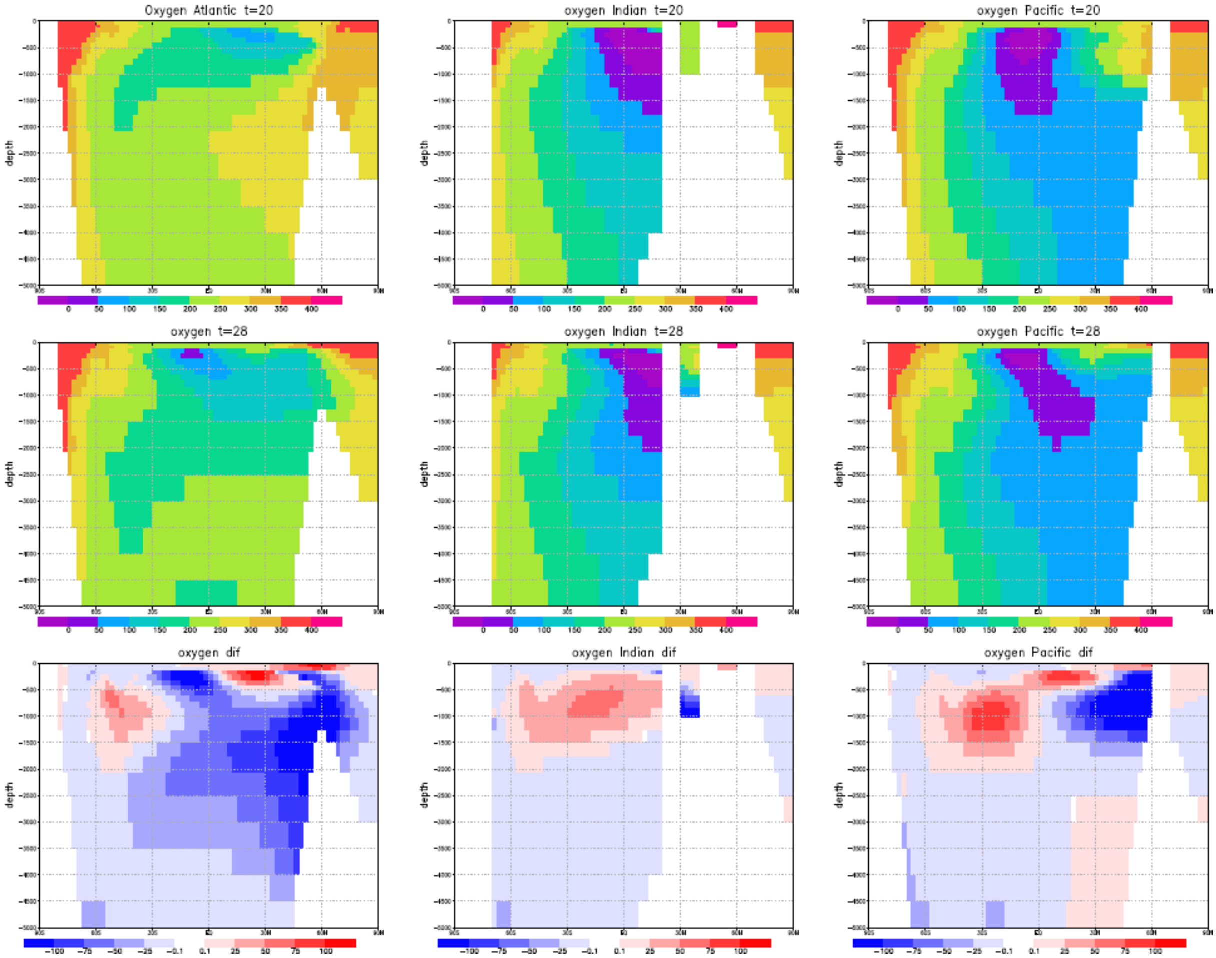

Figure R9. Oxygen distribution (µmol/kg) for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years at (a, b and c) the average of years 990-1000, (d, e and f) the average of years 1390-1400 and (g, h and i) the difference between the two for the three basins: (a, d and g) Atlantic, (b, e and h) Indian and (c, f and i) Pacific.

In the manuscript, the following paragraph has been added:
"In the ocean, because of the addition of fresh water in the North Atlantic, the salinity decreases (Figure 4a) and the formation of deep water in the North Atlantic shuts down (Figure 5a). The potential density becoming relatively denser in the South Hemisphere (Figure 4g, h and i) it gives rise to the formation of intermediate water in the three basins (Figure 5). Because of the warming in the South Hemisphere it brings warm water deeper so that heat penetrates in the upper part of the ocean (above -2000m, Figure 4d, e and f). Due to the lowering of the solubility of CO$_2$ in warmer water, this upper part of the ocean (which excludes smaller areas in the northern part of the Atlantic and Pacific) contains less inorganic carbon (Figure 6a, b and c). In the deep ocean (below -2000m) and in the northern parts of the Atlantic and Pacific, there is more carbon as the exchange with the surface has diminished, the carbon can stay longer. Moreover the surface in the North Hemisphere is cooler and can contain more carbon. The greatest change in the organic carbon happens in the northern part of the North Hemisphere (Figure 6d, e and f). Because the sea ice covers a greater area, the light availibility diminishes and so does the production of organic carbon. But this effect is smaller compared to the change of inorganic carbon which dominates (Figure 6). Overall, the

loss of carbon from most of the upper ocean (especially in the South) dominates leading to a net loss of carbon from the ocean."

4. Other comments

Referee #1: *Throughout the text I think the wording could be more specific. Sometimes we read things like "In Menviel et al. (2008) the ocean first takes up more carbon then looses it, while the vegetation looses carbon then takes it up." When do the changes occur with respect to the freshwater fluxes? This is a little bit too sloppy.*
Answer: The sentence has been modified as follow:
"In \citet{menviel_2008b}, as soon as the AMOC decreases due to the addition of fresh water flux, the ocean takes up carbon and the terrestrial biosphere releases carbon. Then, in a second phase, the opposite occurs."

Referee #1*: In the abstract it reads "atmospheric CO2 concentration rapidly increases and decreases by around 15 ppm at the same time as climate experiments an abrupt cooling in the North Hemisphere and warming in the South Hemisphere." I think the ice core data show things a little bit different. CO2 changes as gradually as Antarctic temperatures, so not rapidly as suggested here (how rapid is rapid?) and CO2 normally switches from increasing trends to decreasing trends when both Antarctic temperature switches from warming to cooling and Greenland temperature happens to rapidly rise. You might also note ()and maybe comment on) the different behaviour of some Dansgaard/Oeschger events in MIS 4 and for the Bolling/Allerod as discussed in Ahn and Brook (2008) and in a recent paper in Climate of the Past (Köhler, P.; Knorr, G.; Buiron, D.; Lourantou, A. Chappellaz, J. Abrupt rise in atmospheric o at the onset of the Bølling/Allerød: in-situ ice core data versus true atmospheric signals, Climate of the Past, 2011, 7, 473-486). It is furthermore not correct to speak of temperature changes in the northern and southern hemisphere, because the bipolar seesaw leads to different (more gradual) changes in Antarctica than in the South Atlantic because of the heat capacity of the Southern Ocean, see Barker et al 2009, NG and Stocker and Johnsen 2003, PO for details, see also next comment.*
Referee #2: *Abstract: line 1 to 3 This first sentence does not portray the paleo record and the statements are wrong. CO2 changes roughly in parallel with the Antarctic temperature.*
Answer: This sentenced has been changed and has been replaced by: "During glacial periods, atmospheric CO2 concentration increases and decreases by around 15 ppm at the same time as climate experiments abrupt changes in Antarctica."

Referee #1: *The introduction needs also some more clarification. The description of the bipolar seesaw is not precise. It reads "... are characterised by cool conditions in the north and simultaneous gradual warming in the south, followed by a return close to initial values (EPICA community members, 2006; Ahn and Brook, 2008; Barker et al., 2009). During these events, ice core records indicate that atmospheric CO2 increases rapidly by around 15 ppm, and then decreases back to its initial level (Ahn and Brook, 2008)." This is in detail not correct: The bipolar seesaw describes a gradual warming in the south during cool conditions in the north, which flips to gradual cooling conditions in the south during a abrupt warming in the north. Where here "south" means Antarctica, while in the South Atlantic the changes in temperature should be as fast as in Greenland (see Barker et al., 2009). Details on that were elaborated first by Stocker, T. F. Johnsen, S. J. A minimum thermodynamic model for the*

bipolar seesaw Paleoceanography, 2003, 18, 1087, doi: 10.1029/2003PA000920, which was not cited. Furthermore the changes in CO2 are NOT rapid, they are as fast (or slow) as the gradual southern warming. These details should also put right in the abstract.
Answer: The introduction has been changed to the following:
"During glacial periods, the global climate experiences rapid temperature shifts as recorded by numerous proxies from ice and sediment cores. These changes, called abrupt events \citep{clement_2008}, are characterized by an abrupt warming followed by a cooling in the North Hemisphere. In the South hemisphere, Antarctica starts warming before Greenland, then temperature decreases when it rapidly increases in Greenland \citep{epica_2006,ahn_2008,barker_2009}. During these events, ice core records indicate that atmospheric CO$_2$ increases rapidly by around 15 ppm within 2,000 to 4,000 years, and then decreases back more gradually than the Antarctic temperature decline \citep{ahn_2008}."

Referee #1: *The review of Kageyama et al., 2010 on simulated changes in the AMOC is mentioned in the discussion, but it might also be mentioned right at the beginning (intro), or/and the discussion section needs to be expanded largely. Please also note, that in Kageyama new model experiments of LOVECLIME and UVic are investigated, the two models used in Schmittner and Menviel and thus the model discrepancies concerning the physics of the climate system (not the C cycle) between these two studies might have been analysed there already.*
Answer: In agreement with the suggestion we discuss the results of LOVECLIM and UVic from Kageyama et al., 2010. Please see the response to L. Menviel above.

Referee #1: *What are the data saying? Can you reproduce the rapid temperature shift in the South Atlantic as illustrated by Barker et al., 2009? For example, there was a whole special issue in QSR (Volume 29, Issues 21-22, Pages 2823-2980, October 2010) on "Vegetation Response to Millennial-scale Variability during the Last Glacial", which also included the Kageyama paper. I do not think that every details found in paleo data should be compared with the model, but some main features might need to be discussed. For example, the Bozbiyik paper find large changes in terrestrial C in South America and therefore discusses proxy evidences for that during the Younger Dryas cold period.*
Answer: Because CLIMBER-2 is a low resolution intermediate complexity model it has allowed us to test numerous different fresh water fluxes with different background climate states. However, due to its low resolution it is not a model very well suited for regional comparisons contrary to much more complex models such as the GCM used in Bozbiyik et al., 2011. Besides, CLIMBER-2 also simulates important changes in South America as Bozbiyik et al., 2011, although with a different pattern (see figure 7).

Referee #1: *For the design of the experiments (sec 2.3) you might not only discuss, what Schmittner and Menviel were doing, but also what freshwater fluxes others were using (see again Kageyama, e.g. Knutti using ECBILT-CLIO (same physics as LOVECLIM = Menviel)) used 0.3-0.5 Sv (used in Köhler et al. 2005), Bozbiyik used up to 1 Sv put in either the North Atlantic or two different areas in the Southern Ocean.*
Answer: A difficulty in comparing model results arises from the very different model setting used in the literature, in particular in terms of freshwater fluxes. Moreover, the models generally have a different sensitivity to the additional fresh water flux. Hence the amplitude of the fresh water flux is not as important as the response of the AMOC. In the simulations we

have tested different fresh water fluxes to study the effect of different AMOC changes. The shape, duration, amplitude and location of the fresh water fluxes span a large range and some of them are similar to other studies with intermediate complexity carbon-climate models so that it is easier to compare the results.

Referee #2: *5) Why are there no factorial experiments to disentangle different drivers or to distinguish between land and ocean changes?*
Answer: Factorial experiments would require an important number of additional simulations. Moreover, **t**he effect of the geochemical feedback from the change of CO2 is small because the modelled CO2 change is itself small. Most of the changes are thus driven by the physical changes, contrary to the simulations run in the context of the IPCC.

