Clim. Past Discuss., 6, C1359–C1369, 2011
www.clim-past-discuss.net/6/C1359/2011/

Climate of the Past Discussions

Interactive comment on "Fingerprints of changes in the terrestrial carbon cycle in response to large reorganizations in ocean circulation" *by* A. Bozbiyik et al.

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Received and published: 24 January 2011

We thank all the reviewers for their extensive and constructive comments. Below given is a detailed response (bold/italic font) to the issues raised by anonymous referee 1 (normal font). As the extent of the comments and the questions span a wide range, we have decided not to include our whole detailed answer to each question in the revised paper. Our intention is not to diversify to the issues which are not of immediate concern to the topic at hand, that has a focus on the particular region of South America. A thorough analysis of the features observed in the oceans as a result of each experiment is non-trivial

and would require a more dedicated study with a focus on the oceans. Even though we try to address each question as well as possible without exceeding the scope of our topic, we find that, for the purposes of this paper, it is not necessary to include a lengthier discussion and leave an in-depth analysis of the issues raised in the questions 3-5 for a possible future study.

Major points:

1. Two recent publications of L. Menviel and co-authors deal with the carbon cycle response to FW-forcing applied in the North Atlantic and Southern Ocean respectively. (Menviel et al. [2008, Paleoceanography] and Menviel et al. [2010, Paleoceanography, in press]) While the second paper was accepted only 2 weeks ago, I do not understand why there is not a single reference to her first study. (This is in particular surprising, because-according to the University of Bern webpage- both of the corresponding authors seem to work in the same building.) The experiments are very similar and the results are as well to some extent. Furthermore the Menviel et al. [2008] study also covers LGM background climate conditions which was not feasible for the present manuscript. In their revised version the authors need to present a detailed comparison of their results to the findings of Menviel et al. [2008, Paleoceanography], also with respect to how a different background climate and a different FW-pulse can affect the simulated carbon cycle response.

The above mentioned studies by Menviel et al. are indeed quite relevant and we have included a comparison of the results of these two studies and our results in our revised manuscript. Firstly, the following is added on page 1815 line 22:

In another study, using an earth system model of intermediate complexity (LOVECLIM), Menviel et al. (2008) suggested that in the event of an AMOC shutdown, the ocean acted as a carbon sink and the land as a carbon source under both pre-industrial and LGM (Last Glacial Maximum) conditions.

Then, on page 1822 the following text has been added after line 3:

This northward migration of the ITCZ was also simulated in a study by Menviel et al. (2010). In that study, freshwater is applied uniformly over the Southern Ocean leading to similar changes in the ocean circulation and deep water formation. A decrease in the SST and SAT values in the Southern Hemisphere accompanied by subsurface warming in the Southern Ocean are also some of the commonalities.

Later on page 1823 after line 24, the changes in the carbon cycle is compared as follows:

A similar experiment performed with the LOVECLIM climate model did not lead to any significant changes in atmospheric CO_2 Menviel et al. (2010).

A discussion of the effects of different background climate on the climate and carbon cycle response in the light of the study by Menviel et al. (2008) is given on page 1830 after line 5:

In a previous study by Menviel et al. (2008), in which the experiments were done under both pre-industrial and glacial boundary conditions, it has been shown that the differences in the amplitudes of the individual contributions from the land and ocean carbon pools may lead to an opposite net effect on the atmospheric CO_2, even though the nature of each contribution is qualitatively the same. In their study, irrespective of the initial state, the roles of the ocean as a carbon sink and of the land as a carbon source remain unchanged. Yet, the emissions from land under glacial conditions are weaker than under the pre-industrial conditions. That is probably due to the lower moisture content of the glacial atmosphere, which leads to the dampening of the effects of the ITCZ shift (Menviel et al., 2008), and relatively large gains in primary

production in some regions such as eastern Asia and southern North America. Compared to our experiments, the main differences seem to be the larger increase in carbon stocks in the Southern Hemisphere and the above mentioned regions in the north, which might be due to some model specific differences as well as the initial conditions.

Line 6 on the same page is also modified as follows:

Nevertheless, as the patterns of the anomalies are very similar in both cases, it is safe to assume that our results are relevant for paleo-reconstructions as a possible ...

2. Is it the trade wind response that leads to the warming of the southern tropical Atlantic? A figure of the wind anomalies would be very helpful. What causes the temperature dipole between northern South America and the adjacent Atlantic? Over most of the lower latitude Atlantic region we see a clear correlation between changes in SAT and precipitation (warmer SAT <> more precipitation and vice versa). What causes the decoupling over northern South America?

A new figure showing the changes in wind patterns over that region has been added (Fig. 10). Warming in the southern tropical Atlantic is indeed partially influenced by weakening south-easterlies. Another factor responsible for this warming is the reduced northward heat transport in the ocean.

