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

Received and published: 9 June 2020

- 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.

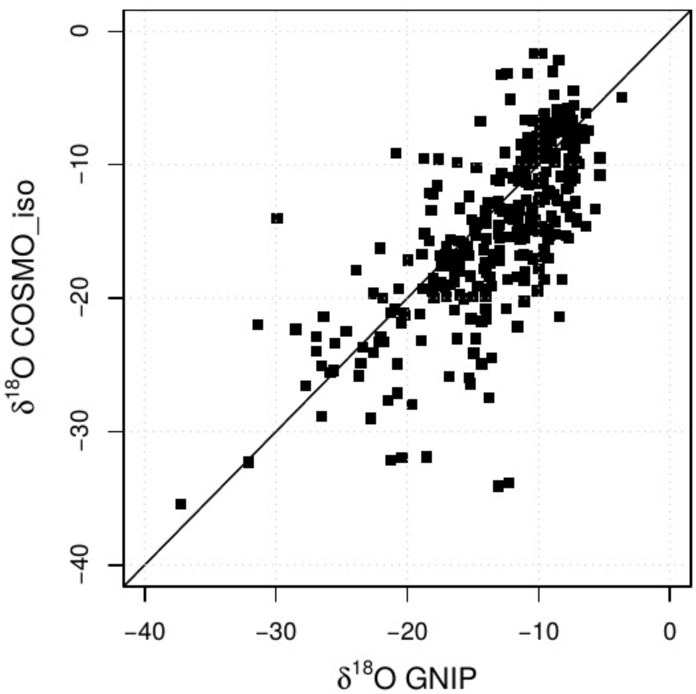

Figure a: Monthly δ18O simulated with COSMO_iso_50km for the period 2008 - 2014 and the corresponding observations for 9 GNIP stations

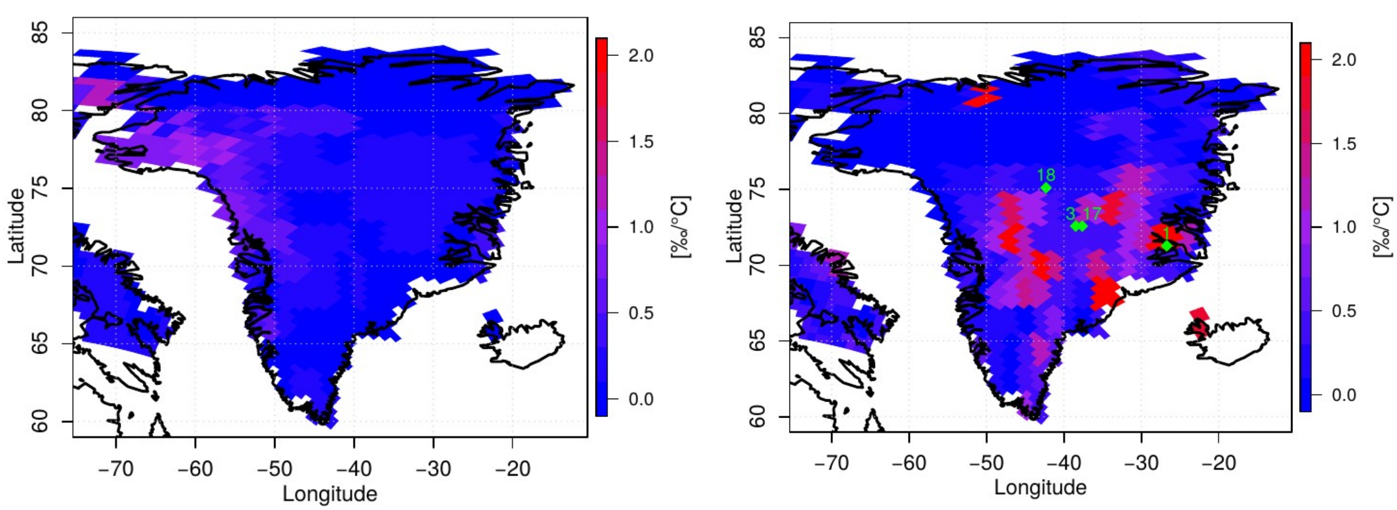

Figure b: Temporal δ18O-temperature slope for Greenland for the present-day (left) and the mid-Holocene (right)

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. However, we agree with your assessment that COSMO-iso simulations with the same driving model for the present-day and the mid-Holocene would have been more consistent. But, as already mentioned, this was not possible in the framework of this study.
Therefore, we cannot guarantee that the different driving models substantially affect the general characteristics of the regional COSMO-iso simulation results. But in this context, a direct comparison of ECHAM5-wiso and MPI-ESM-wiso under present-day conditions is from our point of view not meaningful. The ECHAM5-wiso simulation, used as driving data for the present-day COSMO-iso run, was nudged to the ERA-Interim reanalysis with prescribed monthly varying oceanic boundary conditions, while MPI-ESM-iso is a free running and fully-coupled atmosphere-ocean Earth System Model. Like many fully-coupled ESM, the simulated present-day climate of MPI-ESM has some biases as compared to the observed present-day climate and thus, systematic deviations in the COSMO_iso_50km mid-Holocene simulation results, cannot be excluded. For this reason, we refrain from calculating and discussing any modelled mid-Holocene - present-day anomalies in the manuscript, and just look at the absolute values in our analyses (e.g. in Fig. 8a.). The only exception is Fig. 8b, where we stay in the MPI-ESM model world.
Nevertheless, the results of the COSMO_iso_50km mid-Holocene simulation show remarkable similarities to the present-day simulation results, despite the two very different forcing approaches. This finding indicates that the spatial and interannual $\delta^{18}O$ variability of COSMO_iso_50km within a GCM grid box over Greenland is independent of the oceanic boundary conditions. This aspect is discussed in more detail in the revised manuscript (Lines 334-340 and 391-403):

“In contrast to the present-day simulations, for the mid-Holocene, COSMO_iso_50km is not anymore driven by ECHAM5-wiso, but by MPI-ESM-wiso. While in ECHAM5-wiso oceanic boundary conditions are prescribed by monthly varying sea surface temperatures and sea ice cover, ocean states are calculated internally in the fully-coupled atmosphere-ocean Earth-System-Model MPI-ESM-wiso. Systematic deviations between the COSMO_iso_50km simulations for mid-Holocene and present-day, caused by these different forcing approaches, therefore, cannot be excluded. For this reason, a comparison of the mid-Holocene δ18O anomalies to the present-day conditions is omitted and an analysis is performed for simulated absolute δ18O ratios and their differences to observed δ18O values.”