Referee #2: *7) Shortcomings are general features of models. a) I miss a discussion on potential limitations and shortcomings of this study and CLIMBER 2. b) The authors should place their model in the available model hierarchy and highlight deficiencies that are potentially relevant for the current study. A discussion on how the choice of CLIMBER 2 could affect conclusions should be provided. For example, more sophisticated model studies and proxy data reveal a shift in the ITCZ in response to an AMOC shutdown. How is this represented in the statistical atmosphere of CLIMBER 2. The 2-d ocean of CLIMBER 2 has been developed about 20 years ago. Changes in AMOC can be related to shifts in convection pattern and the 3-dimensional structure of ocean circulation could affect results. VECODE features a very limited set of plant functional types, e.g. in comparison to the LPJ model used by Köhler et al., 2005. How those CLIMBER 2 compare to models applied in other studies. What are strengths and weaknesses? How could the inclusion of a peat module affect results?*
Answer: CLIMBER-2 has some advantages and drawbacks. As discussed above the shift of the ITCZ location, which is linked to the atmospheric temperature meridional structure, is simulated with CLIMBER (figure 3).
As suggested a discussion on them has been added in the manuscript:

"CLIMBER-2 is an intermediate complexity model that can run very fast (approximately 1000 years in an hour) which is a great advantage to run numerous simulations for a long time. In particular it allows us to test different fresh water fluxes (changes in amplitude, duration, shape and location) in the context of different climates (preindustrial and glacial). It also allows analyzing what happens for a few thousand years after the addition of the fresh water flux. However the rapidity of CLIMBER-2 is balanced by some simplifications such as the coarse resolution and zonally averaged ocean. Such simplifications can have different impacts in the context of fresh water flux experiments. First the gyres and the ACC are prescribed in the model, whereas in reality they could change. It can also introduce some biases in the carbon cycle such as too much remineralization in intermediate waters. Yet the temperature distribution in the ocean seems to be coherent with other models. The use of a simplified atmospheric model could result in less realistic precipitation fields which then impact vegetation. Nonetheless, the pattern of precipitation change is not very different from other models. The terrestrial biosphere is also a simple one with only two types of vegetation: grass and tree, which is also used in LOVECLIM. Finally the low resolution can have an impact especially on the vegetation distribution which might change more on regional scales."

Referee #2: *8) The suggestion on page 1374, line 23 ff that the CO2 amplitude and the duration of the AMOC shut-down can be used as a proxy for the initial 'rate of AMOC'*

appears not realistic given the wide range of responses found in different studies. This claim should be deleted.
Answer: As highlighted by the reviewer the response found in different studies spans a wide range, we have thus modified the sentence as follow, the link between the duration of the AMOC shut down and the change of CO2 being until now qualitative and not quantitative yet. “The CO$_2$ amplitude change during AMOC shutdown thus gives an indication of the length of disruption of the AMOC.”

Referee #2: *9) 1377, conclusion: The conclusion that the model results support the crucial roles of brines (as parameterized in CLIMBER 2) appears hard to defend given the small differences between simulations with and without brine parameterization (Fig 5,6, 8) and the large uncertainties surrounding the terrestrial and oceanic responses. This claim should be deleted.*
Answer: This part has been deleted and the conclusion has been rewritten as follow:
“In conclusion, we have explored the impact of different fresh water fluxes in several climate background states with the CLIMBER-2 model. The duration, amplitude, and shape of the fresh water flux all modulate the evolution of the carbon cycle. The longer or greater the flux, the bigger the increase of atmospheric CO$_2$ is. However they cannot explain the differences obtained in different models, i.e. why in some models the ocean takes up carbon while the vegetation releases it, and the opposite in other models. In CLIMBER-2 the AMOC takes time before it recovers, which can lead to a greater role of the deeper ocean. The different background states have an important impact on the carbon cycle, especially as the carbon inventory between the three reservoirs: the ocean, terrestrial biosphere and atmosphere, is different. Taking into account the sinking of brines in the Southern Ocean in a glacial climate allows CO$_2$ to start from a value which is closer to proxy data and gives a more similar evolution compared to the ice core records. The location of the fresh water flux has a strong impact on the evolution of the carbon cycle as it results in a very different climatic response. In CLIMBER-2 it leads to a decrease of CO$_2$ contrary to the addition of fresh water in the North Hemisphere. Finally, as shown by previous studies the response of the carbon cycle strongly depends on a close interplay between the ocean and vegetation responses. The results are very model dependent, both because of the response of the AMOC to the addition of fresh water and because of the climatic response to this fresh water flux. Better understanding of these differences will require an intercomparison of the impact of the addition of fresh water fluxes in carbon-climate models.”

Referee #1: *Furthermore, the comparison of your freshwater experiments with that of Schmittner is incomplete. Schmittner in UVic needs to have a negative freshwater flux to get the AMOC back on again (Fig 2b top in their paper).*
Answer: In CLIMBER-2 it is not necessary to apply a negative fresh water flux to get the AMOC again hence we do not apply it. It is now mentioned in the manuscript:
“We consider three sets of additional fresh water fluxes (Figure 1). The first one (``duration'') is similar to the \citet{schmittner_2008} experiments in which the duration of the fresh water flux varies between 400 years and 1700 years, with an amplitude of 0.2 Sv (Figure 1a), although here no negative flux is applied at the end contrary to \citet{schmittner_2008}, as it is not necessary for the circulation to start again in CLIMBER-2”

Referee #1: *Concerning the physics of your results, the temperature anomalies shown on Fig 3, 4, 7 is not the typical behaviour of the bipolar seesaw. The northern hemispheric* *temperature rise at the end of the freshwater flux is in your results very gradual and not abrupt. Maybe one needs to show time series of specific regions. The temperature anomaly in Schmittner covers the behaviour more closely to the data than here (but as said above, Schmittner needs a negative freshwater flux at the end, maybe you should investigate this also). This model results / disagreement to the data needs to be discussed more widely. For my understanding there are only a few model application available, which are able to generate the right speed and magnitude in the temperature change as seen in the Greenland ice cores, e.g. see Smith, R. S. Gregory, J. M. A study of the sensitivity of ocean overturning circulation and climate to freshwater input in different regions of the North Atlantic, Geophysical Research Letters, 2009, 36, L15701, doi: 10.1029/2009GL038607. From the NGRIP ice core it was shown that temperature / climate changes within about 50 yr, while the change in the _18O is even happening in less than 10 yr, see Steffensen, J. P.; Andersen, K. K.; Bigler, M.; Clausen, H. B.; Dahl-Jensen, D.; Fischer, H.; Goto-Azuma, K.; Hansson, M.; Johnsen, S. J.; Jouzel, J.; Masson-Delmotte, V.; Popp, T.; Rasmussen, S. O.; Rothlisberger, R.; Ruth, U.; Stauffer, B.; Siggaard-Andersen, M.-L.; Sveinbjörnsdóttir, A. E.; Svensson, A. White, J. W. C. High-resolution Greenland ice core data show abrupt climate change happens in few years, Science, 2008, 321, 680-684, doi: 10.1126/science.1157707.*

Answer:

In Schmittner et al., 2008, the Greenland temperature closely follows the evolution of the AMOC. The temperature thus increases when the AMOC recovers. Because the AMOC stays in the "off" mode after the fresh water flux has stopped the temperature also stays at low value. It is only when a negative fresh water flux is added that the AMOC recovers and the temperature increases. The abrupt temperature increase is thus very dependent on the negative freshwater flux applied. In CLIMBER-2, as in other models such as LOVECLIM there is no need for a negative freshwater flux to have the AMOC recover. Adding a negative freshwater flux would make the AMOC recovery and the temperature increase more abrupt, however such an experiment has no physical basis. It would nonetheless be interesting as sensitivity experiments in future studies. It also potentially highlights a missing mechanism in the link between the AMOC evolution and the addition of fresh water flux, if the fresh water flux does not result in an abrupt enough response of the AMOC. This is beyond the scope of this study which focuses on the impact of the fresh water flux on the atmospheric CO2. Moreover, as noted by the reviewer temperature changes can differ locally. However CLIMBER-2 is not well suited for regional studies as discussed previously.

Referee #1: *In the LGM (and LGM+brine) experiments only CO2 radiative forcing is changed. What about changes in CH4 and N2O? For LGM they contribute together about –0.6 W m□2 to the radiative forcing, while CO2 is responsible for –2.1 W m□2. As said already, the results section needs a good revision to get more precise description of the results.*

Answer: As done previously, CH4 and N2O are not explicitly considered in the model, but the CO2 is an "equivalent CO2" that considers the change of CH4 and N2O (Brovkin et al., 2007). This precision has been added in the text in the method section:

"CH$_4$ and N$_2$O are not explicitly considered in the model, but the CO$_2$ is an ``equivalent CO$_2$'' that considers the change of CH$_4$ and N$_2$O \citep{brovkin_2007}."

Referee #1: *Page 1369: "When the additional fresh water flux is too small to change the AMOC (below the threshold value of 0.2 Sv) the resulting change of CO2 is small (less than 10 ppm, Fig. 2c and f)." This is not correct. AMOC changes in all experiments, it needs to say*

“STOPPING AMOC” or “switching to off mode” or so. Furthermore, I see in Fig 2 changes of less than 5 ppvm, not less than 10 ppmv, but maybe the details are difficult to see here.
Answer: The suggested changes have been made in the text:
“When the additional fresh water flux is too small to stop the AMOC (below the threshold value of 0.2 Sv the AMOC does not switch to the ``off'' mode)” the resulting change of CO$_2$ is small (less than 5 ppm, Figure 2 c and f)

Referee #1: *The section 3.4 (discussion and data) is very short. Is your experiment comparable to all Heinrich stadials or to all Dansgaard/Oeschger events? Concerning the idea of an impact of the freshwater fluxes in the Southern Ocean, and the Bolling Allerod, is this connected to meltwater pulse 1A? Please also see a recent paper on a different interpretation of this CO2 (Köhler et al. 2001 Clim Past, full citation was already given above).*
Answer: As is always the case with model experiments, a close comparison with data is difficult since the experimental setup is closer to a sensitivity experiment than to a true simulation of some specific event. Using a LGM basis is better than using a pre-industrial one, but the climate or the ice sheet size at the time of most Heinrich or DO events is quite different from LGM. Similarly, our experiment with a FWF in the south is more a theoretical experiment than a suggestion of a connection between MWP1A and the Bolling-Allerod.

Referee #1: *In the caption to Fig 10 you should say right at the beginning (not the end) that here freshwater was put into the Southern Ocean, not North Atlantic, to give the reader a chance to see quickly what is plotted here.*
Answer: It is now stated at the beginning of the caption:
“Evolution of oceanic variables in respnse to the addition of fresh water fluxes in the South Atlantic following the ``Amplitude'' experiments (Figure 1c). (a, b) NADW export (Sv) (maximum of the AMOC), (c, d) AABW export (Sv) (minimum of the AMOC, the sign indicates that the transport is from the South to the North), (e, f) atmospheric CO$_2$ (ppm), (g, h) carbon content anomaly in the terrestrial biosphere (GtC) and (i, j) carbon content anomaly in the ocean (GtC). The simulations are performed with two background climate states: (a, c, e, g, i) during the Last Glacial Maximum (LGM) and (b, d, f, h, j) during the Last Glacial Maximum with the sinking of brines (LGM+brines).”

Referee #2*:* *Line 12 to 15: These are not new findings and have been highlighted before*
Answer: This part has been deleted and the abstract rewritten. The new abstract is now:
“During glacial periods, atmospheric CO$_2$ concentration rapidly increases and decreases by around 15 ppm at the same time as climate experiments abrupt changes. Such climate changes can be triggered in models by adding fresh water fluxes in the North Atlantic. Yet the impact on the carbon cycle is less straightforward, and previous studies give opposite results. Because both models and added fresh water fluxes were different in these studies, it prevents any direct comparison and hinders finding whether the discrepancies arises from using different models or different fresh water fluxes. In this study we use the CLIMBER-2 coupled climate carbon model to explore the impact of different additional fresh water fluxes in various background conditions. In both preindustrial and glacial states the addition of fresh water flux and resulting slow down of the AMOC lead to an uptake of carbon by the ocean and release by the terrestrial biosphere. The different duration, amplitude and shape of the fresh water flux cannot explain the opposite evolution of ocean and vegetation carbon inventory in different models. The different CO$_2$ evolution thus depends on the AMOC

response to the addition of fresh water flux and the resulting climatic change, both model dependent. In CLIMBER-2, the increase of CO$_2$ recorded in ice cores during abrupt events can be simulated in glacial conditions, especially when the sinking of brines in the Southern Ocean is taken into account. The addition of fresh water flux in the South Hemisphere leads to a decrease of CO$_2$, contrary to the fresh water flux in the North Hemisphere."

