Referee #2 comments

- In *Italic* : referees' comments
- In normal font : our answers
- In blue: what was added in the text.

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1. *Here, a more critical discussion of the proxy data and limitations of this novel quantitative approach is needed. Though I clearly see the merit of this manuscript, I am concerned about the robustness of the (already published) dinocyst data base and suggest that also qualitative (or semi-quantitative) sea ice reconstructions based on non-dinocyst data are taken into account for the evaluation of the models' performance. Some useful references are already provided in section 3.2 but here only discussed referring to the dinocyst reconstructions.*

Thank you for your comment. The point related to the limitation of the proxy-based reconstructions is discussed in the answer to the second comment below.

Data assimilation requires a quantitative estimate of the model-data agreement in order to compute the likelihood of each model state. Such an estimate is also required in the evaluation of the models' performance. Quantitative reconstructions are thus needed in our study. This is the reason why the new reconstructions of de Vernal et al. (2013a) have been selected. Besides, qualitative or semi-quantitative reconstructions provide a way to validate the results using independent data. This was discussed in the submitted version in the section 3.1 (Sea-ice changes at 6 ka deduced from observations). As suggested by the referee, this discussion is extended in the revised version. Available sea-ice reconstructions from various sources are presented in a new Fig. 1 and in the table 3. The text, mainly in section 3.1, is modified to include this additional information.

2. *Assuming that the productivity of dinoflagellates in the Arctic Ocean is highly reduced during winter months (due to the absence of light - which also limits the food availability for heterotrophic dinoflagellates), the expression of reconstructed sea ice cover in terms of annual mean concentrations leaves me puzzled. The meaning and relevance of calculating annual mean sea ice concentrations is not clear to me - in particular with regard to the outstanding seasonal variability in Arctic sea ice cover. The herein adopted approach by de Vernal et al. (2013) to calibrate dinocyst records to annual and not to seasonal means needs to be explained and discussed in more detail. Further, uncertainty in the reconstructed sea ice concentrations is relatively high (11%) in comparison to the Mid Holocene-Pre Industrial sea ice concentration anomalies. Figure 1 shows that only anomalies derived from the two cores (1, 2) in the Chukchi Sea and cores 4 and 5 from the Barrow and Nares Strait exceed the standard error of 11%. This uncertainty in the proxy reconstruction certainly weakens the significance of the model-proxy comparison and the data assimilation approach.*

The methodology applied in the reconstructions and their limitations have been discussed extensively in the twin papers of de Vernal et al. published in the special QSR issue in 2013. A detailed description of the reference sea-ice data used for the reconstructions in addition to the methods for calculating the error of prediction are presented in the methodological paper to which we now refer as de Vernal et al. (2013b). The topic of this study is not to further discuss these reconstructions themselves but to test, for the first time, if data assimilation of sea-ice concentration for the mid-Holocene conditions is possible technically and instructive. In this framework, the most direct choice is to use the variable selected by de Vernal et al. (2013b) for the reconstruction (annual mean sea-ice concentration) and the uncertainty they obtained as a result of their analyses. As explained in de Vernal et al. (2013a), the mean annual concentration is derived from the mean monthly concentration and directly correlates with the number of months per year with dominant sea ice coverage. Hence any of these parameters can be used (months/year or mean concentrations).

The sea-ice parameter that is ecologically relevant in the seasonality of the sea ice cover, but sea ice concentration is most often used in modelling. In any case, we agree that the discussion in the submitted version was not sufficiently explicit. In the revised version, the uncertainties of the proxy data are discussed in more detail as well as the implication of those uncertainties for our analyses:

- This sentence has been added at the end of the section 3.1 (Sea-ice changes at 6 ka deduced from observations) : However, out of the 18 proxy-based reconstructions, only 4 (id 2, 4, 5 and 7 on Fig. 1) have a larger signal than their error, i.e. does not have zero within the error bar. This has two implications for the following of this study to keep in mind. First, the potential of this dataset to test the models' performance is weak and second, the constraint applied on the LOVECLIM results during the process of data assimilation will not be large.
- A paragraph on limitations was added in section 2.3 (Proxy-based sea-ice reconstruction): The sea-ice reconstructions have inherent uncertainties that are linked on one side to the intrinsic variability of sea ice and accuracy of observations and, on the other side, to limitation related to the proxy and its application (see the discussion in de Vernal et al., 2013b). Whereas interannual variations of sea-ice cover as measured instrumentally over the last decades account for a standard deviation close to 10% on the average, the largest source of uncertainties is probably the mismatch between the time interval of instrumental data used as reference (here, 1953-2003) and the time interval represented by dinocyst populations in surface sediment samples, which may cover centuries. Such limitations apply to all sedimentary proxies. In the case of dinocyst data, which include 66 taxa and 1492 reference data points from the Northern Hemisphere, about half of them being representative of seasonal sea-ice environment, the application of the modern analogue technique (MAT) permits quantitative reconstruction with an accuracy of ±11%. Regardless the sources of uncertainties inherent to both the reference and proxy data sets, the accuracy is calculated from the residuals or difference between observed and estimated values and corresponds to the standard deviation of the residuals. Beyond the accuracy, uncertainties in reconstruction of past sea ice conditions may come from poor analogue situations or low counts making weaker the statistics for reconstructions. This is why indices of reliability have been proposed in order to assess the quality of reconstructions. In the present case, more than 95% of reconstructions are labelled with high quality indices (cf. de Vernal et al., 2013a and data posted on the Geotop website).