“In general, the results of the COSMO_iso_50km mid-Holocene simulation exhibit the same spatial characteristics as for the present-day simulation (Figure 7 and Figure 9). Comparable spatial patterns are simulated for the surface temperature variability (Figure 7b and Figure 9b) as well as the δ18O variability (Figure 7a and Figure 9a) within a GCM grid box, although regions of increased δ18O variability in Central Greenland are more widely present in the mid-Holocene run than in the present-day one. The contrast in the spatial δ18O-temperature slope between the coastal regions and the inland plateau is therefore in the mid-Holocene less clearly pronounced than under present-day conditions (Figure 7c and Figure 9c). 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 (Figure 7d and Figure 9d). This broad consistency in the COSMO_iso_50km simulation results for the mid-Holocene and the present-day is remarkable, considering that both simulations are driven by two different forcing approaches (ECHAM5-wiso nudged to ERA-Interim reanalysis with prescribed monthly varying oceanic boundary conditions vs. the fully-coupled atmosphere-ocean Earth-System-Model MPI-ESM-wiso). This finding indicates that the spatial and interannual δ18O variability of COSMO_iso_50km within a GCM grid box over Greenland is independent of the oceanic boundary 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).

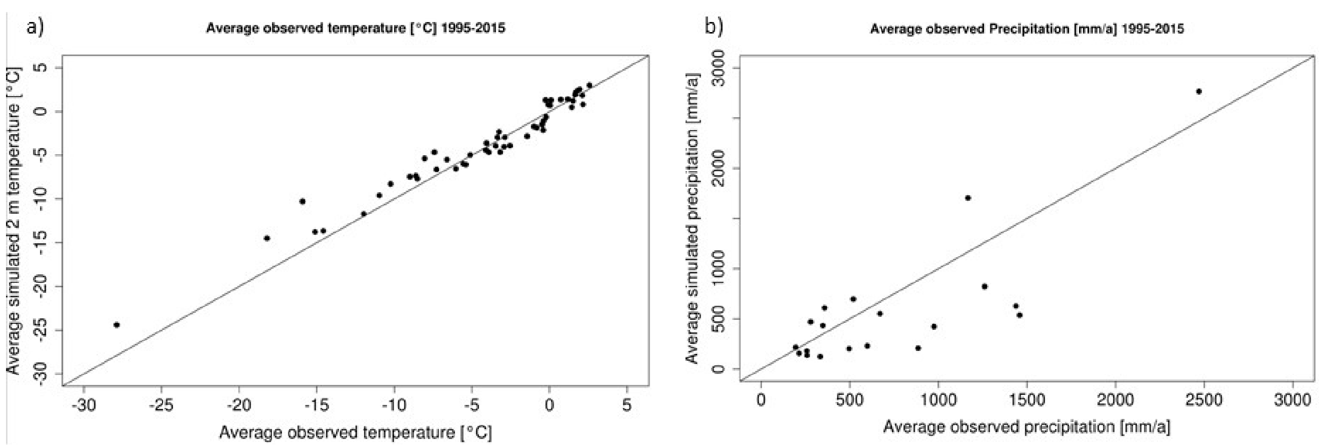

Figure c: Simulated yearly mean (a) 2 m temperatures and (b) precipitation sums of a standard COSMO simulation, driven with ERA-Interim, for Greenland over the period 1995-2015 compared to DMI observations.

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.

- The scale of the y-axis in this figure (now Figure 8b) is reduced as you recommended. In this context we have to admit that we used a wrong data file to calculate the 6ka-PI_MPI anomalies. We are very sorry for that. However, the corrected 6ka-PI_MPI anomalies are now in godd agreement with the measured mid-Holocene-PI δ18O anomalies (also in sign), facilitating the analysis. Accordingly, the discussion of the results is adapted (Lines 365-371):

"In Figure 8b, the MPI-ESM-wiso model anomalies with reference to the pre-industrial period (PI) conditions, which are based on an MPI-ESM-wiso PI-reference simulation performed by Cauquoin et al. (2019), are compared to the measured mid-Holocene-PI δ18O anomalies of the ice cores. The positive δ18O anomalies between mid-Holocene and PI for both ice core data and MPI-ESM-wiso model results are associated with higher temperatures, especially during the summer and a reduction in Arctic sea-ice during mid-Holocene (Cauquoin et al., 2019). In Renland and NGRIP simulated anomalies are slightly underestimated, in GRIP and GISP2 anomalies are slightly overestimated. But overall, the biases of the MPI-ESM-wiso mid-Holocene-PI model anomalies to the observed mid-Holocene-PI anomalies are for all ice cores very small."

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 not resolved in the GCM simulation results. 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 444-456 and 461-465):

"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 not resolved 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 174-176).

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 – 403):

"The spatial surface temperature variability in the COSMO_iso_50km mid-Holocene simulation is shown in Figure 9b. The mid-Holocene simulation shows a high spatial surface temperature variability near the coastline and almost no variability in Central Greenland. As a consequence, the spatial δ18O-temperature slope is low at the coastline and high in Central Greenland (Figure 9c). Moreover, the interannual δ18O-temperature slope is very small over Greenland in the mid-Holocene, although in some regions high temporal slopes are simulated (Figure 9d). But in principle, the influence of interannual surface temperature variations on the temporal δ18O variability in the mid-Holocene is small.

In general, the results of the COSMO_iso_50km mid-Holocene simulation exhibit the same spatial characteristics as for the present-day simulation (Figure 7 and Figure 9). Comparable spatial patterns are simulated for the surface temperature variability (Figure 7b and Figure 9b) as well as the δ18O variability (Figure 7a and Figure 9a) within a GCM grid box, although regions of increased δ18O variability in Central Greenland are more widely present in the mid-Holocene run than in the present-day one. The contrast in the spatial δ18O-temperature slope between the coastal regions and the inland plateau is therefore in the mid-Holocene less clearly pronounced than under present-day conditions (Figure 7c and Figure 9c). 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 (Figure 7d and Figure 9d). This broad consistency in the COSMO_iso_50km simulation results for the mid-Holocene and the present-day is remarkable, considering that both simulations are driven by two different forcing approaches (ECHAM5-wiso nudged to ERA-Interim reanalysis with prescribed monthly varying oceanic boundary conditions vs. the fully-coupled atmosphere-ocean Earth-System-Model MPI-ESM-wiso). This finding indicates that the spatial and interannual δ18O variability of COSMO_iso_50km within a GCM grid box over Greenland is independent of the oceanic boundary conditions."