Referee #2: *Line 1, line 15: What means "rapid"*
Answer: "rapid" is no more in the abstract, so we have added some detail in the introduction: "During these events, ice core records indicate that atmospheric CO2 increases rapidly by around 15 ppm within 2,000 to 4,000 years"

Referee #2: *Line 17/18: This sentence is unclear.*
Answer: This sentence has been erased in the process of rewriting the abstract (see before).

Referee #2: *Line 20 to 23: I do not believe that this statement is accurate and entirely true. What about sensitivities of different carbon cycle models to the same changes in physical drivers?*
Answer: This statement has also been deleted and is not present any more in the new abstract.

Referee #2: *Page 1365, line5: does CO2 really decrease to its initial level? The ice core records shows it differently.*
Answer: In most of the abrupt events recorded between approximately 65000 and 30000 years ago CO2 decreases back to a value close to the initial one. But before 65000 years ago it stops at a higher level and after 30000 years ago at a lower level (excluding the deglaciation). This sentence has been erased and replaced by the following one:
"During these events, ice core records indicate that atmospheric CO$_2$ increases rapidly by around 15 ppm within 2,000 to 4,000 years, and then decreases back more gradually than the Antarctic temperature decline \citep{ahn_2008}."

Referee #2: *1365, line 27: there are more than two modeling studies available.*
Answer: As advised earlier other studies have been added.

Referee #2: *1368, figure 1 etc. The freshwater fluxes should be described by their form, rectangular and triangular, as done in earlier studies. Calling them Schmittner and Menviel scenarios is too much of a personal call and is not accurate as these types of freshwater release have been used much earlier.*
Answer: As suggested, the experiments have been renamed as: "duration", "triangle" and "amplitude".

Referee #2: *1370, line 24: "waters are less soluble" – language*
Answer: The sentence has been changed to:
"because of the temperature rise, the solubility of CO2 in the ocean diminishes and therefore the ocean takes up less carbon."

Referee #2: *1370, line 24: A quantitative and regional analysis is required that includes also the other driving forces.*

Answer: As suggested in more details in previous comments additional analysis has been provided (see before).

Referee #2: *1373, line 19 to 21: So what is the insight here?*
Answer: It is not an insight, just an observation.

Referee #2: *Fig 3 and fig. 7 could be easily combined.*
Answer: the former figures 3 and 7 have now been modified and combining them would likely make the discussion more complex.

Manuscript prepared for Clim. Past Discuss.
with version 2.2 of the LaTeX class copernicus_discussions.cls.
Date: 30 September 2011

Systematic study of the fresh water fluxes impact on the glacial carbon cycle

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Abstract

During glacial periods, atmospheric CO_2 concentration increases and decreases by around 15 ppm at the same time as climate experiments abrupt changes in Antarctica. Such climate changes can be triggered in models by adding fresh water fluxes in the North Atlantic. Yet the impact on the carbon cycle is less straightforward, and previous studies give opposite results. Because both models and added fresh water fluxes were different in these studies, it prevents any direct comparison and hinders finding whether the discrepancies arise from using different models or different fresh water fluxes. In this study we use the CLIMBER-2 coupled climate carbon model to explore the impact of different additional fresh water fluxes in various background conditions. In both preindustrial and glacial states, the addition of fresh water flux and resulting slow down of the AMOC lead to an uptake of carbon by the ocean and release by the terrestrial biosphere. The different duration, amplitude and shape of the fresh water flux cannot explain the opposite evolution of ocean and vegetation carbon inventory in different models. The different CO_2 evolution thus depends on the AMOC response to the addition of fresh water flux and the resulting climatic change, both model dependent. In CLIMBER-2, the increase of CO_2 recorded in ice cores during abrupt events can be simulated in glacial conditions, especially when the sinking of brines in the Southern Ocean is taken into account. The addition of fresh water flux in the South Hemisphere leads to a decrease of CO_2, contrary to the addition of fresh water flux in the North Hemisphere.

1 Introduction

During glacial periods, the global climate experiences rapid temperature shifts as recorded by numerous proxies from ice and sediment cores. These changes, called abrupt events (Clement and Peterson, 2008), are characterized by an abrupt warming followed by a cooling in the North Hemisphere. In the South hemisphere, Antarctica starts warming before Greenland, then temperature decreases when it rapidly increases in Greenland (EPICA community members, 2006; Ahn and Brook, 2008; Barker et al., 2009). During these events, ice core records indicate that atmospheric CO_2 increases rapidly by around 15 ppm within 2,000 to 4,000 years, generally synchronously with Antarctic warming, and then decreases back more gradually than the Antarctic temperature decline (Ahn and Brook, 2008).

Fresh water flux (FWF) inputs in the Atlantic Ocean have been suggested as a trigger for such abrupt changes. Model simulations show that adding fresh water fluxes into the North Atlantic results in a significant Atlantic Meridional Overturning Circulation (AMOC) decrease (Stocker and Wright, 1991; Ganopolski and Rahmstorf, 2001). It leads to less heat being transported from the South Hemisphere to the North Hemisphere, hence a cooling in the north and warming in the south (the "bipolar seesaw", (Crowley, 1992; Stocker, 1998)). Proxy data (presence of ice rafted debris), indicate that massive iceberg discharges happened simultaneously with some of these events (Heinrich events), which brings support to the hypothesis of fresh water input (Bond et al., 1993; Heinrich, 1988; Ruddiman, 1977). Yet the causes of the iceberg discharges are still debated (Alvarez-Solas et al., 2010).

Additionally, models studies have shown that fresh water inputs can also impact the carbon cycle. However, studies of the impact of fresh water fluxes on atmospheric CO_2, especially during glacial periods, are sparser and their results vary widely. Using an ocean model only, Marchal et al. (1998) simulated a CO_2 increase of 10-30 ppm due to the decrease of ocean solubility (caused by the warming of the southern hemisphere) during preindustrial conditions. On the other hand, simulations performed with a terrestrial biosphere model also give a CO_2 increase of approximately 6 ppm and then a decrease back to the initial value (Köhler et al., 2005) with glacial conditions, with a fresh water flux of 0.3 Sv during 1000 years. When both the ocean and terrestrial biosphere are taken into account, it results in the coupling of the three main carbon reservoirs relevant for such time scales of a few thousand years, i.e. the ocean, terrestrial biosphere and atmosphere. In preindustrial conditions, two Atmosphere-Ocean Global Climate Model (AOGCM) and an intermediate complexity model (EMIC) give a CO_2 increase in response to the addition of fresh water in the North Atlantic, mostly due to a decrease of terrestrial biosphere (Obata, 2007; Bozbiyik et al., 2011; Menviel et al., 2008). Additionally, two intermediate complexity climate-biogeochemical models were also used with glacial conditions. The UVic model results in a CO_2 increase of 25 ppm when forced by 0.2 Sv during 1700 years (Schmittner and Galbraith, 2008). The atmospheric CO_2 increase is due to the ocean which looses carbon, while the terrestrial biosphere stores more carbon. Another study gives opposite results, with the ocean taking up more carbon and the terrestrial biosphere less, resulting in a CO_2 decrease of around 13 (Menviel et al., 2008) (with the FWF input as a triangular function increasing up to 2 Sv during 200 years). Such different results could arise from the differences in the models themselves, the type of experiments (i.e. the type of fresh water fluxes added) or the background climate state considered (e.g. relatively cold/warm climate). To disentangle these effects we use a single model and test the impact of different fresh water flux experiments and different climate states.

In this study, we perform simulations with a an intermediate complexity climate-carbon coupled model that includes the ocean and the terrestrial biosphere. We systematically study the impact of different fresh water fluxes by modifying their amplitude, shape and duration, with three different background climate conditions. We first perform similar simulations as Schmittner and Galbraith (2008) and Menviel et al. (2008) by adding fresh water fluxes of different duration and shape in the North hemisphere in Preindustrial and Last Glacial Maximum (approximately 21,000 years ago) conditions, which allow a direct comparison to their results (Figure 1a, b). We also run additional simulations with different amplitudes of the fresh water flux to assess its impact (Figure 1c). We then explore the impact of the same fresh water fluxes in a situation with more realistic glacial CO_2 levels obtained with the ”brines sinking” mechanism previously studied (Bouttes et al., 2010, 2011). Finally we evaluate the impact of adding fresh water fluxes in the Southern Hemisphere.

2 Methods

2.1 CLIMBER-2 climate-carbon model

We use the climate-carbon coupled model CLIMBER-2 (Petoukhov et al., 2000; Ganopolski et al., 2001; Brovkin et al., 2002, 2007). CLIMBER-2 is a model of intermediate complexity fast enough to run numerous long simulations. The simulations are run for 20,000 years to ensure the carbon cycle equilibrium. Running numerous simulations allows us to span various fresh water fluxes (changing the amplitude, shape and duration of the flux), background climates (modern and glacial) and location (North or South Hemisphere). Hence we can both compare the results with previous studies and complete with additional ones. CLIMBER-2 includes a statistical atmosphere, a zonally averaged ocean and a terrestrial biosphere model (VECODE) (Brovkin et al., 1997). The model computes the carbon cycle both in the ocean and on land, and takes into account carbonate compensation. It has already been used for a number of studies on the links between the climate and the carbon cycle (Brovkin et al., 2002, 2007; Bouttes et al., 2010, 2011).

2.2 Sinking of brines in CLIMBER-2

Brines are small pockets of very salty water released by sea ice formation. Indeed, sea ice is mainly formed of fresh water and most of the salt is rejected from the ice during its formation. In the standard version of CLIMBER-2, the flux of salt released to the ocean goes to the surface oceanic cell. The volume of the latter is quite big due to the coarse resolution, and the salt flux is diluted. Yet as brines are very dense because of their high salt content, they should rapidly sink to the deep ocean when the local conditions allows it. To avoid the dilution of such an effect the brine sink has been previously parameterized and studied in CLIMBER-2 (Bouttes et al., 2010, 2011). The relative importance of the brine mechanism is set by the parameter $frac$, which is the fraction of salt released by sea ice formation that sinks to the bottom of the ocean. The rest of the salt (1-$frac$) is mixed in the corresponding surface oceanic cell as done in the standard version. This mechanism was shown to result in a net glacial CO_2 decrease. Previous studies also showed that $frac$=0.6 is a good estimation of the frac value (Bouttes et al., 2010, 2011). In this study the $frac$ parameter is thus set to 0.6 when the sinking of brines is taken into account.

2.3 Design of experiments

We consider three sets of additional fresh water fluxes (Figure 1). The first one ("duration") is similar to the Schmittner and Galbraith (2008) experiments in which the duration of the fresh water flux varies between 400 years and 1700 years, with an amplitude of 0.2 Sv (Figure 1a), although here no negative flux is applied at the end contrary to Schmittner and Galbraith (2008), as it is not necessary for the circulation to start again in CLIMBER-2. The second one ("triangle") is similar to the one of Menviel et al. (2008) with a linear fresh water flux increasing from 0 to 2 Sv in 100 years then a symmetrical decrease during the following 100 years (Figure 1b). Finally we complete these two sets with one with varying amplitude of the fresh water flux between 0.05 Sv and 1 Sv for a duration of 400 years ("amplitude", Figure 1c). These additional fresh water fluxes correspond to a "meter sea level equivalent" of approximately 7 to 30 m for the "duration" experiments, 18 m for the "triangle" experiment and 0.3 to 36 m for the "amplitude" experiments.

