Interactive comment on "The dependency of the δ18O discrepancy between ice cores and model simulations on the spatial model resolution" by Marcus Breil et al.

Anonymous Referee #1

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- Dear Reviewer. Thank you very much for your constructive comments. We think that you addressed some important issues and we hope that we are able to respond satisfactorily.

This manuscript presents first outputs of the COSMO-iso model for the Arctic regions over the present-day and mid-Holocene. The results are compared to measurements performed in snow and ice cores and the agreement is rather good, better than with a GCM, between model and data hence validating the use of a RCM equipped with isotopes to look at fine spatial scale the variability of water isotopes in this region.
Even if I am not very enthusiastic with this manuscript, this is a valuable contribution but I feel that the study could be developed a bit more following the comments given below. In general, I am a bit disappointed by the manuscript compared to the previous study on the same subject, Sjolte et al., 2011. This previous study using a regional model with isotopes presented numerous applications especially on the temporal variability, an aspect which is fully absent here. Could perhaps the authors elaborate a bit more on the temporal variability (seasonal and interannual variability) and compare to available data or to this previous study?
- Beside an increased spatial variability, RCMs can show a different (increased) temporal variability in comparison to GCMs. These differences in the temporal variability can, of course, lead to differences in the yearly mean values, as shown by Sjolte et al., (2011) for systematic δ18O biases in different seasons. In addition, such seasonal δ18O differences can be used to reveal systematic model deficiencies related to, for example, large-scale circulation patterns (Werner et al. 2000), in turn affecting the interpretation of paleo-climate periods.
In order to investigate this potential impact, an analysis of the temporal δ18O variability in precipitation in the present-day GCM and RCM results is added to the manuscript. In this context, the simulated monthly δ18O values are compared to observed monthly δ18O values in precipitation, collected at arctic stations of the Global Network of Isotopes in Precipitation (GNIP). In general, the modeled δ18O values in precipitation of COSMO-iso are in good agreement with the monthly GNIP data (Figure a, Figure 5 in the manuscript). But in contrast to Sjolte et al., (2011), no systematic over- or underestimation of observed isotope ratios is simulated with the RCM. This is true for each season. Neither in winter (low δ18O values), nor in summer (high δ18O values) systematic deviations to the observations are simulated. Thus, the seasonal variability in the COSMO-iso results has no systematic impact on the yearly mean δ18O values and is therefore not the reason for systematic differences between model results and observations.
In order to investigate the interannual variability in the simulation results, an analysis of the temporal δ18O-temperature slope is included in the manuscript, in addition to the spatial δ18O-temperature slope analysis (Figure b, included in Figure 7 and 9 in the manuscript). This temporal δ18O-temperature slope is calculated for both periods, present-day and mid-Holocene, based on the yearly mean isotope and temperature values. The results show that the temporal δ18O-temperature slope is in both periods smaller than the spatial slope, which is in accordance with the results of Sjolte et al., (2011). The interannual δ18O variations are consequently all over Greenland rather small and lowly correlated with the surface temperatures. The impact of temporal surface temperature variations on the temporal δ18O variability is therefore small in Greenland.

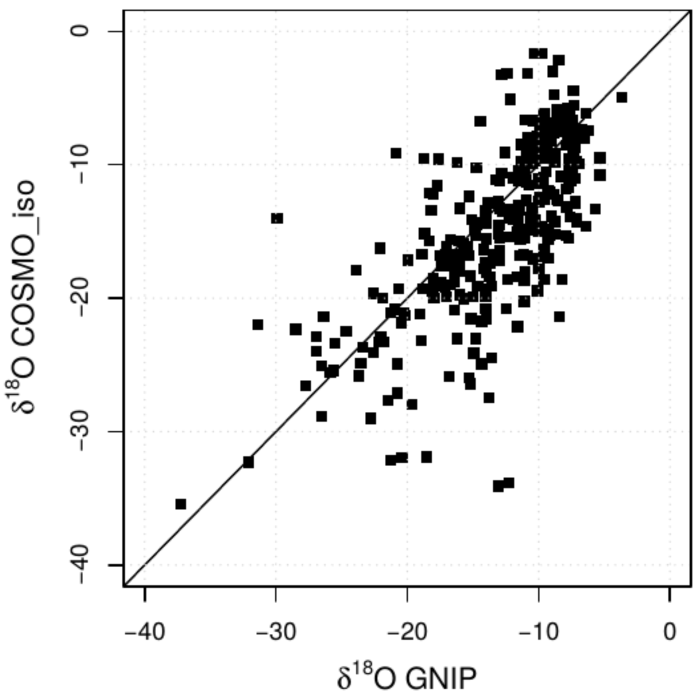

Figure a: Monthly δ18O simulated with COSMO_iso_50km for the period 2008 - 2014 and the corresponding observations for 9 GNIP stations