Review: The dependency of the d18O discrepancy between ice cores and model simulations on the spatial model resolution

Marcus Breil, Emanuel Christner, Alexandre Cauquoin, Martin Werner, Gerd Schädler

This study examines outputs of a regional climate model (RCM) enabled to compute fractionation of water isotopes over the Greenland ice sheet. The COSMO_iso RCM is forced at the lateral boundaries with isotope enabled GCM simulations with atmospheric nudging. Outputs of COSMO_iso simulations for the present day and the mid-holocene (at a 50 km spatial resolution)are compared against ice core isotopic measurements. For the present-day simulations the RCM simulations generally improved the agreement with observations compared to the GCM results, with the improvements generally occurring in regions with coarser GCM resolution. Higher-resolution RCM simulations at 7 km did not further improve the agreement, producing a worse agreement in some instances. For the mid-Holocene simulations, there was not a large improvement resulting from the RCM simulations (although data were available only from four ice cores). The authors note that the higher-resolution simulations provide a range of spatial variability for the coarse resolution grid that can be used to generate a distribution for comparison against ice core measurements. They also examine gradients of isotope ratio relative to temperature, finding higher variability in temperature and isotope ratios along the ice sheet margins.

General Comments

In general, the study appears to be scientifically sound, and well-organized. The work represents an important step in developing an improved understanding of the relationship between measured isotopic ratios and historical climate. The presentation, particularly the language, needs improvement, with many grammatical errors. The figures are somewhat difficult to read at first glance and also require improvements.

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

I also have some concerns about the manuscript, in particular:

1. The in situ measurements are all located within the high-elevation center of the ice sheet, with one exception. It is therefore difficult to evaluate the degree to which the model simulations capture the spatial variability. While the RCM simulation improves the agreement with the southern-most observations, it introduces a positive bias in the north. It seems this could be due to differences in the dynamical simulation in the RCM relative to the ESM rather than increased variability in the higher resolution RCM as the authors argue.

- we agree and changed the argumentation according to your suggestion. Thank you very much for this helpful comment (Lines 229 – 233):

"As visible in Figure 3, these systematic differences are rather caused by a southward shift of the area of low yearly mean δ18O values in central Northern Greenland in COSMO_iso_50km relative to ECHAM5-wiso. As a result, the simulated δ18O values in central Northern Greenland in COSMO_iso_50km are higher than in ECHAM5-wiso. Since there, ECHAM5-wiso has already a high agreement with the observed δ18O values, a model bias is introduced in COSMO_iso_50km, causing the deviations relative to the observations in Northern Greenland."

2. Given the above points, the added value of the RCM simulation is not entirely clear, even in the present-day simulation, although the plots seem to suggest that it does provide some improvement in

the mean value. The authors should provide quantitative estimates as to the improvement associated with the RCM.

- we agree and mention now quantitative estimates of the RCM improvements in the present-day simulations (Lines 215 and 244). The average bias reduction of COSMO_iso_50km over all snow pit samples is 0.7‰, the average reduction of COSMO_iso_7km is 0.6‰.

3. The method of averaging observational data (which may contain missing values) is not entirely clear. The authors have not discussed potential errors in the observations.

- of course, observations are also associated with uncertainties. The impacts of firn diffusion, post-depositional erosion of surface snow by wind and the spatial uncertainties related to micrometeorological effects are now discussed in the revised paper (e.g. Lines 166-172). Since the used observational datasets do not contain missing data, no special averaging method is applied (See comments 16 & 17).

“Since all snow pit samples cover different time periods, the present-day δ18O values (black numbers in Table 2) are calculated as an average of all available δ18O values measured between 1940 and 2007. With this procedure uncertainties in snow pit samples and top ice core samples, associated with post depositional diffusion and the resulting constraints in analysing annual and interannual top ice core data (e.g. Johnson et al., 2000), can be neglected. However, further uncertainties in snow pit samples and ice core data remain, regarding the timescale assignment (Steig et al., 2005) and the spatial variability (Weißbach et al., 2016b).”

4. I think the authors’ approach of using the high-resolution variability as an indicator of the potential spatial variability within a coarse resolution grid cell, that can then inform the point observation to model grid cell comparison, is interesting. If the authors can find any literature supporting this argument, I think this would strengthen the manuscript.

- With the publication of Shi et al., (2020), an additional reference substantiating our argumentation is now cited in the revised manuscript. In this study, the importance of small-scale processes to understand the measured water isotope variability is highlighted. According to this, GCM deficiencies in simulating this isotope variability are therefore caused by the missing representation of such small-scale processes in GCM simulations (this statement is no included in Lines 441-443). However, the authors are not aware of any further supporting literature.

Shi et al., (2020): https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JD031751

5. This is not essential but the presentation of the manuscript could be improved if the authors use a different projection that doesn’t distort the Greenland ice sheet, and if they label figures with brief headings that summarize each sub-figure without necessitating a thorough reading of the caption.

- as you already mentioned in your first comment, most of the point measurements are located in Central and Northern Greenland very close to each other. The chosen projection is therefore beneficial to better distinguish between these observations (especially in Figure 3). For that reason, we would like to stick to this projection.

In the revised manuscript, all figures are labeled with headings.

Specific Comments

1. Title: The title could be improved to better describe the study. The title should include mention of Greenland and types of models that are used. Possible revision: "Applying an isotope-enabled regional climate model over the Greenland Ice Sheet: effect of spatial resolution on model bias"
- the title is changed as you suggested. Thank you very much for your suggestion

2. Lines 7-9: The authors should mention here the motivation and purpose of the study, which is described well in the introduction section.
- the motivation of the study is now mentioned at the beginning of the abstract (lines 8-10):

"In order to investigate the impact of spatial resolution on the discrepancy between simulated δ18O and observed δ18O in Greenland ice cores, regional climate simulations are performed with the isotope-enabled Regional Climate Model (RCM) COSMO_iso."