These three sets of additional fresh water fluxes are first applied in the North Atlantic (between 50^{o}N and 67.5^{o}N) with three background climate states: the Preindustrial (PI), Last Glacial Maximum (LGM, approximately 21,000 years ago), and Last Glacial Maximum with the sinking of brines (LGM+brines). The LGM climate is obtained by modifying the orbital parameters (Berger, 1978), ice sheets (Peltier, 2004), sea level (Waelbroeck et al., 2002) and atmospheric CO_2 (Monnin et al., 2001) for the radiative code. As done in previous studies (Brovkin et al., 2002, 2007; Bouttes et al., 2010, 2011), the radiative CO_2 is imposed so as to obtain a glacial climate. CH_4 and N_2O are not explicitly considered in the model, but the CO_2 is an "equivalent CO_2" calculated to reproduce the cumulative radiative effect arising from the changes in CO_2, CH_4 and N_2O (Brovkin et al., 2007). This fixed radiative CO_2 is different from the geochemical CO_2 which is computed interactively by the geochemical model and discussed in this study. This allows for a better comparison with previous work and for a simpler analysis of the carbon cycle response to climate. Finally, we also assess the impact of fresh water fluxes in the Southern Ocean (between 60^{o}S and 75^{o}S) during glacial climate (LGM and LGM+brines) with the third set of fresh water fluxes (different amplitudes).

3 Results and discussion

3.1 Experiments with Preindustrial background climate

We first perform a set of experiments with fixed preindustrial boundary conditions, so that the global climate is characteristic of the preindustrial one. Whatever the amplitude or duration of the additional freshwater flux, the AMOC is slowed down as a result of the additional fresh water (Figure 2 a, b, c). If the amount of fresh water reaches the threshold value of 0.2 Sv, the AMOC is even momentarily stopped, a situation called the "off" mode and previously studied with this model in more details (Ganopolski et al., 2001). The duration of the "off" mode depends both on the amplitude and duration of the fresh water flux: the longer and the bigger the flux, the longer the "off" mode lasts.

In agreement with past studies with CLIMBER-2 (Ganopolski et al., 2001), the alteration of the oceanic circulation leads to warming in the South Hemisphere and cooling in the North Hemisphere, with greater amplitude at high latitudes (Figure 3a and c). The precipitation field is also modified albeit with a more complex pattern (Figure 3b and d). Precipitations generally decrease north of 40^oN. They tend to slightly increase between 15^oN and 40^oN. As observed in other studies (Menviel et al., 2008; Bozbiyik et al., 2011), closer to the equator a dipole forms with less precipitation around the equator and more around 25^oS, in link with an ITCZ shift southward.

These changes impact the carbon cycle. When the additional fresh water flux is too small to stop the AMOC (below the threshold value of 0.2 Sv the AMOC does not switch to the "off" mode) the resulting change of CO_2 is small (less than 5 ppm, Figure 2 c and f). Above the 0.2 Sv threshold, when the AMOC shuts down, the impact on the carbon cycle is much more important. The atmospheric CO_2 first decreases for at least 1000 years, and longer if the "off" mode still persists after 1000 years (with a maximum amplitude of around 10ppm). It then starts increasing (with a maximum amplitude of around 25ppm) after the AMOC has started increasing again, and reaches a new equilibrium with higher CO_2 value (around 300 ppm) as the AMOC also stabilizes at a higher level (around 24 Sv compared to 20 Sv initially). The existence of multiple equilibria is indeed a classical feature of some climate models (Rahmstorf, 1995) and corresponds here to a small shift in the location of convection in the North Atlantic. As we focus our study on the carbon exchanges during the transitory phase of the simulations, the final equilibrium state is here not relevant to our discussion.

The impact of additional fresh water fluxes on the carbon cycle during the preindustrial has previously been studied with atmosphere-ocean-vegetation carbon-climate coupled models (Menviel et al., 2008; Obata, 2007; Bozbiyik et al., 2011). In these studies the terrestrial biosphere becomes a source of carbon and the ocean a sink. It results in an increase of atmospheric CO_2. In particular, the LOVECLIM model, which is also used in glacial conditions, when forced by a fresh water flux as in the “triangle” experiment results in an atmospheric CO_2 increase of around 20 ppm in approximately 100 years followed by a more gradual decrease of approximately 25 ppm in 400 years. The results obtained with CLIMBER-2 are very different. In the similar experiment, CLIMBER-2 simulates a 10 ppm decrease in approximately 1000 years, then an increase of around 25 ppm in 1000 years (Figure 2 e). Both the duration and sign of the response are thus different.

These differences originate from the different evolutions of the oceanic and terrestrial biosphere carbon reservoirs. In Menviel et al. (2008), as soon as the AMOC decreases due to the addition of fresh water flux, the ocean takes up carbon and the terrestrial biosphere releases carbon. Then, in a second phase, the opposite occurs. Because the vegetation reacts faster than the ocean, the CO_2 evolution is primarily driven by the vegetation. The ocean tends to mitigate the changes. On the contrary, in CLIMBER-2, the terrestrial biosphere takes up carbon while the ocean looses carbon (Figure 2 h and k). Because the amplitude of the change of terrestrial biosphere is twice the one of the ocean, it dominates the CO_2 evolution, the uptake of carbon by the vegetation resulting in the CO_2 decrease. Contrary to LOVECLIM, in all CLIMBER-2 simulations, ocean looses carbon while the terrestrial biosphere takes it up (Figure 2), why is the ocean loosing carbon and the terrestrial biosphere taking up carbon?

In the ocean, because of the addition of fresh water in the North Atlantic, the salinity decreases (Figure 4a) and the formation of deep water in the North Atlantic shuts down (Figure 5a). The potential density becoming relatively denser in the South Hemisphere compared to adjacent waters (Figure 4g, h and i). It gives rise to the formation of intermediate water in the three basins around 50^oS(Figure 5). Because of the warming in the South Hemisphere it brings warm water deeper so that heat penetrates in the upper part of the ocean (above -2000m, Figure 4d, e and f). Due to the lowering of the solubility of CO_2 in warmer water, this upper part of the ocean (which excludes smaller areas in the northern part of the Atlantic and Pacific) contains less inorganic carbon (Figure 6a, b and c). In the deep ocean (below -2000m) and in the northern parts of the Atlantic and Pacific, there is more carbon as the exchange with the surface has diminished, the carbon can stay longer. Moreover the surface in the North Hemisphere is cooler and can contain more carbon. The greatest change in the organic carbon happens in the northern part of the North Hemisphere (Figure 6d, e and f). Because the sea ice covers a greater area, the light availability diminishes and so does the production of organic carbon. But this effect is smaller compared to the change of inorganic carbon which dominates (Figure 6). Overall, the loss of carbon from most of the upper ocean (especially in the South) dominates, leading to a net loss of carbon from the ocean.

The terrestrial biosphere reacts to both to the air temperature and precipitation changes. The main changes take place at low latitudes (Figure 7), contrary to Köhler et al. (2005), but as in Bozbiyik et al. (2011). However the changes of vegetation are different in CLIMBER-2. In Africa there is a decrease of carbon in the vegetation around the equator, but an increase North of 10^{o}N and South of 10^{o}S, while in Bozbiyik et al. (2011) there is an increase between the equator and 20^{o}S. In South America there is a decrease between 10^{o}S and 30^{o}S but an increase everywhere else while in Bozbiyik et al. (2011) there is an increase between the equator and 20^{o}S on the West and a decrease in the North. Overall, the vegetation decreases in the colder and dryer North and increases in the warmer and globally wetter South (Figure 8). However, the carbon content in the soil increases in both hemispheres. In the North the colder and dryer climate leads to less decomposition. In the South, because the vegetation increases the stock of carbon in the soils also becomes larger. Overall it results in an increase of carbon in the terrestrial biosphere. Hence the carbon content increase is mostly driven by the soil carbon changes from the climate response.

Why is the carbon-cycle response different in LOVECLIM? First we can note that the fresh water flux is similar and can thus not be the cause of this discrepancie. Moreover, the terrestrial biosphere model (VECODE) is the same in both models, although the resolution is coarser in CLIMBER-2. However, although the additional fresh water flux is the same for both models, the response of the AMOC is different: the AMOC increases as soon as the fresh water flux stops in LOVECLIM (i.e. after 200 years) and recovers quickly in approximately 400 years, i.e. 600 years after the beginning of the fresh water flux. In CLIMBER-2 it takes more time for the AMOC to recover, it reaches its new stable level around 800 years after the stop of the fresh water flux, i.e. 1000 years after the beginning of the fresh water flux. The timing of circulation and climate change is thus different: the changes take more time in CLIMBER-2 compared to LOVECLIM. Because the recovery of NADW is slower in CLIMBER-2, it could lead to a greater role of the subsurface part of the ocean through solubility changes. In both models, the colder waters in the North can take up more carbon while the warmer waters in the South can takes less due to the solubility effect. However, when the formation of deep water recovers in the North Atlantic it brings carbon from the surface to the deep ocean. In CLIMBER-2 this transport of carbon remains stopped longer than in LOVECLIM, so that even though the cold upper ocean can contain more carbon, the latter is not efficiently transported deeper in the ocean. Furthermore, in CLIMBER-2, the formation of intermediate water in the South Hemisphere when the formation of NADW is topped plays an important role. A complete explanation could only be obtained by running additional simulations with LOVECLIM.

In Obata (2007); Bozbiyik et al. (2011) the ocean globally takes up carbon as in Menviel et al. (2008). However the fresh water flux experiments differ, e.g. the duration is shorter. In Obata (2007) it results in a small change of carbon content in the ocean of around +10 GtC. In this experiment, the AMOC slowly recovers and does not stay in an “off” mode. In Bozbiyik et al. (2011) with an addition of 1Sv in the North Atlantic, the AMOC stays at a low level. The effect on the carbon cycle is more important with an uptake by the ocean of around 30 GtC. This uptake of carbon by the ocean is due mostly to the North Atlantic but also (with a smaller amplitude) to most of the ocean in the South Hemisphere (excepth in the Atlantic). This is different in CLIMBER-2 in which the ocean in the South Hemisphere tend to contain less carbon because of the warmer waters.

It thus appears that applying different types of fresh water fluxes changing either their duration, amplitude or shape, can not explain the differences obtained with different models. In CLIMBER-2, the type of fresh water flux modulates the change of CO_2: a longer or bigger fresh water flux will result in a more important CO_2 increase. But it does not change the sign of the CO_2 evolution as the terrestrial biosphere systematically releases carbon and the ocean takes up carbon. We then analyse the impact of the same fresh water fluxes during the glacial period to test whether the evolution of the carbon reservoirs changes, and how it compares to paleo data.

3.2 Experiments with LGM background climate

In the following, we explore the response of the model to additional fresh water fluxes in the context of the Last Glacial Maximum (LGM, approximately 21,000 years ago). Two background conditions are considered: a standard glacial one (LGM) that can be compared to previous studies (Menviel et al., 2008; Schmittner and Galbraith, 2008) and a new one taking into account the sinking of brines rejected by sea ice formation around Antarctica (LGM+brines).

3.2.1 Experiments with the standard LGM background climate

We now analyze the impact of fresh water fluxes on the carbon cycle with a LGM background climate. As for the preindutrial simulations, the addition of fresh water flux slows down the Atlantic meridional oceanic circulation resulting in a cooling in the North and warming in the South (Figure 10a). The pattern of precipitation change is also similar to the PI one (Figure 10b).

With respect to the carbon cycle, compared to the preindustrial climate results, the simulations with the LGM background climate present one major difference (Figure 9).The carbon cycle equilibrates at a different level than the initial one due to the AMOC evolution during the PI, while the final level is the same as the initial one with the LGM climate, because the AMOC stabilizes at its initial value. Other than that, because the pattern of climate change is close to the PI one, the evolution is roughly similar, although the initial values are different due to the different background conditions. This confirms that the final equilibrium state that was found in the PI experiments is not relevant to the transient fluxes of carbon during the FWF perturbation. Consequently, the general evolution of CO_2 is a relatively small decrease (less than 12ppm), then a bigger increase (up to 25ppm) and a decrease to the initial level.

Two ocean-atmosphere-vegetation models have already studied the carbon cycle response to fresh water fluxes during the LGM. With the LOVECLIM model (Menviel et al., 2008), it again results in an oceanic carbon uptake and loss of carbon from the terrestrial biosphere, but the result is slightly different. Because the ocean takes up carbon more rapidly, it results in a decrease of CO_2 during the first 400 years, then a small increase. On the other hand, the UVic model (Schmittner and Galbraith, 2008) gives opposite results: the ocean looses carbon while the terrestrial biosphere takes up carbon. It leads to a CO_2 increase in the UVic model and a CO_2 decrease in LOVECLIM, then a return towards near initial conditions.

