Review of the manuscript 'Using data assimilation to investigate the causes of Southern Hemisphere high latitude cooling from 10 to 8 ka BP' by P. Mathiot et al.

Anonymous Referee #1

General:

The authors carry out model simulations with a model of intermediate complexity using data assimilation of proxy data to investigate climate changes over the high latitude southern hemisphere in the late glacial/early Holocene between 10 ka and 8 ka BP. The hypotheses and the according experimental model setup are explained in detail and results are presented in a concise manner and in the context of already existing studies. Moreover, the topic fits well into the scope of Climate of the Past. I therefore suggest publication of the article with minor revisions outlined below.

Specific comments:

Abstract:

In the abstract mechanisms and hypotheses are somehow mixed: one might just include information on the origin of the hypotheses, i.e. " Based on empirical information from [proxy #1) the hypothesis related to a change in atmospheric circulation was suggested. Information contained in [proxy #2] provoked the hypothesis of a cooling in the Southern Ocean. With our model study we addressed theses hypotheses by. . ." This would help the reader to see at a glance which proxy or which combination of proxy record supports the respective hypothesis. This differentiation might also be helpful to account for the different susceptibility of different proxies to different processes.

P. Mathiot and co-authors: Following the Reviewer's advice the abstract has been largely modified. However we think that specifying the proxies which lead to the first or second hypothesis is not relevant for abstract because it is too specific. This point is described in detail in the introduction. The revised abstract is now: "*…The selected proxies represent oceanic and atmospheric surface temperature in the Southern Hemisphere derived from terrestrial, marine and glaciological records. Two mechanisms previously suggested to explain the 10-8 ka BP cooling pattern are investigated using the data assimilation approach in our model. The first hypothesis is a change in atmospheric circulation, and the second one is a cooling of the sea surface temperature in the Southern Ocean, driven in our experimental setup by the impact of an increased West Antarctic melting rate on ocean circulation. For the atmosphere hypothesis, the climate state obtained by data assimilation produces a modification of the meridional atmospheric circulation leading to a 0.5°C Antarctic cooling from 10 to 8 ka BP compared to the simulation without data assimilation, without congruent* *cooling of the atmospheric and sea-surface temperature in the Southern Ocean. For the ocean hypothesis, the increased West Antarctic freshwater flux constrained by data assimilation (+100 mSv from 10 to 8 ka BP), leads to an oceanic cooling of 0.7°C and a strengthening of Southern Hemisphere westerlies (+6%). Thus, according to our experiments, the observed cooling in Antarctic and the Southern Ocean proxy records can only be reconciled with the reconstructions by the combination of a modified atmospheric circulation and an enhanced freshwater flux.* "

Introduction:

P 5547, ll 1ff: one should also include internal variability as a potential factor – the large oceanic areas around Antarctica including sea ice and land ice might also show long term internal changes that might indirectly respond to external forcings. A second issue relates to changes in greenhouse gases, for instance the release of CO2 from the southern ocean in the late glacial.

P. Mathiot and co-authors: We think that adding information about the potential role of internal variability in the introduction will confuse the reader because this mechanism is not discussed in the manuscript. In order to keep a clear and focus introduction we decide to not modify the first paragraph. However we added a few words about this in the section describing the performance of STD simulation.

About the release of CO2 from the Southern Ocean in the late glacial, we think this issue does not play an important role in our study because GHG concentrations are prescribed from ice core data. Thus, these data already integrate the release of CO2 from polar ocean and the CO2 concentration changes are not able to explain the observed signal between 10 and 8 ka in our model. A next step could be to assess the impact of the climate states on the ocean-atmosphere carbon fluxes, but this is well beyond the scope of our study.