3. Line 9: Change "isotopic ratios in Greenland" to "isotopic ratios in Greenland ice cores".
- is changed.

4. Line 10: Explain that ECHAM5-wiso and MPI-ESM-wiso are GCM simulations and spell out acronyms.
- in the revised manuscript, it is now mentioned that ECHAM5-wiso and MPI-ESM-wiso are isotope-enabled GCMs. The acronym MPI-ESM-wiso is now spelled out in the model description section 2.1.2. Since the GCM ECHAM is well-known in the modelling community and its acronym is very complex (a combination of **EC**MWF, which is already an acronym, and **Ham**burg, the location of the Max-Planck-Institute), we decided to not spell out ECHAM.

5. Lines 15-16: This sentence is confusing. Suggest revising to something like: "...the COSMO_iso estimates provide a distribution of values representing spatial uncertainty that give context to comparison with observed isotopic ratios."
- the abstract is rephrased in consideration of your suggestions (see comment 6).

6. Lines 20-23: These sentences are confusing. I think the authors can simply say something like: "Despite the lack of improvement in model biases, the RCM simulations provide a distribution that allow the effects of spatial uncertainty to be taken into account in the comparison between point measurements and model outputs."
- the abstract is rephrased in consideration of your suggestions (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 not resolved 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."

7. Line 60: The authors mention temporal resolution here, but this is not discussed in the rest of the manuscript. I suggest providing further details here about temporal downscaling and noting that the focus of the present study is on spatial downscaling.
- in the revised manuscript, the text is adjusted as follows (Lines 66-71):

“Therefore, in the presented study, isotope-enabled GCM simulation results for the Arctic region are dynamically downscaled with an isotope-enabled RCM to a higher temporal and spatial resolution. By means of such regional simulations, the spatial and temporal variability of the isotopic ratios in the Arctic is potentially increased, accounting for the heterogeneity of local conditions at the different ice core locations and the associated uncertainties. In this way, the impact of highly resolved local conditions on the spatial and temporal variability of isotopic ratios is investigated, and the impact of such small-scale variability on the discrepancy between simulated and observed paleo-climate conditions in the Arctic region is examined.”

According to this, an analysis of the temporal variability is additionally included in the paper (Figure 7d and 9d).

8. Lines 70-75: The text here repeats some information that was mentioned earlier. Suggest revising to avoid repetition.
- this information was only mentioned in the abstract. Therefore we would like to keep it in the text.

9. Line 92: It should be first noted here that snow surface albedo is fixed and is not spatially and temporally variable.
- snow surface albedo is not fixed. An alteration of the snow albedo with growing age is considered in the model. The increase in the snow albedo value from 0.7 to 0.8 refers to the albedo value of fresh snow. This is now specified in the manuscript (Line 97).

10. Lines 120-144: How are the ocean boundary conditions specified? Are these from reanalysis data?
- in the ECHAM5-wiso simulations, sea surface temperatures and sea ice cover are varying monthly based on ERA data. In MPI-ESM-wiso, the ocean component is calculated dynamically with the ocean model MPIOM. This is now mentioned in the text (Lines 131-132 and 151).

11. Line 111: What is meant by “the models”? Please clarify.
- we mean state-of-the-art isotope-enabled models. This is now clarified.

12. Lines 114-119: Are the authors referring to work they have performed comparing COSMO_iso to observations, or is this referring to the Christner et al. (2017) study? Please clarify. Also, please clarify how the processes are treated in the COSMO_iso model.
- these processes are not yet included in state-of-the-art isotope-enabled models. This is, for instance, discussed in Christner et al., (2017). The paragraph is rephrased to avoid confusion and to clarify how fractionation at snow covered surfaces is treated in COSMO_iso (Lines 114-122):

“Isotope fractionation during sublimation from a surface snow layer is poorly understood. Several different processes are suggested to be involved, which are not yet taken into account in state-of-the-art isotope enabled models (see e.g. discussion in Christner et al., 2017), such as non-fractionating layer-by-layer sublimation (e.g. Ambach et al. 1968), kinetic fractionation during sublimation into sub-saturated air, a diurnal cycle of sublimation combined with fractionating vapor deposition on the snow (e.g. Steen-Larsen et al., 2014), and fractionating melt water evaporation combined with recrystallization of residual melt water have been suggested (Gurney and Lawrence, 2004). 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.”

13. Lines 123-124: Note the domain boundaries for the Arctic simulation.
- an additional figure showing the model domains (50 km and 7 km) is now included in the manuscript (Figure 1)

14. Lines 128-130: Is this an additional simulation forced by the coarse resolution run, or a nested domain within the larger domain?
- this simulation is nested in the 50 km simulation with COSMO_iso. This is now clarified in the text (Line 134-135).

15. Line 130: What is meant by "technical reasons"? Please clarify.
- this statement is removed from the text.

16. Lines 152-153: How are the authors dealing with missing data? If there are large temporal gaps in some of the datasets this could influence the average values.
- In the selected time periods, no missing data occurred in the yearly d18O values of the snow pit samples.

17. Table 1: Are all the datasets available for the specified period? What is the effect of missing data on the estimates? Does the depth of the cores/snow pits affect the average? Please comment and perhaps perform calculations to assess these affects.
- No, not all samples cover the whole period. But the individual datasets are consistent in themselves and do not contain missing data. In addition, the averaging periods of the respective snow pit samples are long enough to rule out statistical outliers.

18. Line 183: What is the average reduction in the bias?
- The average bias reduction of COSMO_iso_50km is 0.7‰, the average reduction of COSMO_iso_7km is 0.6‰. This is now mentioned in the text (Lines 215 and 244).

19. Lines 199-205: I don't quite understand the logic here. I think what the authors are saying is that the high-resolution simulation leads to a higher degree of variability in locally simulated values. Due to the uncertainty in the model simulation, this may lead to a larger bias with respect to in situ point measurements, which may actually be closer to the average value on the coarse resolution grid. However, running the high resolution simulation allows for computation of a range of local variability, which can be used to compare model to observed values, accounting for the inherent uncertainty of the in situ measurement associated with local variability. This is an interesting and reasonable argument. I think the authors need to articulate it better here. Also if the authors can find any literature showing similar results this would be helpful in supporting this argument.
- we rephrased the paragraph (Lines 262-265 and 269-274). Thank you very much for your helpful suggestions.