The CLIMBER-2 results are more similar to the UVic ones, with a loss of carbon from the ocean and an uptake from the terrestrial biosphere. The result is however a bit different, with first a small decrease of CO_2. It then increases as in Schmittner and Galbraith (2008). The CO_2 evolution depends on the tight interplay of ocean and terrestrial biosphere. Because the terrestrial biosphere reacts faster than the ocean its response at the beginning of the fresh water flux addition is important for the CO_2 evolution.

As for the preindustrial state, the evolution of the carbon content in the ocean and terrestrial biosphere is the opposite in CLIMBER-2 and LOVECLIM, it is however similar in UVic and CLIMBER-2. Such discrepancies do not arise from the differences in the type of fresh water flux as they were similar in CLIMBER-2 and the other models. Hence they can come from the different AMOC change and the climatic responses of the models to this AMOC evolution.

In both UVic and CLIMBER-2, the AMOC stays in the “off mode” longer which can result in a more important impact of the deeper part of the ocean. The soils can also play a greater role as their timescale is longer. The change of climate can also be different in response to the AMOC shut down.

In a different study with other freshwater experiments (0.2 Sv during 500 years) but without carbon cycle models (Kageyama et al., 2010), the LOVECLIM model exhibits a smaller climate change compared to the UVic model (they were both forced by the same fresh water flux). The “seesaw” pattern is more pronounced in the UVic results, with cooling in the North Hemisphere and warming in the southern hemisphere (Kageyama et al. (2010), figure 6). With the LOVECLIM model the warming in the South Hemisphere is comparatively smaller. Similarly, in the UVic model the addition of this fresh water flux leads to a dryer North Hemisphere and wetter South Hemisphere, whereas it globally becomes dryer in many areas in the LOVECLIM model. The carbon cycle was not included in such simulations but these differences in the climate response should results in very different behaviors of the carbon cycle both in the terrestrial biosphere and ocean. The carbon cycle evolution is very tightly driven by the climate change. As the latter is highly model dependent, the modification of the carbon cycle vary significantly between the different models.

CLIMBER-2 is an intermediate complexity model that can run very fast (approximately 1000 years in an hour) which is a great advantage to run numerous simulations for a long time. In particular it allows us to test different fresh water fluxes (changes in amplitude, duration, shape and location) in the context of different climates (preindustrial and glacial). It also allows analyzing what happens for a few thousand years after the addition of the fresh water flux. However the rapidity of CLIMBER-2 is balanced by some simplifications such as the coarse resolution and zonally averaged ocean. Such simplifications can have different impacts in the context of fresh water flux experiments. First the gyres and the ACC are prescribed in the model, whereas in reality they could change. It can also introduce some biases in the carbon cycle such as too much remineralization in intermediate waters. Yet the temperature distribution in the ocean seems to be coherent with other models. The use of a simplified atmospheric model could result in less realistic precipitation fields which then impact vegetation. Yet the pattern of precipitation change is not very different from other models. The terrestrial biosphere is also a simple one with only two types of vegetation: grass and tree, which is also used in LOVECLIM. Finally the low resolution can have an impact especially on the vegetation distribution which might change more on regional scales.

Changing the background climate has an important effect on the evolution of the carbon when fresh water is added both because the initial state is different, so that the repartition of carbon in the reservoirs in different, and because the climate change is different. With CLIMBER-2 the induced climate change with the glacial state is relatively similar to the one in preindutrial state. Hence the sign of the change of carbon in the terrestrial biosphere and the ocean is the same, but the amplitudes differ. As the initial state plays an important role we also explore the impact of fresh water flux on the evolution of the carbon cycle when the sinking of brines in the Southern Ocean is taken into account during the glacial period.

3.2.2 Experiments with LGM background climate and brines

In the previous experiments, the background climate was the LGM, but the simulated CO_2 level was not coherent with the glacial CO_2 level inferred from ice core data (around 190 ppm during the LGM, between 190 ppm and 220 ppm from -65,000 years to the LGM, compared to approximately 257 ppm in CLIMBER-2). Previous studies have shown that it is possible to simulate the glacial carbon cycle in better agreement with the data by including a brine mechanism (Bouttes et al., 2010, 2011). With the following, the rejection of salt during sea ice formation around Antarctica leads to a sinking of very saline and dense water to the deep ocean. It results in a more stratified deep ocean that contains more carbon. We use this LGM with brines climate background to explore the evolution of the carbon cycle when an additional FWF is put in the North Atlantic.

The addition of FWF still leads to an uptake of carbon by the terrestrial biosphere and a release of carbon by the ocean. However the amplitude of the terrestrial biosphere increase is smaller, while the oceanic one is similar (Figure 11). Hence there is no more CO_2 decrease at the beginning of the experiment: CO_2 increases then decreases. This CO_2 evolution is in better agreement with proxy data (Ahn and Brook, 2008).

What can explain these changes? The initial level of NADW export is lower in the LGM+brines simulations compared to the LGM ones (15 Sv compared to 20 Sv in the LGM experiments). When the fresh water flux is added, the decrease of NADW export is smaller, and the induced climate change is slightly smaller (Figure 12). The changes of terrestrial biosphere are thus less important (Figure 13) and the corresponding uptake of carbon smaller. Indeed, the ultimate driver of the CO_2 change appears to be both the timing and amplitude of the NADW decrease. As shown on figure 14, the maximum CO_2 increase depends on the integral of NADW below its initial value. It thus appears necessary to have a shut down of NADW for a sufficient duration to obtain a CO_2 increase similar to the data (20 ppm). In the model, this requires a substantial addition of fresh water (0.2 Sv during 1700 years). It shall be noted, however, that the amount of freshwater flux to be added in one model to shutdown the AMOC is very model dependent. The CO_2 amplitude change during AMOC shutdown thus gives an indication of the length of disruption of the AMOC. Or, more importantly, if we have a period of time in the past with disrupted AMOC and measures of the CO_2 for the same period, we may have an estimation of the rate of AMOC before the shutdown using the CO_2 change as a measure for the rate.

It appears that the strength of the NADW prior to the event plays a role because it impacts the amplitude of the climate change. The latter directly impacts the evolution of the terrestrial biosphere. In LOVECLIM, the NADW initial level is very high compared to UVic and CLIMBER-2: 30Sv compared to 20 Sv in CLIMBER-2 at LGM, 15 SV for LGMb and only 13 Sv in UVic. The initial value of NADW could partly explain the differences in the amplitude of the vegetation response, but not the opposite sign between Menviel et al. (2008) and the others which arises from the different climatic response obtained in the different models.

3.3 FWF in the Southern Hemisphere: similar or different impacts?

We finally perform the same set of experiments as the “Amplitude” ensemble (Figure 1c), but we now add the FWF in the Southern Hemisphere. We consider two background climate states: the Last Glacial Maximum (LGM) and Last Glacial Maximum with the sinking of brines (LGM+brines). Adding fresh water flux in the Southern Hemisphere impacts mainly the Antarctic Bottom Water (AABW) export whose intensity diminishes (Figure 15 c and d). The NADW export is also slowed down (Figure 15 a and b), but none of them shuts down.

The CO_2 evolution is very different from the one obtained with the FWF in the Northern Hemisphere, showing a decrease (with a maximum amplitude of around 13ppm) then an increase (Figure 15 e and f). This is due to the ocean and terrestrial biosphere reservoirs whose evolutions are the opposite as the ones with the additional FWF in the Northern Hemisphere (Figure 15 g, h, i and j). Indeed, temperature and precipitation now decrease in both hemispheres (Figure 16), with greater amplitudes in the Southern Hemisphere. The colder and dryer conditions result in a decrease of carbon in the vegetation.

In the ocean, the temperature drop makes the water more soluble. As NADW nor AABW are “off”, the surface water which contains more carbon can be sent to the deep ocean, thus the observed ocean carbon uptake. Because the amplitude of the ocean change is more important than the vegetation one, the ocean evolution prevails and it results in a CO_2 decrease. Hence adding fresh water fluxes in the Southern Hemisphere cannot explain the CO_2 increase during Heinrich events. However, it could play a role during the deglaciation, as the data show a momentary stop in the CO_2 increase during the Bolling-Allerod (Ahn and Brook, 2008).

3.4 Comparison with CO_2 data

The results are improved both in amplitude and timing for the CO_2 evolution when the sinking of brines is taken into account during the LGM. Both the amplitude and timing match better the CO_2 change as recorded in ice cores (Figure 17) (Ahn and Brook, 2008). This could be due to the initial state of NADW, whose strength is lower with the brines compared to the simulation without. With the sinking of brines and the induced stratification, carbon is stored in the abyssal glacial ocean (Bouttes et al., 2010, 2011), this different carbon cycle state could explain part of the change, as the ocean contains more carbon and can thus be more sensitive to changes of NADW with respect to loosing or taking carbon. Such an impact of the sinking of brines on the state of the glacial ocean remains to be tested with 3-dimensional models.

A slightly slower NADW is in agreement with data indicating that the intensity of NADW during the LGM is comparable or lower than today, but not shut down nor accelerated (Lynch-Stieglitz et al., 2007; McManus et al., 2004). Furthermore, a more realistic representation of the brines mechanism would depend on climate, with brines deep sinking being reduced when the Southern Ocean temperatures are rising. This additional feedback would likely amplify the carbon oceanic response and consequently the atmospheric CO_2 increase.

Finally, the fresh water flux in the Southern Ocean leads to an opposite CO_2 evolution marked by a decrease followed by an increase. Such an impact of fresh water fluxes from Antarctica could explain the CO_2 plateau observed during the deglaciation, at the time of the Bolling Allerod (around 14,000 to 12,300 years BP) (Monnin et al., 2001). It corresponds to the period when the Antarctic ice melting and retreat becomes more significant (Clark et al., 2009; Mackintosh et al., 2011).

4 Conclusions

In conclusion, we have explored the impact of different fresh water fluxes in several climate background states with the CLIMBER-2 model. The duration, amplitude, and shape of the fresh water flux all modulate the evolution of the carbon cycle. The longer or greater the flux, the bigger the increase of atmospheric CO_2 is. However they cannot explain the differences obtained in different models, i.e. why in some models the ocean takes up carbon while the vegetation releases it, and the opposite in other models. In CLIMBER-2 the AMOC takes time before it recovers, which can lead to a greater role of the deeper ocean. The different background states have an important impact on the carbon cycle, especially as the carbon inventory between the three reservoirs: the ocean, terrestrial biosphere and atmosphere, is different. Taking into account the sinking of brines in the Southern Ocean in a glacial climate allows CO_2 to start from a value which is closer to proxy data and gives a more similar evolution compared to the ice core records. The location of the fresh water flux has a strong impact on the evolution of the carbon cycle as it results in a very different climatic response. In CLIMBER-2 it leads to a decrease of CO_2 contrary to the addition of fresh water in the North Hemisphere. Finally, as shown by previous studies the response of the carbon cycle strongly depends on a close interplay between the ocean and vegetation responses. The results are very model dependent, both because of the response of the AMOC to the addition of fresh water and because of the climatic response to this fresh water flux. Better understanding of these differences will require an intercomparison of the impact of the addition of fresh water fluxes in carbon-climate models, using a well-defined common experimental setup.

Acknowledgements. We thank the editor, reviewers as well as Laurie Menviel and Axel Timmermann for constructive comments that helped improve the manuscript.

