**Response to comments of Anonymous Referee #1**

REPLY: We would like to thank the reviewer for the insightful comments and constructive suggestions. We agree with almost all of the points and will incorporate them in the revised version. Please find our detailed reply below (the reply is denoted by font in blue color).

The manuscript is in general rather descriptive and long and could greatly be improved by including a more solid model-data comparison, a comparison to previous transient modelling work and a general discussion of how these results can be used to inform future modelling exercises and the interpretation of proxy-based climate reconstructions of the period under consideration.

REPLY: We could not agree more with the reviewer that including more model-data and model-model comparisons would provide added value to our analysis. However, as mentioned by both reviewers, the manuscript is already quite long, and in our view, both the comparisons with other model simulations and with proxy-based reconstructions deserve to be done in detail. We therefore propose to discuss these comparisons in separate papers, and to provide only a summary in the present manuscript. Indeed, the objective of the present paper is to present and discuss our new model results, with a focus on temperature, and the mechanisms for climate change according to the simulations. We agree that this objective could be clarified in the introduction, and we will do so in the revised manuscript.

**1.** General comments:

1) The manuscript is fairly long and there is a little too much repetition in the abstract, results and conclusions sections.

REPLY: We agree and will improve the manuscript in our revised version by removing redundancy.

2) The model-data comparison that is presented is very descriptive. Why not use a temperature compilation (such as the one from Marcott et. al. mentioned in the manuscript) to actually compare model and data. A model-data comparison of all the other reconstructions that are discussed in the manuscript is perhaps difficult because they all registered different 'things' (atmospheric temperatures, sea-surface temperatures, sea-ice cover etc). Nonetheless, it would be very useful if the authors can come up with a way to make the model-data comparison more visual because in its current form it is very difficult to follow for the reader and get a good overview of the model-data matches and mismatches.

REPLY: Thanks for these suggestions. We agree and will make a new summary figure about model-data comparison, i.e comparison of our simulated temperature with Marcott et al. (2013) proxy zonal mean temperature curve over 30-90 °N.

3) There is very little discussion on what model-data mismatches can potentially tell us about our interpretation of climate proxies, on the validity of the applied model forcings or the realism of different feedbacks in the climate model.

REPLY: By analyzing the model-data figure, we will briefly discuss the validity of the forcings and the related feedbacks. However, considering that only a summary comparison is provided in this work, we consider it's too ambitious to make conclusions about the interpretation of proxies. As mentioned above, we will deal with that in more detail in our future work.

4) How does the LOVECLIM early Holocene simulation compare to previous model runs? For instance a comparison to the results from the TraCE-21K could be very interesting (http://www.cgd.ucar.edu/ccr/TraCE/).

REPLY: This is a good point. However, the different models report the temperature evolution in different spatial domains and sometimes with different forcings, which makes model-model comparisons demanding more detailed work. For instance, systematic comparisons would be worth conducting. Actually, in our next step, we will collect the simulations performed by different climate models, check their forcings, and compare them in the same spatial domains.

5) The conclusion on what GIS evolution fits best (page 6369 lines 21-24) seems based on rather little evidence and should be weakened a little in the text. What is the influence of the differences in the FIS meltwater flux between the two meltwater scenarios? A more general discussion on the use of different meltwater fluxes to capture the uncertainty in reconstructions of ice sheet decay would be useful. Questions that come to mind are: Are the simulated differences in surface climate (sort of a fingerprint) large enough to use proxy-based reconstructions to discriminate between the two scenarios? Would additional reconstructions from certain key regions allow you to do so?

REPLY: Thanks for this nice suggestion. The corresponding adjustments (weakening the conclusion on GIS evolution, adding the influence of different FIS freshwater fluxes and including the general discussion on uncertainty of freshwater reconstruction) will be done in our revised version. We agree that the differences between the simulation of OGIS_FWF_v1 and OGIS_FWF_v2 resulted from both FIS and GIS freshwater differences. As for the question whether these differences are big enough to be identified in proxy data, we found that the temperature differences are identifiable in the areas which can be influenced by the freshwater (i.e in NW Europe) and these differences improve the consistency with the data. In the areas beyond this range, different freshwater forcing scenarios only cause a minor difference, implying that they have an insignificant influence on the agreement with proxy data.