"As a consequence, an additional spatial variability is introduced in the RCM simulations in comparison to the GCM results. Due to uncertainties accompanied by model simulations, this can potentially increase the RCM bias with respect to in situ point measurements, which may actually be closer to the spatially averaged values simulated by the coarse GCM model."

"However, by performing higher resolved RCM simulations, the subgrid-scale variability of δ18O within GCM grid boxes can be simulated and compared to observed δ18O values. In this way, the inherent uncertainty of in situ measurements, associated with a local micrometeorological variability, can be considered. Thus, in the following, snow pit samples are not anymore solely compared to the model grid boxes covering the samples location. Instead, it is investigated whether the δ18O range of all adjacent RCM grid boxes to a snow pit location is consistent with the observed δ18O value of the same site. For this, all RCM grid boxes located within the corresponding GCM grid box are included in the comparison with the observations."

20. Figure 2: Why are sites 17 and 18 missing here? Are data from these locations missing for this year? Please clarify in the caption and in the main text.
- this is corrected in the revised manuscript. Now the corresponding figures show all data points (now 19).

21. Lines 223-228: This argument does not make sense to me. Looking at the box plots in Figure 3, the variability for these particular stations does not seem to be larger here than at other locations. Rather, there appears to simply be a model bias at this location. One can also see from Figure 1, that COSMO_iso seems to shift the low isotope values in central northern Greenland further south relative to the ECHAM5-wiso, thereby increasing the bias in these areas somewhat. The authors should clarify or revise their arguments here.
- We agree with you and adapted our argumentation according to your suggestions (see general comment 1). Thank you very much for this helpful comment.

22. Lines 251-257: This paragraph would more appropriately follow the first paragraph of the section, detailing the mid-Holocene results.
- this paragraph is relocated according to your suggestions.

23. Figure 4: The y-axis label is confusing. Suggest changing to d18O difference. In the caption labels, suggest replacing with MPI_ESM_wiso –obs. and COSMO_iso_50km –obs.
- We changed the labeling of Figure 4 (now Figure 8) according to your suggestions.

24. Line 261: Is the green point for the 50 km grid cell closest to the measurement location? Please clarify.
- Yes it is. This is now clarified (Line 360).

25. Line 263: Spell out PI.
- is corrected.

26. Lines 266–294: I suggest making this a new section, discussing sub-ESM-grid variability.
- sections are new arranged in the revised manuscript according to your suggestions. Now, we discuss for both, present-day and mid-Holocene, first the simulated δ18O data in comparison to the point measurements and then the GCM δ18O subgrid-scale variability in sub-sections, respectively.

27. Line 286: Calling this a temperature gradient suggest that it is a change in temperature with elevation. Is this indeed a gradient, established through a linear fit of isotope ratio vs. temperature for the sub-grid results for each grid cell, or is it simply a ratio of the standard deviation? Please clarify by revising the text here.
- It is an isotope-temperature slope which constitutes a linear fit between the simulated δ18O ratios and the surface temperatures at all COSMO_iso_50km grid boxes within the respective GCM grid box. The isotope-temperature slope is a measure that is frequently used to analyze how strong isotope ratios and surface temperatures are interrelated. This is now clarified in the text (Lines 301-302):

“The spatial isotope-temperature slope constitutes a linear fit between the simulated δ18O ratios and the surface temperatures at all COSMO_iso_50km grid boxes within the respective ECHAM5-wiso grid box.”

28. Line 294: Change “the same mechanisms” to “similar mechanisms”.
- the sentence is rephrased in the revised manuscript.

29. Figure 5: Site 1 is very difficult to see here and in other figures. Is there a way to improve visibility, perhaps by changing colors? Also label the color axis “d18O standard deviation” and “temperature standard deviation[K]” for clarity.
- We changed the color of the markers to green in the corresponding figures. The labeling is changed according to your suggestions.

30. Line 301: Change “Simulated variability” to “simulated sub-grid-scale variability”.
- is adapted in the revised manuscript.

31. Figure 6: This color map is likely not suitable for red-green colorblind readers. Suggest using a different color map.
- we changed the color map to blue-red.

32. Lines 330-331: As noted earlier, in some cases this may be a result of increased variability, but it could also be a bias introduced in the RCM simulation.
- This was actually a statement meant about the Renland station. This is corrected in the revised paper. Sorry for this mistake (Line 430-432):

“This in turn can lead to additional noise and thus, a deviating RCM behaviour with even an increase in the absolute model bias, as seen for the Renland station.”

33. Line 343: Suggest changing “The same” to “Similar”.
- is corrected

34. Line 358: Change “prove” to “test”.
- is corrected

Technical Corrections

1. Line 7: spell out RCM at the beginning of the line: “isotope-enabled Regional Climate Model (RCM) for Greenland. The capability of the applied RCM COSMO_iso,...”
- is corrected.

2. Line 13: Change “a downscaling” to “dynamical downscaling” for clarity.
- is corrected.

3. Lines 14-15: Revise to “yields improvements only for coastal areas with complex terrain.”
- is corrected.

4. Line 19: Change “already on a high level” to “already agrees well with observations”
- is corrected.

5. Line 26: Change “deviations to” to “deviations relative to”
- is corrected.

6. Line 32: Change “like past changes of temperature, out of” to “such as past temperature changes using”
- is corrected.

7. Line 37: Change “was steadily rising” to “steadily rose”
- is corrected.

8. Line 39: Change “were steadily decreasing” to “steadily decreased”.
- is corrected.

9. Line 40: Change “took place” to “had taken place”.
- is corrected.

10. Lines 41-42: Suggest revising to read “period of particular interest, given recent Arctic warming, as it was characterized by Arctic warming resulting from orbital forcing...”
- we keep the current phrasing

11. Line 43: Change “processes, leading to this warming,” to “processes leading to this warming...”
- is corrected.

12. Line 44: Suggest changing “reflect” to “reproduce”.
- is corrected.

13. Line 46: Remove “which are” before “documented in”.
- is corrected.

14. Line 51: Suggest changing “does not meet” to “does not reproduce” or “does not adequately represent”
- is corrected.

15. Line 54: Change “also often not entirely resolved” to “not well resolved” and “coarsely resolved GCMs” to “coarse resolution GCMs”
- is corrected.

