Answer to referee 2

The referee's comments are shown in black and our answers in blue :

Review of

'Assessing the robustness of Antarctic temperature reconstructions over the past two millennia using pseudoproxy and data assimilation experiments'

by F. Klein et al.

Recommendation: minor revisions

This manuscript presents data assimilation (DA) simulations for Antarctica for the past two millennia using a particle filter with the ECHAM5/MPI-OM and ECHAM5-wiso isotope-enabled GCMs. The simulations comprise pseudo-proxy experiments, which show that the DA can successfully capture the target oxygen isotope pseudoproxies, but that the skill in reproducing temperature variability is limited. It is also shown that this limited skill for temperature reconstructions is due to weak and temporally varying links between regional temperatures and oxygen isotopes, which also means that statistical reconstruction that rely on links fitted during a relatively short period are problematic.

The main objective of the study is to investigate the discrepancies with respect to the beginning of the anthropogenic warming and to the regional temperature trends between statistical temperature reconstructions for Antarctica and forced CMIP simulations. The simulations show an earlier onset and a more spatially homogeneous warming across Antarctica than the empirical temperature reconstructions by Stenni et al. (2017), which shows warming only in some parts including the Antarctic Peninsula and the West Antactic Icesheet. Potential reasons for this are an overestimation of the forced response in the models, or a dominant role of internal variability. Using assimilation of real world oxygen isotope records it is shown in the manuscript that the DA simulations are consistent with the empirical temperature reconstructions and that there is therefore no evidence for a fundamental inconsistency between climate simulations and empirical regional Antarctic temperature reconstructions.

The methods applied are state-of-the-art and well explained, and the conclusions are mostly drawn in a sound way. The manuscript is very clearly written and provides an important contribution to palaeoclimate science. There is only one substantial point I would like to be discussed in more detail, which is the distinction of stationary vs transient offline DA methods and the implications on the conclusions. After this and a number of very minor comments have been addressed I fully support the publication of this very interesting and informative paper.

We would like to warmly thank the reviewer for his careful evaluation of our manuscript and for the interesting comments. All of them will be taken into account in the revised version.

Specific comments

1)
There are two types of offline DA methods. In ‘transient offline’ methods the ensemble used for DA is time-dependent and generated by ensembles of forced simulations, and only the simulated ensemble at or around the time of the assimilation timestep is used DA. In transient offline DA the ensemble size for DA is limited by the computational constraints on performing transient ensemble simulations. The ensemble size for DA can be substantially increased in ‘stationary offline’ DA methods by using all simulated timesteps as the ensemble for DA. The transient offline approach has been used for instance in several studies by Goosse et al., and by Matsikaris et al. (2015); the stationary offline approach has to my knowledge been used the first time by Steiger et al. (2014) and has been applied in several other studies by Steiger et al.

Although it is made clear in the manuscript that a stationary ensemble has been used for DA, the difference between these approaches should be explicitly discussed in section 2.3. Note that the terminology transient/stationary offline is not established yet, but I believe it captures the key difference between the approaches.

Thank you for the remark. We agree that it is important and will thus include in Section 2.3 a paragraph about the difference between those two methods:

There are two types of offline data assimilation methods which differ by the way the model ensembles are produced. They can be referred to as transient and stationary offline methods. In transient methods (e.g. Goosse et al., 2006; Bhend et al., 2012; Matsikaris et al., 2015), an ensemble of simulations is first generated by performing several simulations with one model driven by realistic estimates of the forcing. The ensemble of states used for the data assimilation (i.e. the prior) is time-dependent and changes at every assimilation step since the model results and the data must correspond to the same time (generally the same year). As for online methods, transient offline methods have the advantage to provide reconstructions that are consistent with changes in forcings. However, obtaining skillful reconstructions depends on the range of the ensemble that must be wide enough to capture the full complexity included in the data network. This is directly related to the ensemble size, which is strongly limited in transient offline methods by the computational constraints on performing ensemble simulations. In stationary offline methods (e.g. Steiger et al., 2014; Hakim et al., 2016; Steiger et al., 2018), the ensemble of states used for the data assimilation is obtained by selecting not only the time in the simulations corresponding to the data assimilation time step (and thus the observed changes) but also other simulated time steps. This allows increasing the ensemble size by several orders of magnitude and thus potentially the skill of the reconstructions. However, since the prior includes years with many different forcings, the resulting reconstructions may be inconsistent with changes in the forcing history. This is still valid when internal variability dominates over the forced response, as is the case for instance with hydroclimate-related variables at local scale (e.g. Klein and Goosse, 2018). If the fingerprint of the forcing is large, the data assimilation procedure can also select for the reconstruction during a specific year only simulated years with a forcing similar to the one observed during that year. However, it is also possible

that the forcing contribution is underestimated in the reconstruction due to the selection of the prior inducing some different teleconnections compared to the observed ones and troubles in the interpretation of the reconstructed patterns.

Furthermore there should be a discussion on what type of conclusions can be drawn in the two cases if the DA simulations are in agreement with empirical temperature reconstruction. At the moment the conclusion is that there is no fundamental inconsistency between the models and the empirical data. However the question formulated in the introduction was whether the response of the CMIP simulations to the forcing is too strong, or whether internal variability is responsible for the discrepancies between the CMIP simulations and the empirical reconstructions, and the conclusions do not specifically address these two possibilities. In a transient offline approach an agreement between DA simulations and empirical reconstructions would imply that the superposition of forced and internal variability includes the empirically reconstructed states, and thus there is no indication that the forced signal is unrealistic. In contrast when using a stationary offline approach it would be possible to achieve agreement between assimilated states and empirical reconstructions even if the forcing signal was so unrealistic that the superposition of the forced signal and any realistic realisation of internal variability would not include the empirically reconstructed states, because the agreement could be caused by choosing simulated states from times with a different forcing than the actual forcing at a given time.