A general paragraph addressing the basic concepts of data assimilation would ensure that also the reader who is not familiar with those concepts gets an introduction into the field – a good overview can be found in the paper of Widmann et al. (2010). The paragraph could also include some statements fact that the assimilation also helps to investigate large-scale atmospheric and oceanic patterns that is essential in understanding late-glacial climate change. A short paragraph justifying the application of an EMIC could also be helpful in setting the stage for the paper. For instance, with EMICs it is possible to carry out multiple simulations with different initial conditions and different combinations in external forcing within a short time. The large ensemble allows a probabilistic view of the scientific problem in terms of how likely/unlikely a certain hypothesis inferred from empirical evidence might be. One could also stress that with model simulations it is possible to test the physical plausibility of hypotheses derived from proxy data, although some of the initial conditions and the complexity of the full system might not be available. A critical point might be however the horizontal and vertical

resolution of the model components concerning the oceanic studies, especially for fresh water flux experiments. Some studies for the North Atlantic indicate that the horizontal resolution could be quite crucial for the exact pathways for water masses and related climatic effects (Spence et al., 2012) – even one could not address this point with a coarsely resolved EMIC one could at least address this issue to leave some room for potential inconsistencies between model results and empirical reconstructions.

P. Mathiot and co-authors: We have modified the paragraph about data assimilation and EMIC in the introduction. As suggested, we have added some precisions on data assimilation and also on our EMIC: *"To combine the information provided by proxy data and a climate model, data assimilation methods have been adapted to the long time scales, providing estimates that are compatible with model physics and available data (e.g, Widmann et al., 2010). However, using data assimilation with a high-resolution climate model is not practically possible today for a long time scale because this type of simulation would require a too large amount of CPU time. Consequently, data assimilation has been applied here with an Earth-System Model of Intermediate Complexity (EMIC). Although the full complexity of the system is not resolved in an EMIC model, it is possible to carry out multiple simulations or large ensembles with different initial conditions and different combinations in external forcing within a reasonable time. This allows testing the physical plausibility of hypotheses suggested to explain signals derived from proxy data. However, due to the coarse resolution and simplified model physics, results are associated to large uncertainties. For example, Spence et al. (2012) show that the horizontal resolution could be crucial to define the right water masses pathways, properties and the related climatic effects. This leaves room for potential inconsistencies between model results and empirical reconstructions.* **"**

Experiment setup:

p. 5550 l.16: The authors state that the atmospheric component of the model only consists of three levels – one should add a word which implications this low vertical resolution might have on the conclusions drawn on changes in atmospheric circulation, i.e. how well is the structure of the southern hemispheric jet streams and low-level mean atmospheric circulation represented by the model.

p. 5550 l. 20: – the same for the ocean model – which implication might the restricted depth of 500 m have on oceanic processes such as deep water production, for instance related to fresh water experiments including glacier melt.

P. Mathiot and co-authors: For the atmospheric component, Goosse et al. (2010) show that LOVECLIM reproduces reasonably well the main characteristics of the observed surface temperature distribution as well as the large-scale structure of the near surface circulation. However, the model tends to underestimate the gradients of geopotential height in both hemispheres, leading to simulated winds weaker than the observed ones. This limits the effect of data assimilation to large scale pattern.

About the ocean model, the present North Atlantic overturning circulation shown by Goosse et al. (2010) in LOVECLIM (22 Sv) is quite reasonable compared to the data from the North Atlantic (26.5 °N) hydrographic section RAPID (18.5±4.9 Sv, Cunningham et al., 2007) or from the reanalysis GEBCO 1° (20 Sv, Cabane et al. 2008). Furthermore, even with a coarse bottom resolution, LOVECLIM simulates a reasonable physical response to fresh water flux modification in term of water mass characteristics as well as in term of overturning in north Atlantic and around Antarctica (Swingedouw et al., 2009) that are in agreement with those obtained by other models (e.g., Seidov et al., 2005) and Stouffer et al. (2007). We have also clarified the ocean model resolution. The vertical resolution at the bottom is 500m but the last level depth is about 5500 m.