Additional to Fig. 10, a new panel showing the changes in latent heat flux over the northern South America has been added to Fig. 9 and the text on page 1826 line 8 has been extended in order to better explain the physical mechanisms behind the apparent change in the region:

The response in the northern South America is a combination of changes in the precipitation and the air temperature, which is influenced by the prevailing winds. Over *the ocean, where water vapor availability is primarily governed by the sea surface temperature, a positive correlation between the SAT and precipitation is apparent in most places. Over land, on the other hand, wind-driven transport of moisture from the sea is crucial. The north-easterlies that carry moist air to northern South America are weakened (Fig. 10) and, due to the colder SST in the northern equatorial Atlantic, their moisture content is reduced, which makes the region drier. This in turn results in a substantial drop in the latent heat flux (Fig. 9 last panel), most of which is due to reduced canopy transpiration as a result of the decrease in rain-forest vegetation. Consequently, a larger portion of the heat is transferred as sensible heat, raising the SAT. Removal of the rain-forest type vegetation, hence creates a very important feedback which further reduces the evapotranspiration and the latent heat flux.*

Thus, decoupling of the SAT and precipitation over the northern South America and the consequent temperature dipole between the adjacent Atlantic is the result of a combination of changing winds and moisture availability, of which warming effect is further enhanced by the dramatic decrease of vegetation cover and transpiration.

3. What drives the global SAT response of 1.0Ros and 1.0Wed? Is it the strength of the AABW formation? What drives the differences in the SAT response of 1.0Ros and 1.0Wed?

The global responses of the 1.0Ros and 1.0Wed experiments are related to the deep and bottom water formation in the Southern Ocean, and the northward bottom water transport into the Pacific and Indian Oceans can be taken as an indicator for the strength of the AABW. Fig. R1 (See the supplement for the Figures R1-R9) shows the reduction in the northward transport of the bottom water in the Pacific and Indian Oceans, which is more pronounced in experiment 1.0Ros than in 1.0Wed.

In this respect, the differences in response to the two hosing locations in the Southern Ocean possibly arise from the fact that the freshwater applied in those locations affect the formation of the AABW differently. This causes the subsurface warming in each experiment to differ from each other, with 1.0Ros creating a stronger subsurface warming (Figures R2 and R3). As a result, with more heat trapped in the ocean, the global SAT response becomes more negative. Additionally, the increase in the sea-ice cover is more than double in 1.0Ros than in 1.0Wed (not shown). This also operates as a feedback on the SAT, by increasing the albedo.

The mixed layer depth in each region is solely influenced by the freshwater applied in that region and the surface dilution effect from the Ross Sea to the Weddell Sea (or vice versa) is insignificant in this respect. That is a correction to our initial hypothesis, which has assumed a bigger role for the Ross Sea because of its upstream location. Text on page 1828 line 8 is modified as follows:

That seems to be because the Ross Sea is a more important player in the creation of the AABW in our model than the Weddell Sea, and therefore the perturbation in the Ross Sea has a stronger effect on the global climate. We note, however, that the specific locations of deep water formation are model dependent.

However, this does not discard the possibility of subsurface transport from the Ross Sea to the Weddell Sea, as it might lead to the subsurface warming patterns observed in each experiment.

4. Figure 1 shows a decoupling of SAT and AMOC strength for experiment 1.0NA. While the AMOC remains low after the end of the FW input, SAT suddenly jumps up and decreases again. This is a very puzzling feature that needs to be analyzed. Also it looks like that for 0.5NA SAT starts to recover before the AMOC does.

The warming of the global average SAT before the recovery of the AMOC seems to be a manifestation of decreased cooling in the northern Atlantic region, and to a lesser extent the warming in the high southern latitudes (Figures R4 and R5). The warming in the south can be taken as a delayed effect of the shutdown of the AMOC, while the warming in the north is due to the mixing of the trapped heat in the subsurface layers of the North Atlantic with the surface layer, and consequently with the atmosphere. Subsurface warming as a result of the shutdown of the AMOC is a well-known phenomenon and even though the deep water formation is still halted, mixing in the surface layers might occur through the wind induced circulation. Fig. R6 shows the zonally averaged temperature in the surface of the North Atlantic up to 500m depth. As can be seen from the figure, the subsurface warm anomaly reaches to maximum before the end of the perturbation and mixes with the surface waters as the perturbation ends at the year 100. The text on page 1821 line 3 is also modified to include a short explanation to this interesting feature:

In 1.0NA, this general pattern stays roughly the same even 200 years after the end of the freshwater input, except for a temporary spike in the SAT coinciding with the end of the perturbation. The reason for that temporary warming lies in the subsurface warming in the North Atlantic as a result of the increased stratification. A resumption of the vertical mixing, once the freshwater perturbation is switched off, brings up water to the surface from the subsurface warm pool which was created during the AMOC shut-down. By that time, this subsurface warm pool is mixed with the surface water and, subsequently, the atmosphere. To a lesser extent, the warming is also caused by the delayed warming in the Southern Hemisphere, as it takes time for the warming to penetrate towards Antarctica.