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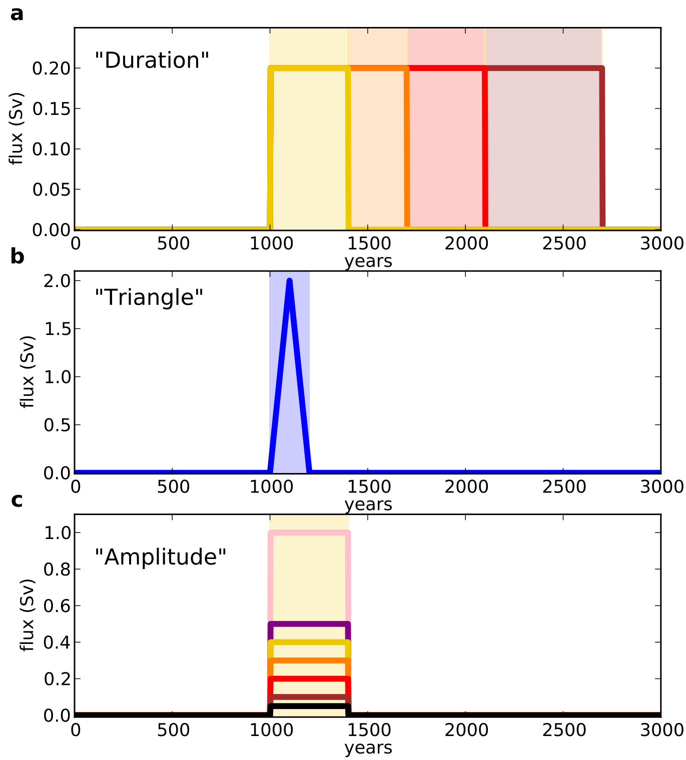

Fig. 1. Evolution of the fresh water flux (Sv) added in the three types of experiments: (a) for the "Duration" experiments with fresh water fluxes of 0.2 Sv added during 400, 700, 1100 or 1700 years, (b) for the "Triangle" experiments with a fresh water flux lineraly increasing for 100 years to 2 Sv, then decreasing again fro 100 years, and (c) for the "Amplitude" experiments with fresh water fluxes added during 400 years of 0.05, 0.1, 0.2, 0.3, 0.4, 0.5 or 1 Sv.

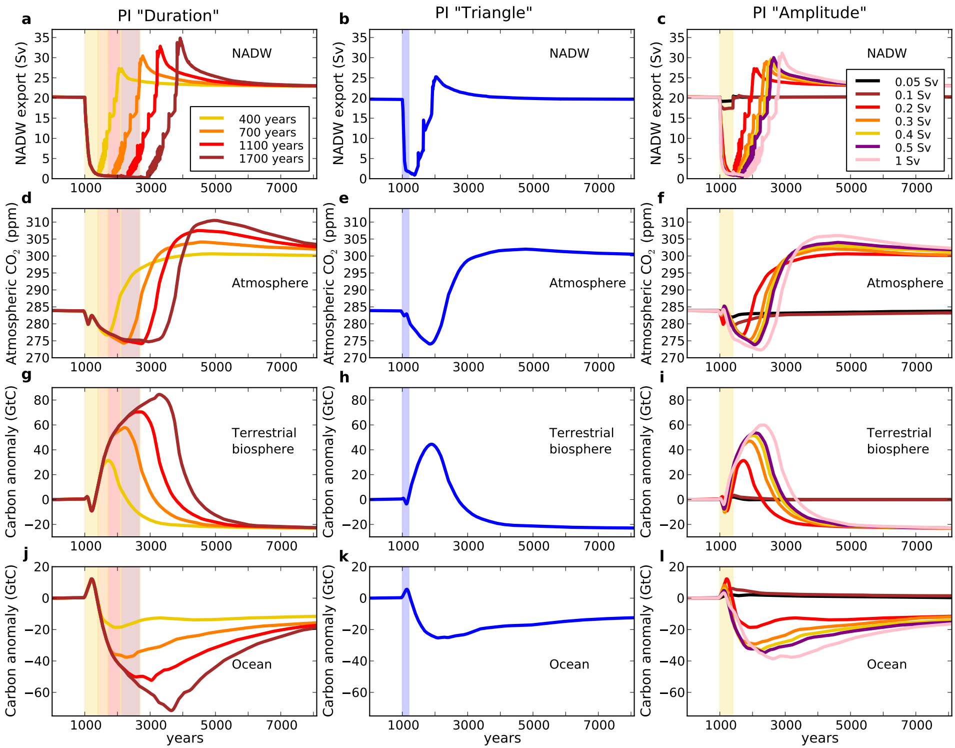

Fig. 2. Evolution of (a, b, c) NADW export (Sv) (maximum of the AMOC), (d, e, f) atmospheric CO_2 (ppm), (g, h, i) carbon content anomaly in the terrestrial biosphere (GtC) and (j, k, l) carbon content anomaly in the ocean (GtC) during the simulations with the Preindutrial (PI) background climate state. The fresh water flux is added in the North Atlantic and vary as described in Figure 1 for the three types of experiments: (a, d, g, i) “Duration”, (b, e, h, k) “Triangle” and (c, f, i, l) “Amplitude”.

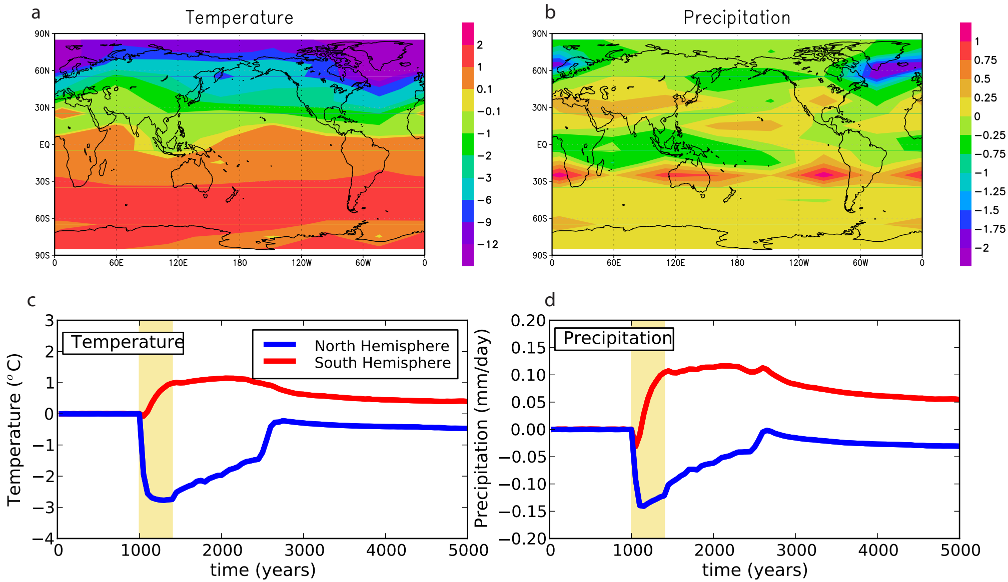

Fig. 3. Difference between the average of years 990-1000 and 1390-1400 for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years for (a) air temperature (^{o}C) and (b) precipitation (mm/day). (c and d) Evolution of (a) air temperature (^{o}C) and (b) precipitation (mm/day) in the North (blue) and South (red) Hemispheres.

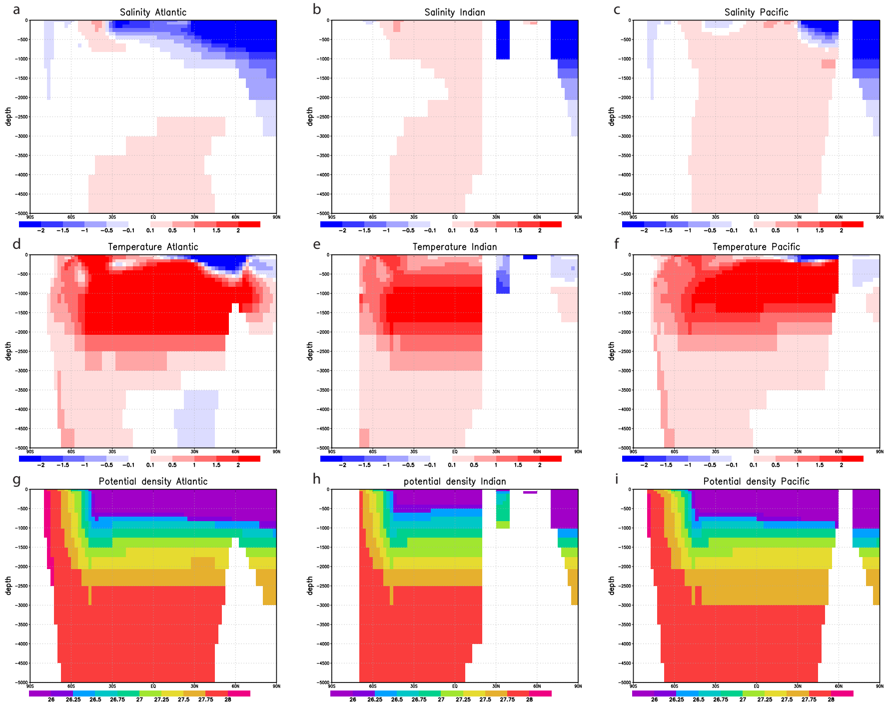

Fig. 4. Zonally averaged salinity (permil), temperature (^{o}C) and density (kg/m^3) for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years: (a, b and c) salinity difference between the average of years 990-1000 and years 1390-1400; (d, e and f)temperature difference between the average of years 990-1000 and years 1390-1400; (g, h and i) density at the average of years 1390-1400. The three basins are: (a, d and g) Atlantic, (b, e and h) Indian and (c, f and i) Pacific.

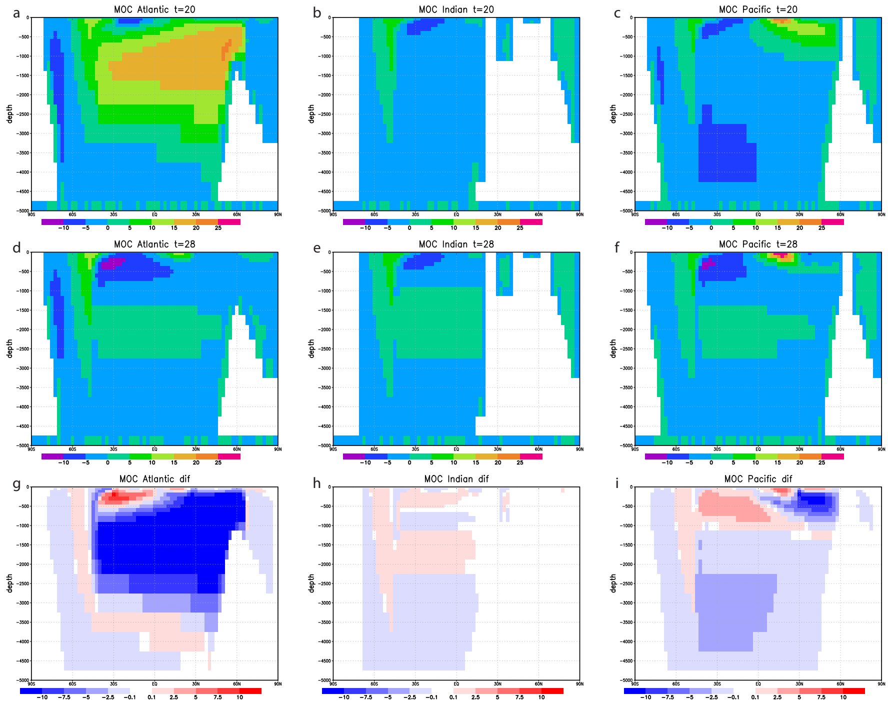

Fig. 5. Meridional overturning streamfunction (Sv) for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years at (a, b and c) the average of years 990-1000, (d, e and f) the average of years 1390-1400 and (g, h and i) the difference between the two for the three basins: (a, d and g) Atlantic, (b, e and h) Indian and (c, f and i) Pacific.