In the manuscript, we now specify that Goosse et al. (2010) describe the model but also assess the performance of LOVECLIM : *"Each model component is briefly described here. A comprehensive description of the model, as well as a description of the model performance for standard cases (present climate, last decade, last millennium and last glacial maximum), is available in Goosse et al. (2010). Besides, we do not consider that it is necessary to repeat the results published in Goosse et al. (2010) here."*

We also clearly precise the depth of the last ocean level: *"CLIO is a general circulation model with a horizontal resolution of 3x3° and a vertical resolution ranging from 10 m near surface to 500 m at 5500 m depth."*

Cabanes, C., T. Lee, et L. L. Fu, Mechanisms of interannual variations of the meridional overturning circulation of the North Atlantic ocean, Journal of Physical Oceanography, 38, 467–480, 2008.

Cunningham, S. A., T. Kanzow, D. Rayner, M. O. Baringer, W. E. Johns, J. Marotzke, H. R. Longworth, E. M. Grant, J. Hirschi, L. M. Beal, C. S. Meinen, et H. L. Bryden, Temporal variability of the Atlantic meridional overturning circulation at 26 °N, Science, 317, 935–938, 2007.

DATA added:

P. Mathiot and co-authors: One data from James Ross Island has been added in the paper for validation. We can't used it for data assimilation because it was published when the simulations were already done. Consequently the RMSE changes a little (some hundredths) but does not change the conclusion. Actions taken are a modification of figure 1 and a modification of the rmse in the text.

" … Some records rejected for data assimilation are kept for independent validation as well as recently released data (Mulvaney et al., 2012) that were not available to us at the time the simulations were launched (Table 1b). **…"**

New rmse:

Experiments	Antarctica	Southern Ocean
STD	1.01	1.26
ATM	0.45	1.04
FWF	0.74	0.77
ATMFWF	0.38	0.66

The WAIS fresh water flux experiment is explained very well with abundant and critical information from the literature – one might add a sentence that despite these uncertainties modelling studies provide a framework the assess the potential bandwidth of possible climatic evolutions taking into account the uncertainties related to the simplicity of the climate model used.

P. Mathiot and co-authors: We modified a little bit the last paragraph to take into account this issue :

"It is therefore difficult to faithfully assess changes in fwf due to WAIS melting between 10 and 8 ka from the existing data. The uncertainties on timing and melting rate are thus large enough to justify the study, with an Earth climate model of intermediate complexity such as LOVECLIM, of how modifications of this fwf can affect the early Holocene SH high latitude climate, and which fwf amount leads to the best consistency between the simulated and reconstructed temperature patterns. We are fully aware that all the results are probably model dependent and subject to many limitations due to the model selected resolution, physics, forcings, the data assimilation method and the target data, as discussed in more details below. "

Results:

p. 5557, l. 25: again, internal variability could be a potential mechanism explaining at least part of the cooling

P. Mathiot and co-authors: Comments about this potential mechanism is now in the manuscript : *"The climate simulated in STD experiments is thus not consistent with data. This might be due to an internal variability of the system driven by a long term changes, an indirect response of ocean, sea ice and ice sheet to the external forcing, an inadequate model physics that prevent a correct response to the forcing or the realism of the model forcing itself."*

p. 5558, l. 10. please change 'observations' to (proxy) reconstructions

P. Mathiot and co-authors: DONE

p. 5559, l. 25ff. the changes in SWW might be more complicated and depending on the very specific latitudinal position of the proxy site. For instance, changes in highlevel jet streams and according wave train patterns could lead to increases of surface winds over some regions (longitudinal bands), while others experience decreases or vice versa.

P. Mathiot and co-authors: For each experiment, we used 48 particles. In this part of the text, we discuss the experiment FWF. The modification of the SWW discussed in the text is a mean value of the 48 particles. Consequently, it already take into account potential changes in high level jet streams and wave train patterns. Furthermore the differences between 8 and 10 ka are significant (99% student test). We agree that changes in SWW can be complex but our goal here is to describe the broad pattern. While we have not modified the manuscript, the caveats associated with our EMIC are clearly stated at the beginning and end of the text.