6) The latest version of the LOVECLIM model (iLOVECLIM) also includes a permafrost module, and permafrost is potentially very important for the early Holocene at high northern latitudes. Can the impact of permafrost changes be taken into account in an additional simulation? Or otherwise, can the effect be discussed based on previous work?

REPLY: We agree that permafrost potentially played a role in the climate system during that time. However, this two-direction coupled permafrost version has not been published and was not yet available at the time of our study. The published version of iLOVECLIM is only one-way coupled with the permafrost module (VAMPERS), namely VAMPERS is forced by the atmospheric component ECBilt (Kitover et al. 2015). This discussion and related literature will be included in our discussion of the Arctic temperature (§4.2) of the revised manuscript.

7) Results from 11.5ka equilibrium simulation are presented and the transient simulation is started from these initial conditions. As described in the manuscript, the deglacial climate is likely far from equilibrium, how does this impact your results?

REPLY: The climatic component in our model with the longest memory is the deep ocean. It is this component that is most likely affected by starting from a 11.5 ka equilibrium state. It is likely that in reality the deep ocean was still relatively cold due to the preceding Younger Dryas, and therefore these deep waters likely had a relatively high density. Deepwater formation is a function of the density gradients, so potentially this deepwater formation was less deep/less vigorous than in our equilibrium experiment, assuming that our meltwater forcings were realistic. We will provide this explanation in the experimental setup section (§2.3).

8) What is the benefit of describing the results of the equilibrium experiments rather than simply an average over the first, say 500-years, of the transient simulations?

REPLY: We agree that we could also have described the average results over 11.5 to 11.0 ka BP instead of the results from the equilibrium experiment with 11.5kyr BP forcings. This would not have made an important difference. However, in our view, it is instructive for the reader to know from what state our transient experiment was starting.

9) Include, if not already there, a short introduction at the start of every section and a short summary at the end. This will greatly improve the readability of the manuscript.

REPLY: We will include it as suggested in the revised version.

10) I would suggest to focus on the OGIS simulations in the results sections since this is the most 'realistic' forcing

scenario. Then the experiments without ice sheet changes can be used to illustrate the role of individual forcings and feedbacks.

REPLY: This would indeed be a clear structure for equilibrium results and we will make the adjustments accordingly. However, please note that OGIS (and also OGIS11.5) is an equilibrium experiment. Using the results of the transient experiments, we would like to discuss the impacts of the two freshwater fluxes scenarios.

**2.** Minor comments:

Page 5346 line 1: “a critical period for climate change”. Please rephrase, do you mean a critical period to study large changes taking place in the climate system that can help us understand future climate change? Or perhaps simply an important climatological period since the last glacial maximum?

REPLY: We rephrased it like this: “The early Holocene is an important climatological period since the last glacial maximum, as it marked the final transition from the last deglaciation to the relatively warm and stable Holocene”

Lines 14 page 5346 to line 28 page 5347: The abstract is rather long and includes a lot of details. Perhaps these two paragraphs can be shortened by about half by solely summarizing the main findings (for instance large spatial differences accompanied by two examples). On the other hand, the abstract lacks any discussion of the comparison of the results to proxy-data or on the importance of the different forcings, especially the two different freshwater forcings. These points could be of much interest to the reader Discussion Paperand should therefore be mentioned in the abstract.

REPLY: We appreciate the practical advice and we will improve the abstract as suggested.

Page 5348 line 5: what ‘many other’ records from further east in Eurasia are you referring to here? Please be more specific.

REPLY: We mean both cave and sediment records, but we only provide the speleothem records from China as an example. We rephrased it to: “In addition, this transition is also documented in high-resolution records further to the East, for example in speleothem records from China (Yuan et al., 2004; Wang et al., 2005)”

Page 5348 lines 10-14: A suggestion for the introduction is to shift this line to the beginning. One could start out by mentioning the general early Holocene NH extratropical temperature evolution based on temperature stacks, how this general trend has previously been explained in modelling work, but how it fails to identify large regional differences. Differences that are potentially important in improving our understanding of the impact of climate forcings and feedbacks.

REPLY: Thanks for this advice and we will take it into account in our revised version.