16. Line 56: Change “deviations to” to “deviations relative to”
- is corrected.

17. Lines 63-64: Suggest changing to “investigated, and the impact of such small-scale spatial variability on the discrepancy between simulated and observed paleo-climate conditions in the Arctic region is examined.
- is corrected.

18. Line 67: Change “separated” to “separate”.
- this sentence is removed in the revised manuscript.

19. Line 82: Spell out “COSMO”.

- is corrected.

20. Line 87: Change “presented” to “present”.
- is corrected

21. Line 100: Change “2 m temperature” to “2 m air temperature” for clarity.
- is corrected

22. Line 114: Add “the” before “best agreement”
- this sentence is removed in the revised manuscript.

23. Line 121: Change “reflect” to “reproduce”.
- is corrected

24. Line 134: Change “simulation has been” to “simulation is”
- we keep the current phrasing

25. Line 138: Is the improvement to surface albedo for all surface types or one particular surface type?
- For ECHAM6, a new land-albedo has been developed (Brovkin et al., 2013, JAMES, https://doi.org/10.1029/2012MS000169). But since we are focusing on Greenland in this study, different surface types are not so relevant. However, the albedo over sea ice area is also considered (treatment of melt ponds on sea ice). For land ice surface, the snow age is taken into account.

26. Line 147: Perhaps remove “different” from before “different observational data”.
- is corrected

27. Line 151: Remove “used” before “d18O values”.
- is corrected

28. Line 172: Change “models capability” to “models’capability”.
- is corrected

29. Line 175: Change “decline stronger” to “decline more rapidly”.
- is corrected

30. Line 179: Change “stonger pronounced” to “more pronounced.
- is corrected

31. Line 181: Change “at which” to “for which”.
- is corrected

32. Line 182: Change “deviations to” to “deviations from”.
- is corrected

33. Line 185: Change “results anymore” to “results further”.
- is corrected

34. Line 188: Change “a complex terrain” to “complex terrain”
- is corrected

35. Line 194: Change “a higher agreement” to “an improved agreement”.
- is corrected

36. Line 196: Change “an enlarged heterogeneity” to “an increased heterogeneity”.
- is corrected

37. Line 236: Change “differences for” to “differences between” and “grid box results to the” to “grid box results and the”
- the sentence is rephrased in the revised manuscript.

38. Line 238: Change “shown as Box-Whiskers” to “shown as a Box-Whiskers”.
- is corrected

39. Lines 277-278: Change “the three regions...”to “in three regions of Greenland with substantially different sub-pixel isotopic ratio variabilities.”
- is corrected

40. Line 281: Change “exhibiting also regional variations” to “which also exhibits regional variations...”
- the sentence is rephrased in the revised manuscript.

41. Line 283: Change “does consequently not only depend” to “consequently not only depends”
- is corrected

42. Line 313: Change “agreement to climate” to “agreement with climate”
- is corrected

43. Lines 322-324: Revise to “But for northern Greenland, regional climate simulations with COSMO_iso increase the bias with respect to observations and
- is corrected

Applying an isotope-enabled regional climate model over the Greenland ice sheet: effect of spatial resolution on model bias

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Abstract. In order to investigate the impact of spatial resolution on the discrepancy between simulated $\delta^{18}O$ and observed $\delta^{18}O$ in Greenland ice cores, regional climate simulations are performed with the isotope-enabled Regional Climate Model (RCM) COSMO_iso. For this purpose, isotope-enabled General Circulation Model (GCM) simulations with ECHAM5-wiso under present-day and MPI-ESM-wiso under mid-Holocene conditions are dynamically downscaled with COSMO_iso for the Arctic region. The capability of COSMO_iso to reproduce observed isotopic ratios in Greenland ice cores [illegible]hese two periods is investigated by comparing the simulation results to measured $\delta^{18}O$ ratios from snow pit samples, GNIP stations and ice cores. To our knowledge, this is the first time that a mid-Holocene isotope-enabled RCM simulation is performed for the Arctic region.

Under present-day conditions, a dynamical downscaling of ECHAM5-wiso with COSMO_iso to a spatial resolution of 50 km improves the agreement with the measured $\delta^{18}O$ ratios for 14 of 19 observational data sets. A further increase in the spatial resolution to 7 km yields improvements only for the coastal areas with its complex terrain. For the mid-Holocene, a fully coupled MPI-ESM-wiso time slice simulation is downscaled with COSMO_iso to a spatial resolution of 50 km. In the mid-Holocene, MPI-ESM-wiso already agrees well with observations in Greenland and a downscaling with COSMO_iso does not further improve the model-data agreement. Despite this lack of improvements in model biases, the study shows that in both periods, observed $\delta^{18}O$ 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 $\delta^{18}O$ ratios are consequently already included but not resolved in the GCM simulation results and just need to be extracted by a refinement with an RCM. In this context, the RCM simulations provide a spatial $\delta^{18}O$ distribution by which the effects of local uncertainties can be taken into account in the comparison between point measurements and model outputs. Thus, an isotope-enabled GCM-RCM model chain with realistically implemented fractionating processes, constitutes a useful supplement to reconstruct regional paleo-climate conditions during the mid-Holocene in Greenland. Such model chains might also be applied to reveal the full potential of GCMs in other regions and climate periods, in which large deviations relative to observed isotope ratios are simulated.

1 Introduction

Stable isotopes of water ($HD^{16}O$ and $H_2{}^{18}O$) are fractionated during any phase transition. This fractionating process depends on temperature (Dansgaard, 1953; Craig and Gordon, 1965; Jouzel and Merlivat, 1984), so that water isotopic ratios (expressed here in the usual δ notation, δD and $\delta^{18}O$ with respect to the Vienna Standard Mean Ocean Water V-SMOW) reflect the atmospheric conditions under which the fractionating process took place (Dansgaard, 1964; Merlivat and Jouzel, 1979; Gat, 1996). This process is generally utilized to reconstruct paleo-climate conditions such as past temperature changes, using isotopic ratios stored in climate archives (Dansgaard et al., 1969; Masson-Delmotte et al., 2005; Jouzel, 2013).