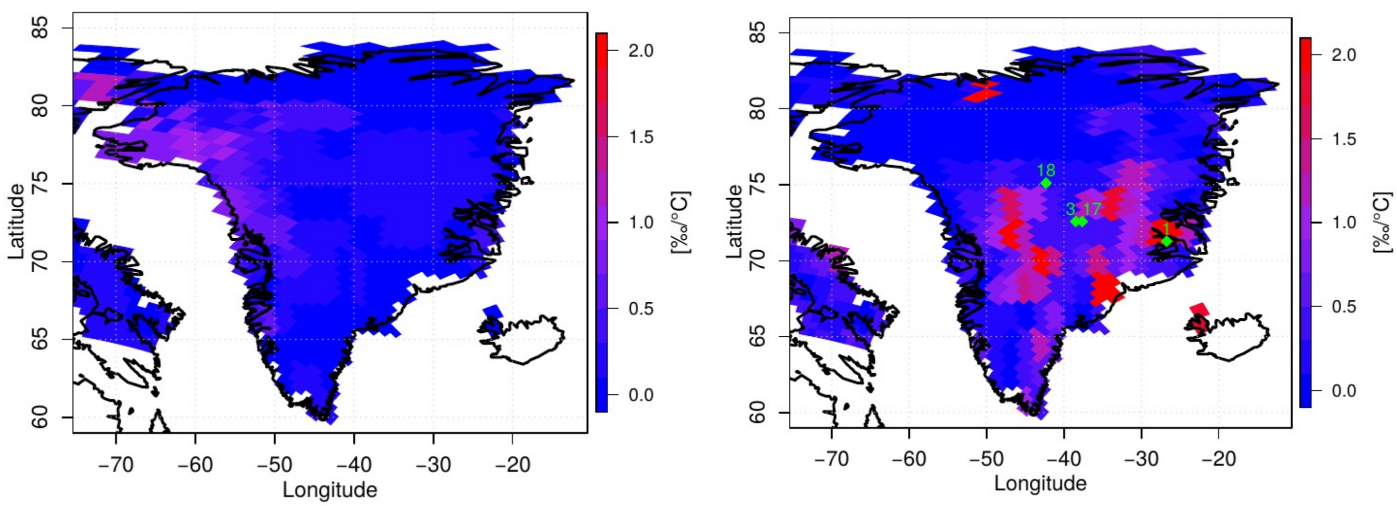

Figure b: Temporal δ18O-temperature slope for Greenland for the present-day (left) and the mid-Holocene (right)

I understand that the authors like to focus their study on the mid-Holocene but it is not clear why. Also, the difference between mid-holocene and PST is not very large so that the comparison between the two periods is not the best to validate the temporal variability of the model.

- We chose the mid-Holocene for our plaeo-climate simulations since it is a period of particular interest for Greenland. By that time an Arctic warming took place due to orbital forcing variations and their related feedbacks on large-scale climate variations, which exhibits similarities to the strong recent Arctic warming. Thus, the mid-Holocene provides the opportunity to investigate the processes, leading to this warming, in more detail and to potentially obtain new insights about the future development of the Arctic region (Yoshimori and Suzuki, 2019). Reliable model data are therefore particularly important to consistently analyze the associated processes.

It is also complicated to perform such a comparison because COSMO-iso is associated with ECHAM-5 wiso for present-day and MPI-ESM-wiso for the mid Holocene. Without a comparison between ECHAM5-wiso and MPI-ESM-wiso which is not discussed here, it is quite complicated to perform comparison between mid-Holocene and PST. Was it really impossible to use the same GCM for both simulations?
- Unfortunately, no present-day MPI-ESM-wiso simulations with dynamical fields nudged to reanalyses exist, as for ECHAM5-wiso. But we wanted such a nudged present-day reference simulation to assess the COSMO-iso model under the best possible conditions.