This shows the limitations of using stationary offline approaches for process studies. The authors' statement 'no fundamental inconsistencies' is fairly vague and a more specific discussion of what is meant by 'fundamental inconsistencies' should be provided.

We concur with this comment and with the importance of specifying what can actually be done or not with such DA method. Several changes will accordingly be made in the manuscript. In sequence starting by the abstract :

A/ For the reasons you mentioned, this is not because our DA-based reconstruction match the observed recent trend that we can state that it is driven by internal variability. Hence, the following sentence (p2l8-11) :

Data assimilation also allows reconciling models and direct observations by reconstructing the East-West contrast regarding the recent temperature trends, indicating that internal variability likely plays a major role in driving this heterogeneous recent warming. This is further supported by the large spread of individual PMIP/CMIP model realizations regarding the recent warming pattern.

will be replaced by :

Data assimilation also allows reconciling models and direct observations by reproducing the East-West contrast in the recent temperature trends. This recent warming pattern is likely mostly driven by internal variability given the large spread of individual PMIP/CMIP model realizations in simulating it.

B/ We will make clear when describing the DA method (Section 2.3) that using a stationary method is not ideal to study the processes responsible for the reconstructed changes (which is out of scope of our study) since they can be the results of a mix between several forced and internal variability-based influences (see the proposed paragraph to be included in Section 2.3 above).

C/ We propose to be more specific when stating in Section 5.2 that there are no fundamental inconsistencies between models and observations about the recent warming pattern (p22l34). From p22l33:

Nevertheless, data assimilation allows reconciling the apparent disagreement on the recent trends between the models ECHAM5/MPI-OM and ECHAM5-wiso and observations. We use a stationary offline data assimilation method. This means that when all simulated years are analyzed, models can simulate a pattern resembling the observed contrasted warming between East and West Antarctica. This implies that such pattern is consistent with model physics and that internal variability has likely a strong role in the this observed pattern, as suggested by the analysis of all the individual model realizations of the recent trends (Fig. 2-a) and of the recent link between each Antarctic subregions (Fig. 4). However, because of our experimental design, there is no guarantee that the contribution of the forcings is well taken into account. For instance, we cannot rule out that although the pattern is compatible with internal variability, it cannot be totally masked in some models by a too strong response to the forcing leading to an incompatibility with observations.

D/ We also propose to slightly change the conclusions. These sentences (p26l32) :

Both reconstructions with data assimilation show the observed contrast, indicating that internal variability likely plays a major role in driving this heterogeneous recent warming. This is further supported by the large spread of individual model realizations without data assimilation regarding the spatial pattern of the recent warming.

will be replaced by:

Both reconstructions with data assimilation show the observed contrast, indicating that this pattern can be represented by climate models. Furthermore, the large spread of individual model realizations without data assimilation regarding the spatial pattern of the recent warming suggests that internal variability likely plays a major role in driving this heterogeneous recent warming.

2)
In section 2.3. it is said that online DA can outperform offline DA when the assimilated data involve a long-term trend. This is just one special case. In general information propagation in time does not have to imply slow changes, as fast changes might still be dynamically related.
However, if the system shows slow changes it is clear that information is propagated forward in time. The explanations should be adjusted accordingly.

Thank you for the comment. We agree that the explanation was not precise enough and we propose to change (p7l7):

An online method can theoretically outperform an offline one when the data assimilated involves a long-term trend since some components of the climate system can propagate information forward in time from one assimilation step to the next one (Pendergrass et al., 2012; Matsikaris et al., 2015).

by:

An online method can theoretically outperform an offline one if the state of the system at one particular time significantly influences its subsequent evolution, as it allows the propagation of the information forward in time from one assimilation step to the next one (Pendergrass et al., 2012; Matsikaris et al., 2015).

Thank you for noticing all the following typing and spelling errors that will be corrected:

3)
Page2, line 17, replace ‘signal’ with ‘change’
This will be modified.

4)
Page 3, line 26, ‘Our study being based ... it is important’; wrong English
This will be changed to ‘As our study is based on model results, ...’

5)
Page5, lines 14/15, ‘ ... simulate similar ... than another ...’, not well phrased, either replace ‘than’ with ‘as’ or reformulate.
‘than’ will be replaced by ‘as’.

6)
Page5, line 19 , replace ‘validating’ with ‘justifying’
This will be replaced.

7)
Page 8, line 1, replace ‘of’ with ‘for
This will be replaced.

8)
Page 8, line 9, replace ‘on’ with ‘to’
This will be replaced.

9)
Page 8, line 18, replace ‘pseudoproxy’ with ‘pseudoproxies’
This will be replaced.

10)
Page 11, line 8, replace ‘simulation’ with ‘simulations’
This will be replaced.

11)
Page 12, line 11, replace ‘model mean’ with ‘model mean correlation’ (if I understand correctly)
The sentence will be modified for more clarity:

The simulated link between East and West Antarctica is rather consistent for each model and similar to the observed one, as deduced from correlation coefficients computed using the mean of all members for each model.

13) Page 14, line 1, replace ‘of’ with ‘for’
This will be modified.

14)
Page 14, line 25/26 ‘in the results with a last century…’, something is wrong with this sentence
Thank you for noticing. ‘with’ will be replaced by ‘showing’.

15)
Page 14, line 28, replace ‘link between’ with ‘links of’
This will be modified.

16)
Page 20, line 17, replace ‘hypothesis’ with ‘assumption’
This will be replaced.

17)
Page 26, line 9, delete ‘has potentially’
This will be deleted.