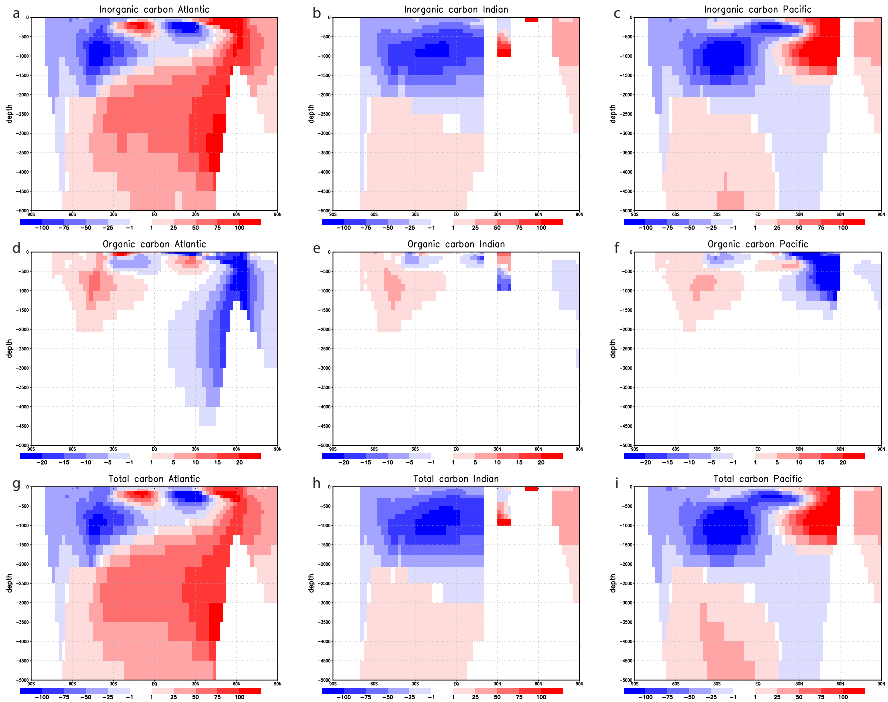

Fig. 6. Change of zonally averaged inorganic, organic and total carbon (μmol/kg) for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years: (a, b and c) inorganic carbon difference between the average of years 990-1000 and years 1390-1400; (d, e and f) organic carbon difference between the average of years 990-1000 and years 1390-1400; (g, h and i) total carbon difference between the average of years 990-1000 and years 1390-1400. The three basins are: (a, d and g) Atlantic, (b, e and h) Indian and (c, f and i) Pacific.

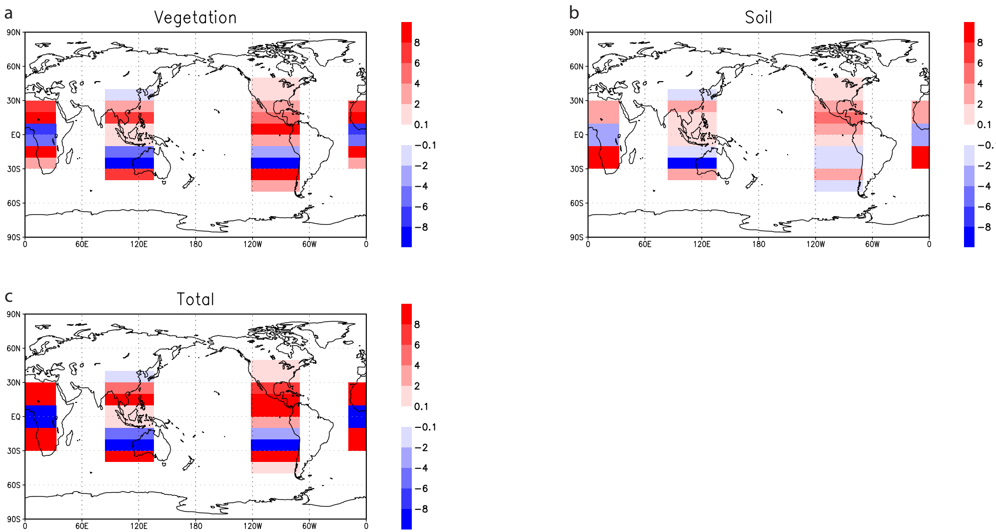

Fig. 7. Change of carbon content (GtC) in (a) the vegetation, (b) soil and (c) total for the simulation during the Preindustrial with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years.

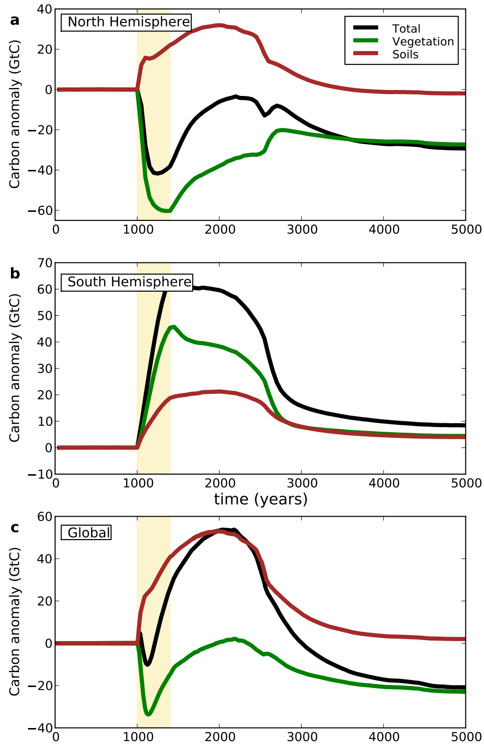

Fig. 8. Evolution of the carbon content anomaly in the terrestrial biosphere (GtC) (a) in the North Hemisphere, (b) in the South Hemisphere and (c) total of the two hemispheres. The total carbon in the terrestrial biosphere (black) is decomposed in its two subreservoirs: the vegetation (green) and soils (brown). In the simulation the fresh water flux added in the North Atlantic has an amplitude of 0.5 Sv during 400 years.

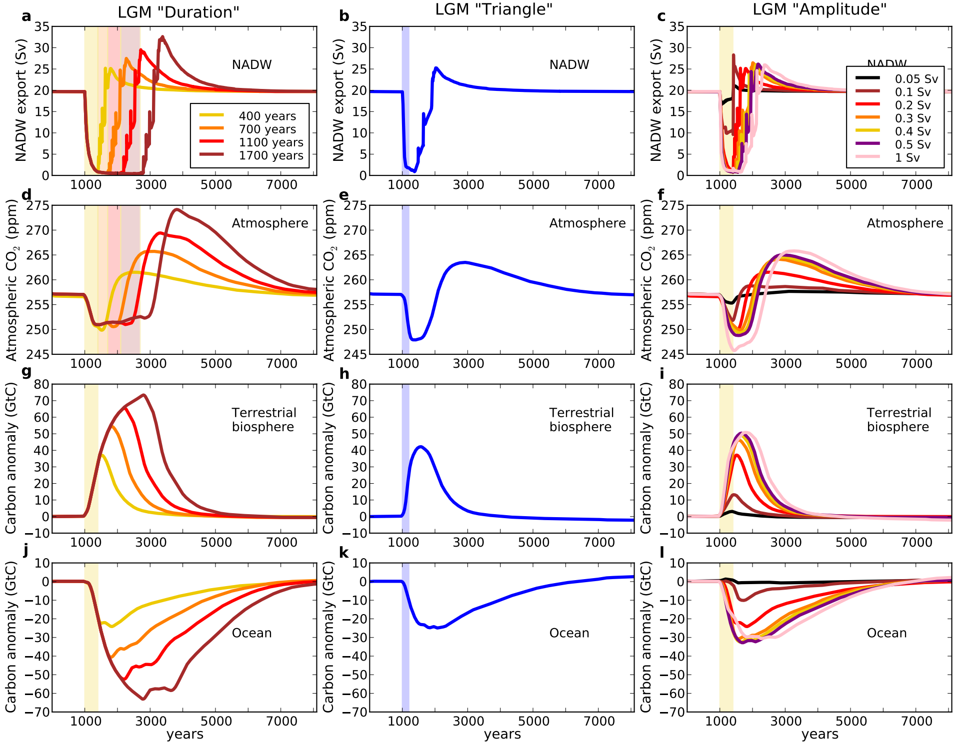

Fig. 9. Evolution of (a, b, c) NADW export (Sv) (maximum of the AMOC), (d, e, f) atmospheric CO_2 (ppm), (g, h, i) carbon content anomaly in the terrestrial biosphere (GtC) and (j, k, l) carbon content anomaly in the ocean (GtC) during the simulations with the Last Glacial Maximum (LGM) background climate state. The fresh water flux is added in the North Atlantic and vary as described in Figure 1 for the three types of experiments: (a, d, g, i) “Duration”, (b, e, h, k) “Triangle” and (c, f, i, l) “Amplitude”.

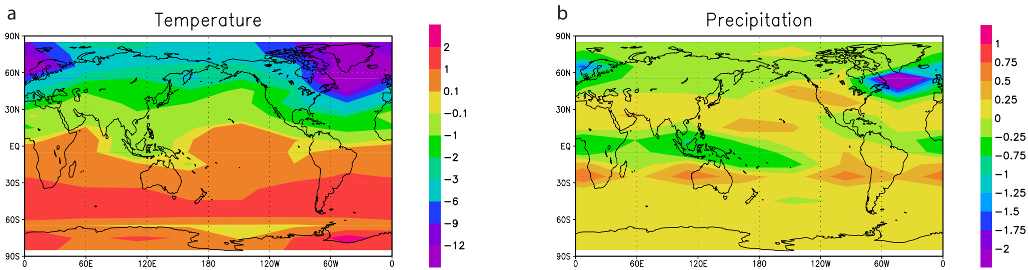

Fig. 10. Difference between the average of years 990-1000 and 1390-1400 for the simulation during the LGM with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years for (a) air temperature (^{o}C) and (b) precipitation (mm/day).

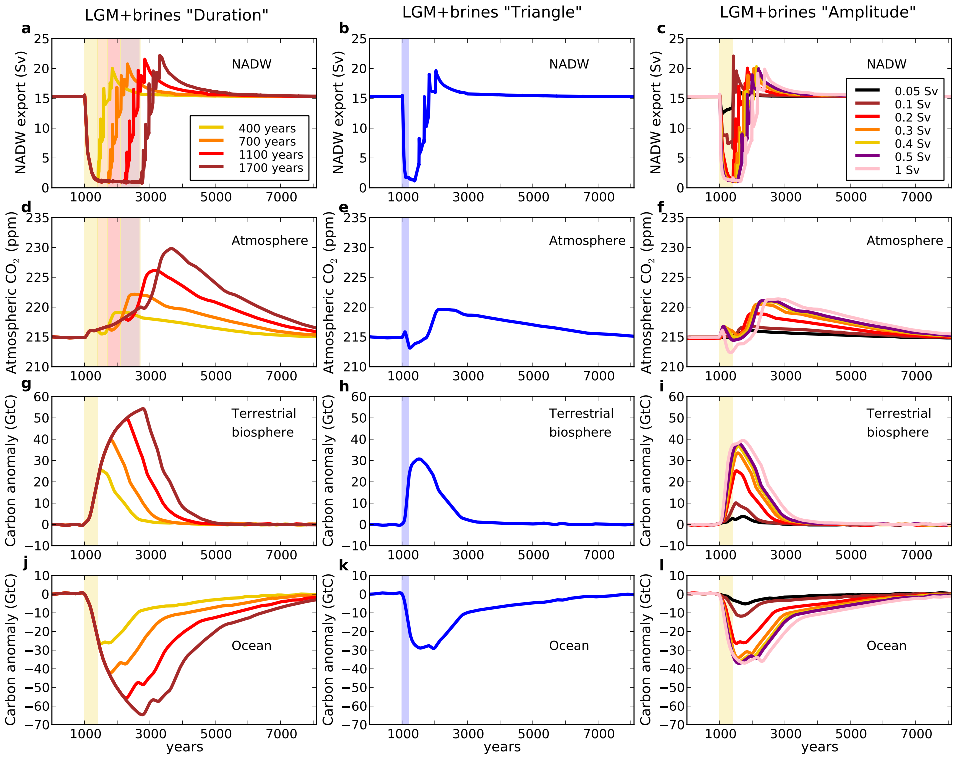

Fig. 11. Evolution of (a, b, c) NADW export (Sv) (maximum of the AMOC), (d, e, f) atmospheric CO_2 (ppm), (g, h, i) carbon content anomaly in the terrestrial biosphere (GtC) and (j, k, l) carbon content anomaly in the ocean (GtC) during the simulations with the Last Glacial Maximum background climate state and taking into account the sinking of brines (LGM+brines). The fresh water flux is added in the North Atlantic and vary as described in Figure 1 for the three types of experiments: (a, d, g, i) “Duration”, (b, e, h, k) “Triangle” and (c, f, i, l) “Amplitude”.