I am quite worried that the present study is submitted while the evaluation of the COSMO model (without isotopes) is not performed (cf sentences 66-67). Why then compared d18O values to observations if we have no validation of basic climatic parameters (temperature, etc...). At least some sentences for the most relevant parameters should be included here.
- the short discussion of the general model performance of COSMO in Greenland, regarding the standard climatic parameters in present-day simulations, is extended in the manuscript (see the new section 3.1.1 which is about the assessment of standard climatological parameters). For this purpose, a new figure about the differences between the simulated 2 m temperatures and precipitation sums to the observed ones, is now included (Figure c, Figure 2 in the manuscript). For this validation, observed temperatures and precipitation amounts in Greenland, collected by the Danish Meteorological Institute, are used (the locations of these stations are listed in Table 1 in the revised manuscript).
Both, simulated 2 m temperature as well as precipitation sums are in good agreement with the observations. Thus, the model is generally able to simulate reasonable near-surface temperatures and precipitation amounts for Greenland and can therefore be used for isotope applications in this region. A detailed analysis of the COSMO performance in Greenland is presented in Karremann et al., (2020).

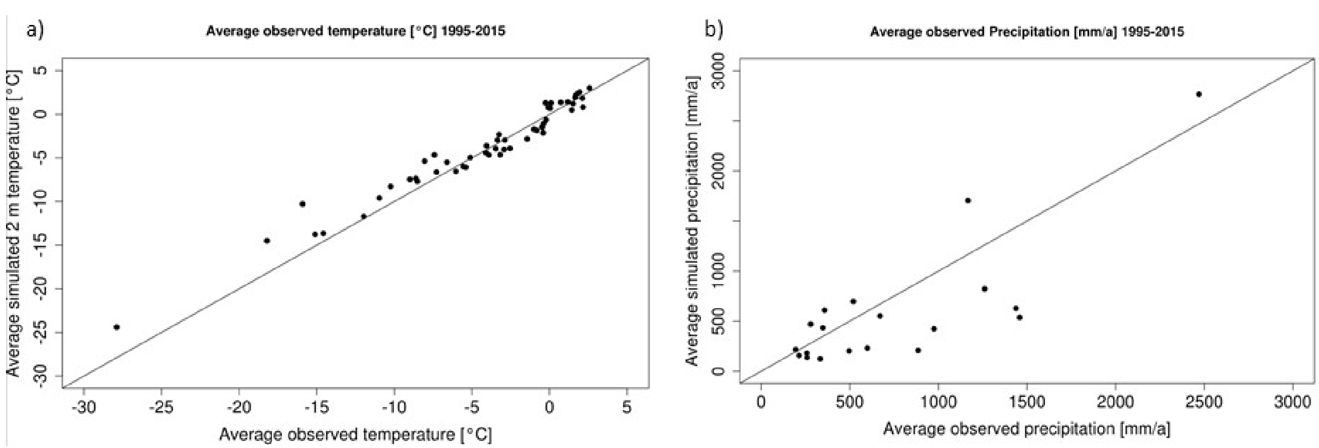

Figure c: Simulated yearly mean (a) 2 m temperatures and (b) precipitation sums of a standard COSMO simulation, driven with ERA-Interim, for Greenland over the period 1995-2015 compared to DMI observations.

I am quite surprised by the paragraph on fractionation at snow covered surfaces. For the work on the Arctic, you have a large number of paper co-authored by Hans Christian Steen Larsen which discuss the isotopic equilibrium or disequilibrium between surface snow, precipitation and water vapor in Greenland. It is quite strange to use a dataseries from Karlsruhe to calibrate fractionation between snow and water vapor in Greenland when data are available there.

- The phrasing of this paragraph was misleading. We did not calibrate the fractionation during sublimation at snow covered surfaces. An equilibrium fractionation was assumed for surface layer snow and sea ice. Simulation results with this approximation were just additionally compared to an observational dataset in Karlsruhe. To avoid confusion, the paragraph is rephrased (Lines 119-122):

"To approximate this complex interplay of different influencing factors, in this study, an equilibrium fractionation during sublimation from surface layer snow and sea ice is assumed. However, the authors are aware that this is just a simplified description of isotope fractionation during sublimation."

Similarly, I am surprised that you do not have more observations gathered in part 2.2.Why only concentrating on core top while you have some series of observations (Bonne et al., ACP, 2014; papers co-authored by Steen-Larsen). You may also want to include the core studied by Furukawa et al., JGR, 2017).