In Arctic regions like Greenland, ice cores constitute an exceptional climate archive. Over thousands of years, accumulated snow was solidified to ice, preserving at some locations the water isotopic ratios since the last interglacial period. Climate reconstructions based on these ice cores show that the climate conditions changed considerably in Greenland during the Holocene (here defined as the period between present-day and 12 ka; Marcott et al., 2013). Between the early Holocene and the Holocene Thermal Maximum in the mid-Holocene (6 ka), a pronounced warm phase took place. Since then, temperatures steadily decreased until the late Holocene (Marcott et al., 2013; Moossen et al., 2015). In this context, the mid-Holocene is a period of particular interest, as by that time an Arctic warming had taken place due to orbital forcing variations and their related feedbacks on large-scale climate variations, which exhibits similarities to the strong recent Arctic warming. For Greenland, 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).

While General Circulation Models (GCMs) are generally able to reproduce the direction and large-scale patterns of past climate changes (e.g. Timm and Timmermann, 2007; Smith and Gregory, 2012), they often fail to reproduce the magnitude of regional changes (Braconnot et al., 2012; Harrison et al., 2014), documented in various local climate archives. Thus, a scale gap might exist between the measured point information and the large-scale climate information generated by GCMs. The comparison of observational and GCM data can therefore be subject to considerable uncertainties (Felzer and Thompson, 2001).

Especially for structured landscapes, the spatial resolution in GCMs is often too coarse to resolve relevant local factors (Jost et al., 2005; Fischer and Jungclaus, 2011). Important properties like topography and surface conditions are consequently only represented in a generalized and imprecise form in climate simulations. In most cases, this does not adequately represent the complex characteristics of the land surface and its associated interactions with the atmosphere. 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.

Therefore, in the presented study, isotope-enabled GCM simulation results for the Arctic region are dynamically downscaled with an isotope-enabled RCM to a higher temporal and spatial resolution. By means of such regional simulations, the spatial and temporal variability of the isotopic ratios in the Arctic is potentially increased, accounting for the heterogeneity of local conditions at the different ice core locations and the associated uncertainties. In this way, the impact of highly resolved local conditions on the spatial and temporal variability of isotopic ratios is investigated, and the impact of such small-scale variability on the discrepancy between simulated and observed paleo-climate conditions in the Arctic region is examined.

To explore this, the isotope-enabled version of the RCM COSMO-CLM (Rockel et al., 2008), COSMO_iso (Pfahl et al., 2012; Christner et al., 2018), is used. In a first step, the general suitability of COSMO_iso to be used for isotope applications in Greenland is assessed. For this purpose, near-surface temperatures and precipitation amounts simulated with the standard COSMO version are compared with observations in the Arctic region. Subsequently, the capability of COSMO_iso to simulate realistic water isotopic ratios for Greenland is tested by downscaling a global present-day simulation with an isotope-enabled GCM for the Arctic region. The GCM and RCM results are then compared to measured water isotope ratios in precipitation and snow pit samples. Afterwards, the tested isotope-enabled COSMO_iso model system is used to downscale an isotope-enabled GCM simulation for a mid-Holocene time-slice. The simulated isotopic ratios are evaluated against Greenland ice core data. Such a dynamical downscaling of global isotope simulations for Greenland under mid-Holocene conditions, is performed for the first time in the framework of this study.

2 Methods

2.1 COSMO_iso

2.1.1 Model Description

In this study, simulated stable water isotope concentrations of $HD^{16}O$ and $H_2{}^{18}O$ with isotope-enabled GCMs (section 2.1.2), are regionally downscaled with COSMO_iso (Pfahl et al., 2012), an isotope-enabled version of the numerical weather prediction model COSMO (Consortium for Small-scale Modeling; Baldauf et al., 2011) (version 4.18). For the purpose of long-term climate simulations, isotope-routines of COSMO_iso were implemented in COSMO-CLM (Rockel et al., 2008), the climate version of COSMO. In this context, the δD and $\delta^{18}O$ ratios in the soil water and the surface layer snow are simulated with TERRA_iso V.1 (Dütsch, 2017; Christner et al., 2018), the isotope-enabled version of the multi-layer Land Surface Model TERRA-ML (Schrodin and Heise, 2001) in COSMO. In several studies, COSMO_iso and TERRA_iso were successfully employed for the simulation of isotopic ratios in the mid-latitudes (Pfahl et al., 2012; Aemisegger et al., 2015; Christner et al., 2018). In the present study, the model system will be applied to the Arctic region. For this, some additional modifications regarding the treatment of snow and ice had to be implemented in the model:

Snow albedo

The surface albedo of fresh snow is increased from 0.7 to 0.8 to improve the model agreement with measured values of short-wave reflectance and 2m temperature at stations from the Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder (CIRES) in Central Greenland.

Snow layer thickness

In the standard configuration of COSMO, the Greenland ice sheet is treated as a constant mass of ice, which is covered by a single snow layer. But in this model structure, dynamical processes within the ice sheet (flow, basal melt) are not included. As a result, the depth of the snow layer is constantly increasing and thus also its heat capacity. To avoid this spurious model behaviour, the snow layer depth is limited to 5 cm in this study. Using this value, realistic diurnal cycles of the 2 m air temperature could be simulated.

Marine regions with sea ice cover

To be able to simulate reasonable fractionation processes for marine regions with sea ice cover, a snow layer is also implemented on top of the sea ice (e.g., as suggested in Bonne et al., 2019). The isotopic composition of this surface snow layer is in this case set to the isotopic composition of the most recent precipitation.

Fractionation at snow covered surfaces

Isotope fractionation during sublimation from a surface snow layer is poorly understood. Several different processes are suggested to be involved, which are not yet taken into account in state-of-the-art isotope enabled models (see e.g. discussion in Christner et al., 2017), such as non-fractionating layer-by-layer sublimation (e.g. Ambach et al., 1968), kinetic fractionation during sublimation into sub-saturated air, a diurnal cycle of sublimation combined with fractionating vapor deposition on the snow (e.g. Steen-Larsen et al., 2014), and fractionating melt water evaporation combined with recrystallization of residual melt water have been suggested (Gurney and Lawrence, 2004). 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.