Page 5348 lines 15-18: Is this in case one looks at greenhouse gas changes as an internal feedback or more general?

REPLY: We are aware that recent studies report on the role of both GHGs and insolation in the last deglaciation (Shakun et al. 2012 & 2015). However, during the last part of deglaciation and the early Holocene, insolation and the ice sheet melt seem to have played a more critical role. We will clarify this in our revised manuscript.

Page 5349 lines 8-10: Is this really as clear as you make it sound?

REPLY: The ice sheet topography can induce the glacial anticyclone if the ice sheet is big enough, which reduces the temperature over the ice sheet. However, the topography effect involves additional complex interactions at a broader scale, for instance through processes involving the surrounding area. Therefore, we rephrased it into: “For instance, large scale ice sheet topography generates a glacial anticyclone that tends to locally further reduce the temperatures (Felzer et al., 1996)”

Page 5353 line 1: Do we know what a ’reasonable’ sensitivity of the climate to a freshwater perturbation is?

REPLY: We agree that the debate about real climate sensitivity to freshwater perturbations is still going on. However, by 'reasonable sensitivity of the climate to a freshwater perturbation' we mean a sensitivity that is comparable with the proxy-based climate response to freshwater fluxes.

Page 5353 line 4: I'm not sure if I understand the forcings of all the different experiments. What forcings are included in OGIS11.5? See also my comment to include a table describing the different experiments.

REPLY: The equilibrium experiment OGIS11.5 includes the full forcings (namely GHG, ORB, ice sheet configuration and corresponding meltwater). Corresponding summary forcings for each experiment are included in a new table (please find below).

Page 5353 line 25: Where they excluded in this study or in the PMIP protocol?

REPLY: In this study, we exclude the GHG concentration rise in the industrial era since we explore the natural variability of the climate system. The sentence was rephrased to: "Overall, this setup of GHG and ORB forcing is in line with the PMIP3 protocol (http://pmip3.lsce.ipsl.fr), except that our simulation excludes the increases in GHG levels during the industrial era"

Page 5353 lines 26-28 and page 5354 lines 1-10: Please be more specific about the ice sheet evolution that has been applied in the simulations. Is it based on previous estimates? How does it compare to previous deglacial model experiments? How often is the ice sheet mask, topography and albedo updated?

REPLY: The extent of ice sheets is based on a number of previous reconstructions and the elevation is derived from the simulation of Ganopolski et al. (2010), which is comparable with the ICE-5G reconstruction (Peltier 2004). The ice sheet configurations were updated every 250 yrs, while the freshwater was updated with smaller irregular steps within 250 yrs (Fig 3). We will clarify this setup in our revised version. As for the albedo, it is automatically calculated by the model according to the local surface features. We will accordingly clarify these points in the revised version.

Page 5354 line 16: Please also provide the corresponding meter sea level equivalent for easier comparison for the reader.

REPLY: We will include it in our revised version.

Page 5354 line 21: What is meant here with 'a lack of climate imprint'? Please explain.

REPLY: Compared with the ice sheet configuration, the freshwater left a limited trace on the land. We rephrased it into: "Given the lack of a direct imprint left by meltwater on terrestrial proxies and hence the relatively large uncertainty, we used two versions of the freshwater flux (Fig. 3b) that represent two possible deglaciation scenarios of the GIS and FIS, named FWF-v1 and FWF-v2"

Page 5354 line 26: On what basis are these two different freshwater scenario constructed? What is the evidence for a faster or more gradually decreasing FIS melt rate?

REPLY: The two freshwater scenarios are based on two different reconstructions of the melting of the ice sheets, representing the classical and updated view. To be more specific, the GIS fwf_v1 is derived from the ice_5G reconstruction (Peltier), while the fwf_v2 is based on the reconstruction of Vinther et al. (in 2009) that suggest a faster GIS thinning. The freshwater flux from FIS is based on two versions of estimated FIS ice sheet melt, since the recent cosmogenic dating (fwf_2) supports much faster melting (Clark in preparation) than previously thought (fwf_1).

Page 5354 line 28: We are perhaps more certain about the total contribution, but what about the spatial pattern of the freshwater fluxes?