For the experiment 0.5NA, the early recovery in the SAT is also connected to the above mentioned phenomenon. However, in that case the contribution of the

delayed southern hemisphere warming is larger.

5. A couple of recent studies (e.g. Schmittner et al. [2007, Paleoceanography], Schmittner & Galbraith [2008, Nature], Okazaki et al. [2010, Science]) show significant changes in ocean ventilation in response to FW-forcing in the North Atlantic. Do the authors find similar features in their experiments?

There is indeed freshwater-induced deep water formation in the northern Pacific Ocean after the perturbations applied in the North Atlantic (Fig. R7). That changes the DIC and the oxygen content in the ocean. In the 1.0NA experiment, even though there is an increase due to air-sea gas exchange, the total DIC in the north Pacific up to 3000 m is reduced because of re-organizational changes (Fig. R8). As for the oxygen concentration, there is an increase until the depth of around 3000 m, and after that a reduction (Fig. R9.

Minor points:

- page 1815 / line 8 Could the authors provide references for "have been shown to be plausible ..."

References added.

- page 1815 / line 22 "support their conclusions" should be "support the conclusions"

Done.

- page 1815 / line 25 The kudos of presenting a "novel feature" is shared with Menviel et al. [2010, Paleoceanography, in press]

The word is removed and the mentioned study is discussed further in the text

(check the answer for question 1).

- page 1816 / line 17 I am just curios what vertical diffusivity parametrization is used in the modified version?

It is based on the Gent-McWilliams eddy mixing parametrization (Gent and McWilliams, 1990) with enhanced resolution near the equator and spatially varying eddy viscosity. See Gent et al. (1998) for details.

- page 1820 / line 24 "(Fig. 2, top row)" should be "(Fig.2 left column)" same for page 1821 / line 23

Done.

- section 3.3.1 It would actually be interesting to see the evolution of the carbon stocks for the experiments 0.3NA and 0.5NA. At least for 0.3NA one could see how they evolve after the AMOC recovery.

Timeseries for 0.5NA and 0.3NA are added to the original figure.

- page 1823 / line 26 ... Is Figure 4 really needed? More words are used to describe what it "cannot capture".

We believe the figure serves its purpose, which is to visualize the zonal distribution of the anomalies in precipitation, SAT, and land carbon and indicate the importance of the changes in the land carbon pool in the tropics relative to the high latitudes. Thus, we would like to keep it.

- page 1824 / line 13 ... Could the authors mention the individual contributions of gas-

exchange, primary production, expansion of DIC-rich AABW, ... to the increased ocean carbon stock in the North Atlantic?

The following text is added to page 1824 line 14: *The main reason for the carbon build-up in the Atlantic is the increased transport of DIC-rich Antarctic Bottom Water and a smaller amount comes from the air-sea gas exchange. The decreased primary production makes a small negative contribution.*

- page 1825 / line 7 How was the linear regression calculated? Using the control run or the FW-perturbation run?

It is calculated using the anomalies, which is the change in the perturbation runs with respect to the 100-year average of the control.

- Figure 1b. SAT is given in C not in K **Done.**

- Figure 5. The manuscript only refers to changes in carbon stocks in the North Atlantic. What causes the changes in carbon stocks in the other oceans?

The following explanation is added to page 1824 line 15: *This re-organization also causes to the reduction of total carbon in the other oceans, especially in the northern part of the Pacific and Indian Oceans. The contribution from the air-sea gas exchange is positive in the Pacific and Indian oceans, whereas in the Southern Ocean outgassing prevails.*

- Figure 9. Why do we see a decoupling of SAT and precipitation right after the FW-forcing was stopped for 1.0NA? This has probably to do with my major point 4.

Figure 9 depicts the timeseries of various variables in a selected region of the northern South America, and the values are averaged over land. It is not directly

related to the issues raised in question 4, which is about the global average. What we see in Figure 9 is that, as the perturbation stops, precipitation starts to increase, which leads to increased latent heat flux and decreased sensible heat, hence cooling. That is explained in more detail in the answer to question 2.

References

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Please also note the supplement to this comment:
http://www.clim-past-discuss.net/6/C1359/2011/cpd-6-C1359-2011-supplement.pdf

Interactive comment on Clim. Past Discuss., 6, 1811, 2010.