- Thanks for the indication on further observational data sets. In the revised paper we included the data set of Furukawa et al., (2017) in our analysis (see Figures 3, 4 and 6) as you suggested. Additionally, we included δ18O data at GNIP stations in the manuscript (see Figure a and Figure 5 in the revised paper) to analyze the temporal variability of the simulated δ18O values in precipitation in COSMO-iso.

I am not so convinced by figure 4b and the associated discussion stating that the bias are very small. First, the scale is much to large, it would be enough to draw the y-axis between -2 and +2 permil. And then, you obtain opposite variations between the red (model, negative d18O anomaly) and orange (observation, positive d18O anomaly) so that the comparison of the results is actually not convincing even if the changes are small in both cases but this is expected since Mid Holocene is not very different from PI. I see this point as a strong weakness.

- For this figure (now Figure 8b), the same y-axis scale was used as in Figure 4a (now Figure 8a) to keep the results comparable. You are right, the sign is different for 6ka-PI_MPI and 6ka-OBS. But this is due to the small deviations between 6ka-PI_MPI and 6ka-OBS. Already small differences can consequently result in a changing sign. The message of this figure is that the high agreement of MPI-ESM-wiso in the mid-Holocene is not achieved by chance. This can be demonstrated by the small deviations between 6ka-PI_MPI and 6ka-OBS, even if these small differences show a different sign.

It would have been nice to discuss the temporal d18O vs Temperature gradient and not only the local spatial one.

- An analysis of the temporal δ18O-temperature slope is now included in the manuscript. See comment above and Figure b.

Also, we are awaiting some discussions / perspectives on the implications of these calculated spatial gradients for ice core interpretation. It would be nice to elaborate on this.

- the results of this study show that a bias in GCM results does not inevitably contradict the measured isotope ratios in an ice core. The measured isotope ratios are potentially included, but hidden within the subgrid-scale uncertainty of a GCM grid box. Thus, a regional downscaling of GCM data is recommended. In this way, locally measured isotope ratios in an ice core can be adequately linked to spatially coarse climate model results and conclusions on the underlying climatic processes leading to these ratios can be drawn in a physically consistent way. This point is now stronger emphasized in the discussion (Lines 432-444 and 449-453):

"As δ18O ratios are used as an indicator for temperatures in past climates (Dansgaard et al., 1969; Masson-Delmotte et al., 2005; Jouzel, 2013), it is important to understand how the presented COSMO_iso simulations might be able to improve these isotope-based temperatures reconstructions. In general, the regional surface temperature variability and the regional δ18O variability show similar patterns for Greenland. In both cases the variability is high at the coast and low on the inland plateau. Similar patterns as in the mid-Holocene can also be seen for the present-day simulations. These spatial variability patterns of δ18O and the surface temperature are in line with the results of Sjolte et al. (2011) for RCM simulations under present-day conditions for Greenland. Based on these variability patterns, it can be derived that the regional surface temperature variability highly depends on the surface characteristics in Greenland. However, for the regional isotopic ratio variability, this dependence appears to be less pronounced. At the coastline, a clear relationship between surface temperatures and measured δ18O ratios in ice cores can be deduced, while in Central Greenland this relation is weaker. These spatial differences might be explained by the fact that isotope changes are an integrated signal of the meso-scale variability of atmospheric processes (Dansgaard, 1964; Merlivat and Jouzel, 1979; Gat, 1996), which might partially be decoupled from surface temperature changes in homogeneous terrain."

"The presented study demonstrates that the isotope-enabled MPI-ESM-wiso - COSMO_iso model chain with realistically implemented stable water isotope fractionation processes constitutes a useful supplement to reconstruct regional paleo-climate conditions during the mid-Holocene in Greenland. By means of such an isotope-enabled GCM-RCM model chain, locally measured isotope ratios in an ice core can be adequately linked to spatially coarse climate model results and conclusions on the underlying climatic processes leading to these ratios can be drawn in a physically consistent way."