REPLY: Yes, the spatial distribution of freshwater discharge indeed makes a difference as the relative locations to ocean circulation (e.g the deep water formation zone) are different. In our simulation, we applied the most likely scenario, based on previous research. GIS freshwater forcing was introduced around the GIS (Bakker et al.2012). FIS meltwater was relatively small and was put into the Eastern Norwegian Sea at the western Scandinavian coast. The location of the LIS freshwater discharge is constrained by isotopic data from nearby ocean sediment cores.

Page 5355 lines 15-19: An experiment with only different freshwater fluxes is interesting because it allows one to isolate this effect. However, it seems that the other characteristics of the GIS and FIS are equally uncertain. What is the reasoning not to perform experiments in which those aspects are also changed? If there are reasons to believe that they might be significant differences in either elevation or extent it would be good to test the impacts with a climate model simulation.

REPLY: We agree that the suggested sensitivity experiments would be helpful to separate these forcings. We did perform the equilibrium experiments with different freshwater combinations and found that the resulting responses in ocean circulation (please find the figure of testing different freshwater scenarios below, in which the variable of mixed layer depth in ocean indicated the strength of circulation is showed) are generally consistent with the published results (Roche et al, 2007). Concerning the uncertainty in the ice sheet topography and extent, please note that our model has a relatively low spatial resolution of 5.6x5.6 degrees lat-lon. This implies that our model is not very suitable to quantify changes in ice sheet extent of a few hundred kilometers or changes in ice sheet elevation of a few hundred metres.

Page 5356 line 25: These numbers are without correcting for the changes in elevation of a particular site? Please clarify in the text.

REPLY: We will incorporate this in our revised version.

Page 5358 line 26: What is the cause of this rapid increase in Arctic winter temperatures around 7ka?

REPLY: The freshwater fluxes are dramatically reduced between 7 and 8 ka. This resulted in a marked strengthening of the ocean circulation and a reduction in the sea ice cover, leading to the noted increase in Arctic winter temperatures. The explanation will be provided in discussion of the two freshwater forcing scenarios (§4.3) in our revised version.

Page 5359 lines 22-24: What causes this summer cooling? One could think that the impact of freshwater on the continental climate is through ocean circulation and or sea ice, both of which often have the largest impact on winter temperatures, quite different from the response described here.

REPLY: This freshwater-related cooling in summer is probably caused by the albedo feedback on land. During summer, the slightly lower temperature can be associated with the higher albedo, while in winter the albedo change in the Arctic region was relatively small, as it was covered by snow in any case.

Page 5365 lines 15-21: This section on the influence of ice sheet changes on atmospheric circulation is somewhat similar to lines 9-22 of page 5363. Consider condensing it into one paragraph.

REPLY: We assume that page 5363 lines 9-22 meant page 5366 lines 9-22. Thanks for bringing this to our attention. The corresponding parts were combined.

Page 5366 line 19: “From the record side”, please explain.

REPLY: We try to say here that there are proxy evidences indicating a different early Holocene ocean circulation from the present. We rephrased this to: “From the proxy perspective,”

Page 5366 line 20: The changes in dust concentrations during the early Holocene are they caused only by circulation changes or perhaps also influenced by changes in dust availability?

REPLY: We agree that the dust concentrations in ice core are influenced by both of these factors. We modified this to: “…also imply a potential change in atmospheric circulation near the N Atlantic”.

Page 5367 lines 5-8: How do insolation changes drive temperature decreases in both summer and winter, please explain.

REPLY: Thanks for noting this confusion. We were trying to say: The slightly negative winter insolation anomaly contributes to lower winter temperature, and thus indirectly impacts the annual temperature. But summer temperature shows only a small deviation from PI, which is caused by the offset between the positive insolation anomalies and the albedo cooling effect. We will clarify this in the revised version.

Page 5371 lines 8-9: “The summer temperature was similar to the preindustrial then these two factors were in similar magnitude.” Please explain.

REPLY: We will rephrase it to “during summer, these two factors were similar in magnitude, and the temperature was similar to that in the preindustrial”

Page 5371 line 26: “in spite of”? Please explain.