Conclusions:

It would be nice to see some concluding remarks on the critical points of the study and its limitations – this could then also be used as an outlook for potential future studies with other modelling tools (more complex models incl. internal variability, higher resolution) or changes in the experimental setup.

P. Mathiot and co-authors: As suggested by referees 1 and 2, we have summarized the main limitations due to the model (EMIC), the method (disagreement between assimilation frequency and processes used to generate the ensemble) and also the fwf data used in the Northern Hemisphere to constrain the model. The revised paragraph devoted to this subject in the conclusion is: *"This study also presents a way to optimise a key unknown parameter (fwf in our case) to obtain a state compatible with proxy records and constrained by model physics. Nevertheless, the uncertainties on such reconstructions are directly related to the uncertainties on the climate model, on the method and on data availability. The climate model LOVECLIM used in this study is a model with a coarse resolution and simplified physics. The results may be somehow different using a more sophisticated climate model. For example, it has been reported that the simulated impacts of Laurentide melting on oceanic water masses and Northern Hemisphere climate are significantly different in a coarse resolution model and a high-resolution model (Spence et al., 2012), potentially affecting the model response in the Southern Ocean.*

Uncertainties on the location and magnitude of the fwf forcing due to ice sheet melting in Northern Hemisphere remain large. Licciardi et al. (1999) show that the total input into Arctic Ocean is about 11 mSv at 10 ka, which represents 12% of the total water injected at 10 ka in STD. Clark et al. (2012) report large changes of the Scandinavian Ice Sheet area between 11 and 10 ka. These sources of melt water in Northern Hemisphere which are not incorporated in our set of simulations could further modulate the intensity of bottom water formation in the Norwegian and Greenland

Seas (Bakker et al., 2012) and affect inter hemispheric tele-connections mechanisms (bi-polar seesaw and advective tele-connection). Northern hemisphere data assimilation may help to constrain those inputs as well as the characteristics of deep water formed in the North Atlantic, and thus on CDW and the southern ocean surface temperature. In our current experimental setup, we cannot modify the the characterisitcs of the CDW at 8 ka compared to 10 kadue to this lack of data assimilation in the NH.

There are also caveats intrinsic to our assimilation method. In the ensemble generation, if we perturb variables related to processes with different time scales, as for example the stream function (1 year) and the fwf in Southern Ocean (50 years), the model, and thus the behaviour of the particle filter, will only be affected by the process which has a time scale similar to the assimilation time step. Consequently, the procedure has to be applied in two separated steps and does not take into account adequately all the interactions between various processes.

Finally, the proxies used cover only a small fraction of the high latitudes of the Southern Hemisphere. Furthermore, they are indirectly related to the freshwater flux to the Southern Ocean. Our experiments suggest that the cooling there at 8 ka is a strong feature of the system. We have shown that this can be achieved through an enhanced freshwater flux but additional reconstructions of surface temperature or of variables directly linked with fwf are required to confirm this hypothesis. "

Figures:

For the difference plot a statistical test on the significance would be helpful even though it can be assumed that most differences are statistically significant regarding the number of degrees of freedom for each experiment.

P. Mathiot and co-authors: DONE. We have deleted all the non significant area. As you expected, most parts of the figure have significant differences. The manuscript has been slightly modified to take into account the small differences between the old and the new figures.

Suggested further References:

Spence, P., O. Saenko, W. Sijp, and M. England, 2012: North Atlantic climate response to Lake Agassiz drainage at coarse and ocean eddy-permitting resolutions. J. Climate. doi:10.1175/JCLI-D-11-00683.1, in press.

Widmann, M., H. Goosse, G. van der Schrier, R. Schnur and Jan Barkmeijer, 2010: Using data assimilation to study extratropical Northern Hemisphere climate over the last millennium. Climate of the Past, 6, 627-644.