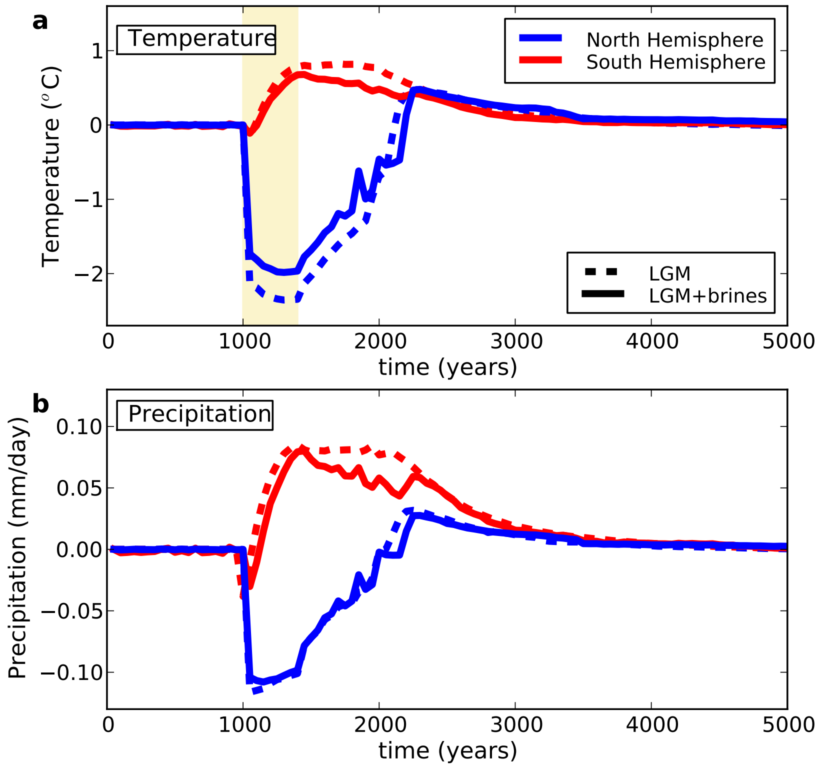

Fig. 12. Evolution of (a) air temperature (^{o}C) and (b) precipitation (mm/day) in the North (blue) and South (red) Hemispheres for the simulation with a fresh water flux added in the North Atlantic of 0.5 Sv during 400 years. Two background climate states are considered: the Last Glacial Maximum (LGM, dashed lines) and the Last Glacial Maximum with the sinking of brines (LGM+brines, solid lines).

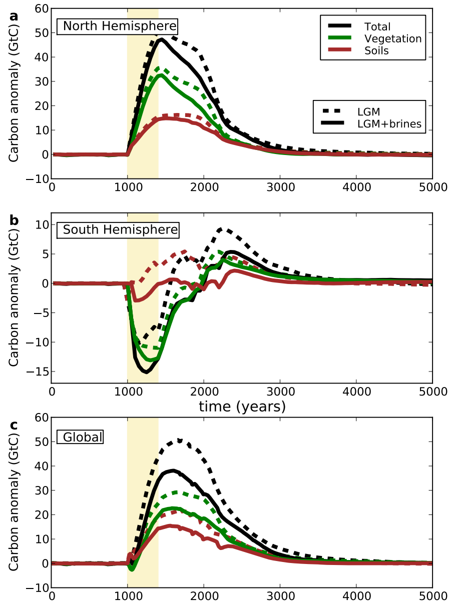

Fig. 13. Evolution of the carbon content anomaly in the terrestrial biosphere (GtC) (a) in the North Hemisphere, (b) in the South Hemisphere and (c) total of the two hemispheres. The total carbon in the terrestrial biosphere (black) is decomposed in its two subreservoirs: the vegetation (green) and soils (brown). In the simulation the fresh water flux added in the North Atlantic has an amplitude of 0.5 Sv during 400 years. Two background climate states are considered: the Last Glacial Maximum (LGM, dashed lines) and the Last Glacial Maximum with the sinking of brines (LGM+brines, solid lines).

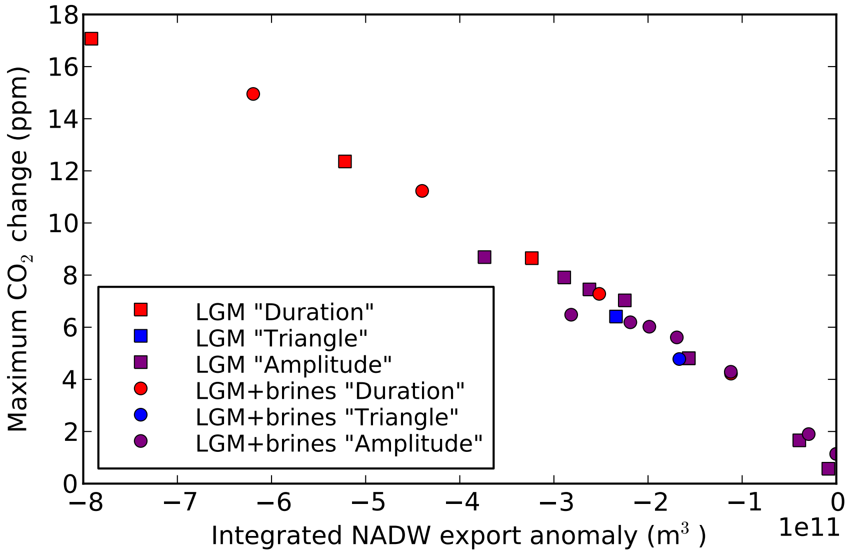

Fig. 14. Maximum of the CO_2 change (as a difference from the initial value) (ppm) as a function of the integrated export of NADW anomaly (taken as the maximum of the AMOC, as a difference from the initial value).

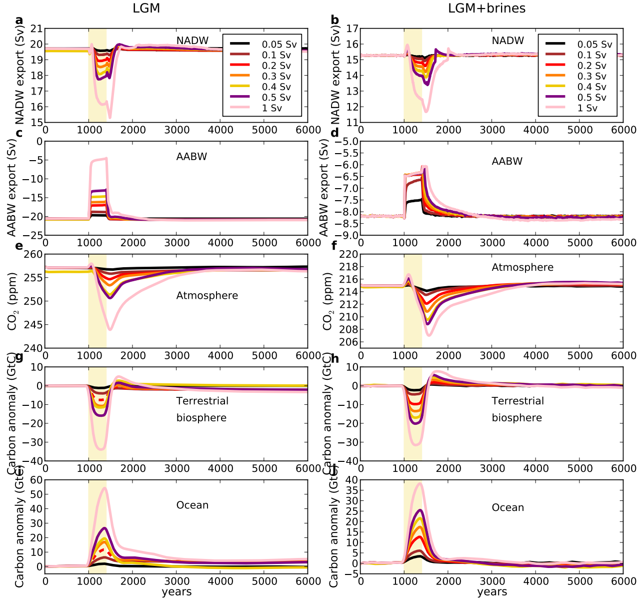

Fig. 15. Evolution of oceanic variables in respnse to the addition of fresh water fluxes in the South Atlantic following the "Amplitude" experiments (Figure 1c). (a, b) NADW export (Sv) (maximum of the AMOC), (c, d) AABW export (Sv) (minimum of the AMOC, the sign indicates that the transport is from the South to the North), (e, f) atmospheric CO_2 (ppm), (g, h) carbon content anomaly in the terrestrial biosphere (GtC) and (i, j) carbon content anomaly in the ocean (GtC). The simulations are performed with two background climate states: (a, c, e, g, i) during the Last Glacial Maximum (LGM) and (b, d, f, h, j) during the Last Glacial Maximum with the sinking of brines (LGM+brines).

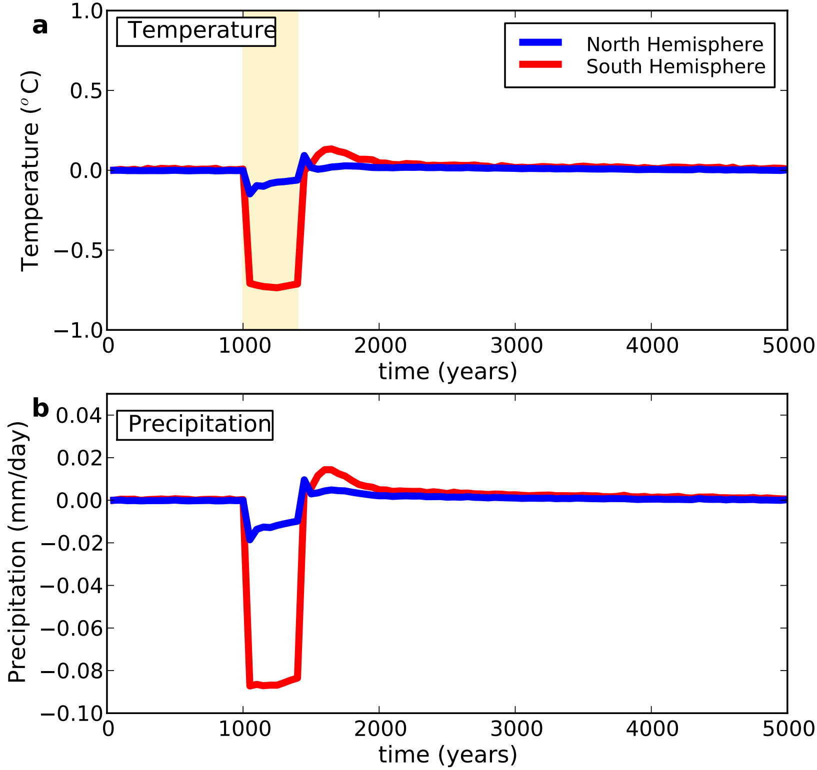

Fig. 16. Evolution of (a) air temperature (^{o}C) and (b) precipitation (mm/day) in the North (blue) and South (red) Hemispheres for the simulation during the Preindustrial with a fresh water flux added in the South Atlantic of 0.5 Sv during 400 years.

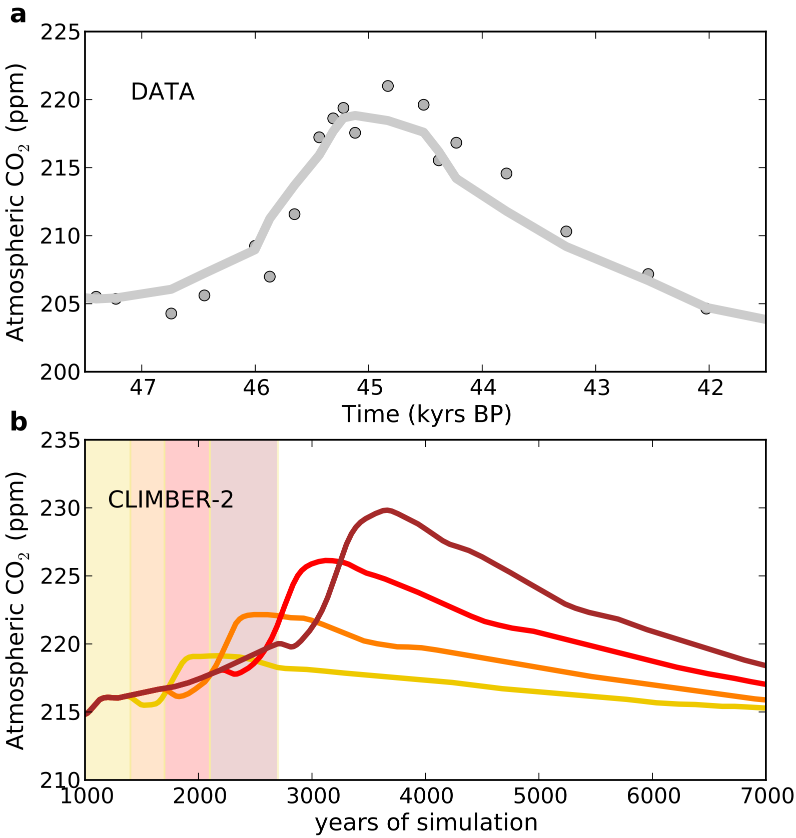

Fig. 17. Evolution of the atmospheric CO_2 (ppm) (a) from ice core data for the H5 event (the dots are the data and the solid line the smoothed signal) (Ahn and Brook, 2008) and (b) as simulated by the CLIMBER-2 model with additional fresh water fluxes in the North Atlantic following the "Duration" experiments (Figure 1a).