REPLY: We mean to say that the warming rates in different regions were influenced by different mechanisms. The overall warming rates were intermediate (around 0.5 ◦C ka-1). We rephrased it like: “Although in NW Europe, Arctic and Siberia different mechanisms played a role, the overall warming was similar in these regions, with an intermediate rate of about 0.5 °C $ka^{-1}$.”

At several places in the manuscript you describe 11.5ka temperatures as “reaching maximum cooling” (for instance page 5370 line 8). This suggests that 11.5 is a temperature minimum, but since your simulation starts at 11.5ka we cannot know if this is true. What I mean to say is that 11.5ka is during the deglaciation and thus somewhere between minimum (LGM) temperatures and maximum (Holocene thermal maximum) temperatures and it is thus not likely that 11.5ka was in fact a temperature minimum. Please go through the manuscript and carefully check your wording.

REPLY: We mean that at 11.5 ka, the temperature reached the lowest levels in N Canada compared to other places. We were not referring to a temperature minimum in time. We will modify text to avoid the misunderstanding.

**3.** Technical comments:

REPLY: Thanks for the suggestions and corrections. We will incorporate them in our revised version.

**4.** Tables and figures:

Tables: Please include a table outlying the different forcings that are included in the different simulations that are presented in this study.

REPLY: We added the table as suggested:

| Equilibrium exp. | | Transient exp. | |
|---|---|---|---|
| Name | Forcing | Name | Forcing |
| OG11.5 | ORB+GHG | OG | ORB+GHG |
| OGIS11.5 | ORB+GHG+IS+FWF | OGIS_FWF_v1 | ORB+GHG+IS+FWF_v1 |
| | | OGIS_FWF_v2 | ORB+GHG+IS+FWF_v2 |

Figures in general: Although perhaps a personal preference, readers are not used to seeing the time axis of model output depicted from right to left. Consider changing.

REPLY: We changed the direction of the time axis.

Figure 4: the numbers on the axis are difficult to read.

REPLY: We enlarged the font size of the text on the axis.

Figures 5-9: Why is the OGIS11.5 simulation not included? It could highlight the effects of ice sheets vs meltwater (same for figure 15). Another question: How are thermal maximum periods calculated?

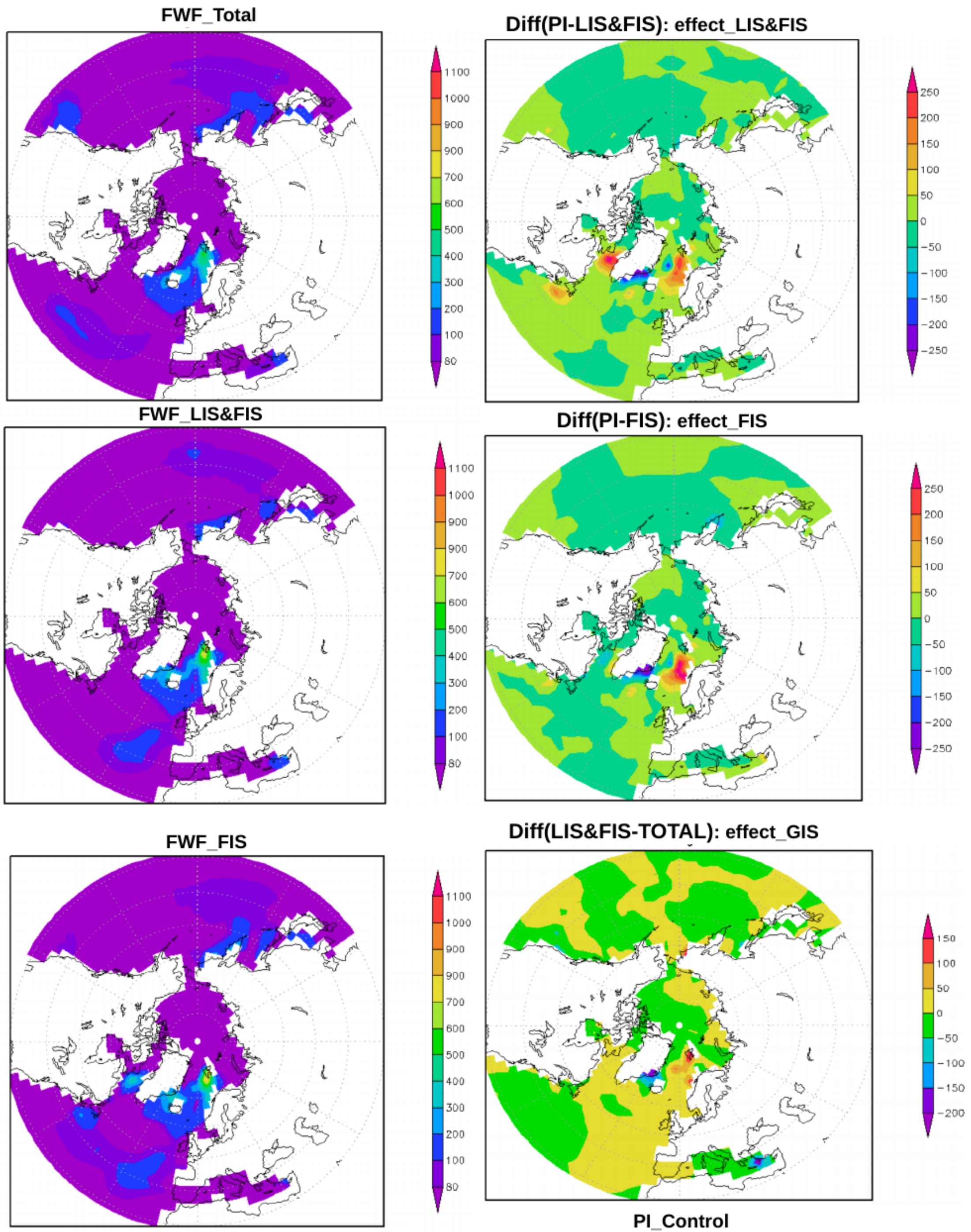
REPLY: The simulation OGIS11.5 is an equilibrium experiment with full forcing. However, figs. 5-9 and 15 show the results of transient experiments. As for the thermal maximum, it is a simulated temperature peak with the full forcing during which the temperature was over 1 °C higher than PI.