We have added on Fig. 6 the mean signal of each model which is smaller than the mean signal of the data, itself smaller than the data error. Based on this, we have modified the discussion about the skill of the models at the local scale, saying that it is hard to evaluate the skill of the models quantitatively since the data errors are higher than the signal of both the data and the models. The abstract, the conclusions and a full paragraph in section 3.2 have been updated.

We also agree that because of the seasonality of the changes, having quantitative reconstructions for the different seasons would be most useful. This is specified in the conclusion of the revised version.

3. *Interestingly, the dinocyst record used within this study indicates a higher Mid Holocene sea ice cover in the Chukchi Sea (page 6523, line 1) which contradicts the identification of a significantly reduced sea ice extent and higher sea surface temperatures in the Chukchi Sea at 6 ka by de Vernal et al. (2005; Paleoceanography, DOI: 10.1029/2005PA001157). This inconsistency in the dinocyst approach needs be explained.*

The results from the 2005 manuscript in Paleoceanography are actually consistent with those presented here. The early-mid Holocene record of core B15 was also characterized by dense sea-ice cover reconstructions. The large amplitude variations in sea ice cover with dense early-mid

Holocene sea ice are rather a consistent feature of all cores analyzed from the Chukchi (B15, GC19, HLY005). Core B15 was not used here because of too low time resolution.

5. *Further, the study by Anderson et al. (2001) revealing that Alaskan lake temperatures were lower during the Mid Holocene than at present (page 6523, lines 26-29) is not an appropriate reference to support the marine dinocyst data.*

The reference is correct and consistent with dinocyst data but it refers to one record of inland environments. Another reference with more direct evidence from marine sediments has been given (Farmer et al., 2001) in addition to reference to the multi-proxy compilation by Kaufman et al. (2004). Hence the text in section 3.1 (Sea-ice changes at 6 ka deduced from observations) has been modified accordingly as follows : Further west, the higher sea-ice concentration recorded over the Chukchi Sea at the MH (id 1 and 2) is in agreement with the bottom water on the shelf as recorded from oxygen isotopes in benthic foraminifers (Farmer et al., 2011) as well as with relatively low MH temperature recorded from several proxies in Alaska (Kaufman et al., 2004).

6. *It is even noted in the manuscript that "the recent period is far from being adequate" to reflect PI conditions which is true as it mainly reflects the current polar amplification of global warming.*

Indeed, this is the reason why “We have thus decided to reconstruct the reference dataset by computing a linear interpolation of those time series up to the period 1850–1900 AD” (at the end of section 2.3), instead of using recent sea-ice cover observations.

7. *I also consider the references provided to support the Nares Strait sea ice reconstruction (page 6523, lines 4-10) are not well suited since they refer to sea ice conditions north off Greenland - a completely different setting (governed by different ice drift patterns)*

We agree and this restriction is clearly mentioned in the revised version of the manuscript.

8. *Finally, a map of the simulated (seasonal) sea ice cover (extent and concentration) would add value to the manuscript and could serve as a useful reference for further proxy-model studies.*

Following your suggestion, the revised version includes:

- Maps showing the sea-ice edges at the MH and PI as well as the sea-ice concentration anomalies for the annual, winter (March) and summer (September) means are added for each model. Those maps are available in the supplementary materials, except for LOVECLIM without data assimilation that are in the core of the manuscript..
- The first 3 paragraphs of section 3.2 (Simulations without data assimilation) were modified in order to take into account these new figures.

References

- de Vernal, A., Hillaire-Marcel, C., Rochon, A., Fréchette, B., Henry, M., Solignac, S., and Bonnet, S.: Dinocyst-based reconstructions of sea ice cover concentration during the Holocene in the Arctic Ocean, the northern North Atlantic Ocean and its adjacent seas, Quaternary Science Reviews, 79, 111–121, doi:10.1016/j.quascirev.2013.07.006, 2013a.
- de Vernal, A., Rochon, A., Fréchette, B., Henry, M., Radi, T., Solignac, S. : Reconstructing past sea ice cover of the Northern hemisphere from dinocyst assemblages: status of the approach. Quaternary Science Reviews,79:122-134, doi.org/10.1016/j.quascirev.2013.06.022, 2013B.
- Farmer, J.R., Cronin, T.M., de Vernal, A., Dwyer, G.S., Keigwin, L.D., Thunell, R.C. Western Arctic Ocean temperature variability during the last 8000 years. *Geophysical Research Letters*, 38, L24602, doi:10.1029/2011GL049714. 2011.

- Kaufman, D.S., et al., Holocene thermal maximum in the western Arctic (0–180°W). Quaternary Science Reviews 23, 529-560, 2004.