Other comments to consider:
- I do not understand the following sentence in the abstract: "Furthermore, by investigating theδ18O ratios in all COSMO_iso grid boxes located within the corresponding ECHAM5-wiso grid box, the observed isotopic ratios can be classified as a possible localδ18O ratio within the spatial uncertainties, derived by the regional downscaling approach."
This sentence in the abstract is not very concrete "But again, the range of the COSMO_iso_50kmδ18O variability in the corresponding MPI-ESM-wiso grid boxes around each station is consistent with the observed δ18O values"
- both statements are rephrased in the revised manuscript (Lines (21-26):

"Despite this lack of improvements in model biases, the study shows that in both periods, observed δ18O values at measurement sites constitute isotope ratios which are mainly within the subgrid-scale variability of the global ECHAM5-wiso and MPI-ESM-wiso simulation results. The correct δ18O ratios are consequently already included but hidden in the GCM simulation results, which just need to be extracted by a refinement with an RCM. In this context, the RCM simulations provide a spatial δ18O distribution by which the effects of local uncertainties can be taken into account in the comparison between point measurements and model outputs."

I am surprised in the introduction by the discussion about mid-holocene. In Greenland, the temperature better seems on a plateau between the beginning of the Holocene (optimum) and the mid-Holocene.
- the text is adapted (Line 41-42):

“Between the early Holocene and the Holocene Thermal Maximum in the mid-Holocene (6 ka), a pronounced warm phase took place”

L. 46: why do you discuss the ability of a GCM to reproduce the regional changes –why not discuss better the (dis)ability of a GCM equipped with isotopes to reproduce the regional changes of water isotopic composition.
- we included a discussion about the disability of isotope-enabled GCMs to reproduce regional changes and the added value of isotope-enabled RCMs in the manuscript according to your suggestions (Lines 57-65):

“For stable water isotopes, key physical processes of isotope fractionation are therefore not well resolved in coarse resolution GCMs, leading to differences between simulated and observational isotope data, especially in complex terrains (Sturm et al., 2005; Werner et al., 2011). Isotope-enabled GCMs are consequently not able to reproduce regional changes in isotope ratios quantitively (e.g. Risi et al., 2010), and the simulated isotope ratios with GCMs exhibit in many cases larger deviations relative to observed ratios than the results of corresponding Regional Climate Model (RCM) simulations. For instance, Sturm et al., (2007) were able to reduce the bias of simulated isotope ratios in precipitation, by a regional downscaling of an isotope-enabled GCM run in South America. Comparable results were achieved by Sjolte et al., (2011) for isotope-enabled RCM simulations in Greenland.”

Table 1: Please correct the date for the reference of Weissbach et al., 2016...; also give the units for d18O
- is corrected.

It is very difficult to compare data and measurements on figure 1
- Since we are aware of this, differences between simulated δ18O values and observed ones are additionally shown in Figure 2 (now Figure 4) as a bar plot.

How is the yearly mean d18O value calculated? Is there any weighting by the precipitation amount? Could this effect be discussed when compared to the observations?
- The modeled δ18O in precipitation is weighted with accumulation rate, i.e. months with high precipitation amounts get a higher weight compared to months with small precipitation amounts. We forgot to mention this in the manuscript. This is statement is now included (Lines 174-177).

L. 289: I do not understand this sentence “At the coastline, the δ18O temperature- gradient is low, reflecting the high surface temperature and δ18O variability in this region” – in general the whole paragraph needs to be rewritten since it is largely unclear (last sentence of the paragraph is particularly vague -> to what mechanisms do you refer?)
- the whole paragraph is rewritten and restructured (see Lines 385 – 395):

“The spatial surface temperature variability in the COSMO_iso_50km mid-Holocene simulation is shown in Figure 9b. Again, the mid-Holocene simulation shows the same surface temperature variability characteristics over Greenland as the present-day run with a high spatial variability near the coastline and almost no variability in Central Greenland. As a consequence, similar patterns of the spatial δ18O-temperature slope are simulated for the mid-Holocene and the present-day, with low gradients at the coastline and high gradients in Central Greenland (Figure 9c). But in the mid-Holocene simulation, the contrast between the coastal regions and the inland plateau is less clearly pronounced than in the present-day run, due to the higher spatial δ18O variability in Central Greenland.

Nevertheless, the spatial δ18O-temperature interrelations are in both periods comparable. This is also the case for the temporal variabilities of δ18O and the surface temperature. As shown in Figure 9d, the annual δ18O-temperature slope is again very small over Greenland, although in some regions higher temporal slopes are simulated. But in principle, the influence of surface temperature variations on the temporal δ18O variability in the mid-Holocene is also small."