Figure 14: Why are maps shown for 10ka temperatures?

REPLY: Since there is a small peak in the temperature evolution in NW Europe at this time, we analyze 10 ka temperature (Fig 14) and winter albedo (Fig 16), and explore the possible reasons for this and/or valuate how robust our simulation is at this point.

Figure 15: Between 8ka and 7.5ka the AMOC jumps back to a 'full strength' state. I'm surprised that this is not reflected in the NH sea ice area (Figure 15b) or in the temperature evolution of the Artic or NW Europe (Figures 5-6). Please explain.

REPLY: The jump in AMOC strength between 8ka and 7.5 ka is a response to the dramatic reduction of freshwater forcing around 7.8 ka. However, there is a smooth response in the NH Arctic sea ice, which is probably caused by the fact that the AMOC is not only affected by the sea ice, but also by other factors. The similar reaction in Arctic temperature can be explained by this sea ice coverage. Regarding the temperatures in NW Europe, they are impacted by the AMOC, but are more determined by the configuration of LIS.



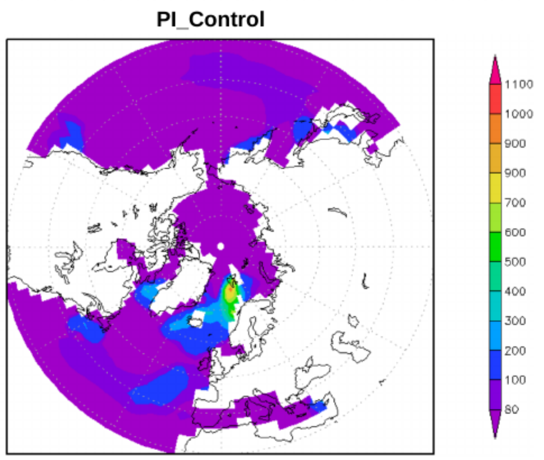




**Figure**: The left column is annual mix layer depth (in m) in ocean with corresponding freshwater pertubations, and their difference from the reference is showed in the right (please note the last planel is reversed subtraction).

By performing these experiments with different feshwater scenarios, we tested how the freshwater discharges impact the ocean circulation, that has been found closly related to the climate spatial pattern.