2.1.2 Model Simulation Setup

The capability of COSMO_iso to realistically reproduce the fractionating processes of stable water isotopes in Greenland is evaluated. For this, the nudged simulation outputs (standard and isotopic) from an isotope-enabled atmospheric model ECHAM5-wiso (Werner et al., 2011) simulation are dynamically downscaled with COSMO_iso for the whole Arctic region. The data from the same ECHAM5-wiso simulation have been already used as boundary conditions for COSMO_iso simulations over Europe by Christner et al. (2018). The simulation outputs from ECHAM5-wiso are at a T106 horizontal spatial resolution (1.1° x 1.1°) and on 31 atmospheric vertical levels. The dynamical fields were nudged every 6 hours towards ERA-Interim reanalysis data (Dee et al., 2011). Monthly varying sea surface temperatures and sea ice cover were prescribed as lower boundaries over sea, also based on the ERA-Interim data. The simulation period is 2008-2014. The spatial resolution of COSMO_iso is 0.44° x 0.44°, corresponding to 50 km x 50 km in rotated coordinates (COSMO_iso_50km). Afterwards, an additional COSMO_iso simulation with a spatial resolution of 0.0625° x 0.0625° (corresponding to about 7 km × 7 km) for Greenland (COSMO_iso_7km) is nested in the COSMO_iso_50km simulation. This high-resolution simulation covers the year 2011. In the COSMO_iso runs, the horizontal wind fields above the 850 hPa level are spectrally nudged (von Storch et al., 2000) towards the reanalysis-based dynamical fields of ECHAM5-wiso. This method ensures that consistent atmospheric boundary conditions build the framework for the fractionating processes simulated in COSMO_iso. The model domains of both simulations is shown in Figure 1.

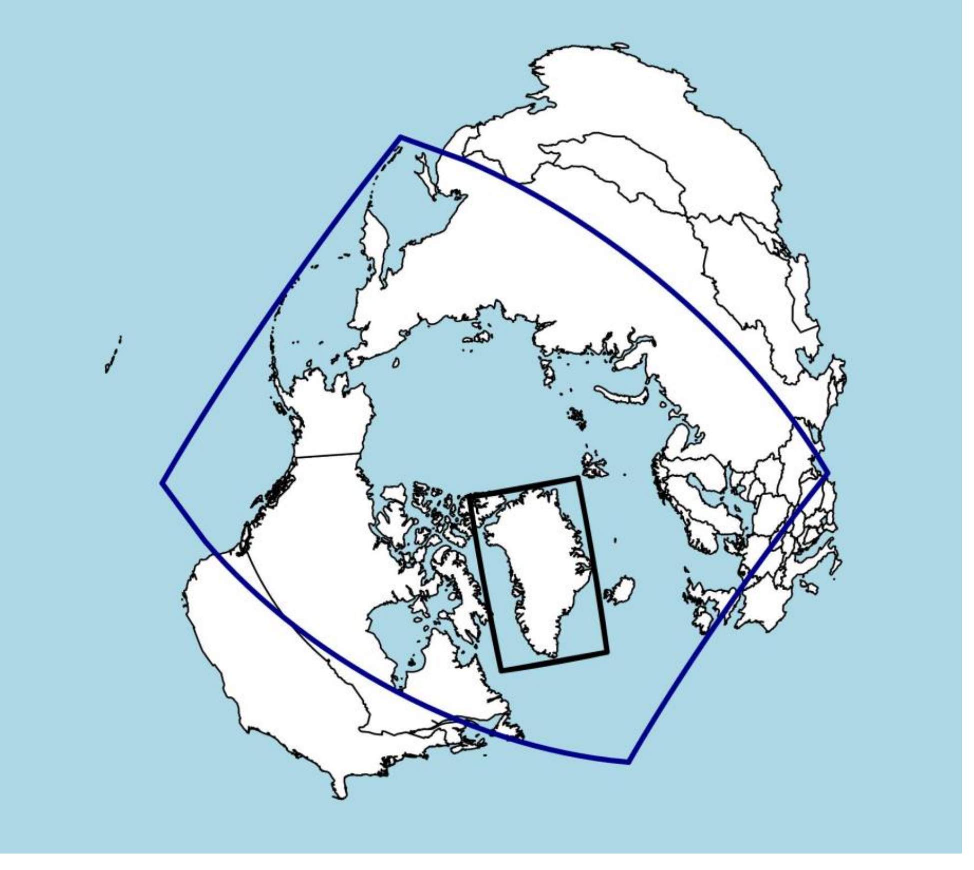

Figure 1: COSMO_iso model domain of the 50 km (blue) and the 7 km (black) simulation.

The same model chain is applied to the mid-Holocene period. Atmospheric fields have been retrieved from a mid-Holocene simulation of the fully-coupled isotope-enabled Max Planck Institute Earth System Model (MPI-ESM-wiso, Cauquoin et al., 2019), whose atmospheric component is ECHAM6-wiso. The major ECHAM6 model changes compared to ECHAM5 include an improved representation of radiative transfer in the solar part of the spectrum, an improved representation of surface albedo, a new aerosol climatology and an improved representation of the middle atmosphere (Stevens et al., 2013). The ocean component is the Max Planck Institute Ocean-Model (MPIOM, Jungclaus et al., 2013). With COSMO_iso, a representative time slice of 30 years is simulated for this climate period, only, since the regional COSMO_iso simulations are computationally very expensive. The greenhouse gas concentrations and the orbital parameters are adapted, according to the Paleoclimate Modelling Intercomparison Project 4 experiment design (PMIP4, Kageyama et al., 2018). The model domain of the COSMO_iso simulations is identical to the present-day simulations.

2.2 Observations

The capability of the isotope-enabled regional climate model COSMO_iso to reproduce measured isotopic ratios in Greenland is evaluated by comparing the simulation results to observational data. The simulated isotopic composition in precipitation is assessed by comparing the model results in the arctic region with observed monthly data from the Global Network of Isotopes in Precipitation (GNIP) of the International Atomic Energy Agency and the World Meteorology Organization [IAEA/WMO, 2016] over the period 2008-2014 (Table 1). Furthermore, simulated $\delta^{18}O$ ratios are compared to snow pit samples collected during the North Greenland Traverse (Fischer et al., 1998; Weißbach et al., 2016a) and top core samples from five ice core locations (Renland (Vinther et al., 2008), Neem (Masson-Delmotte et al., 2015), GISP2 (Grootes and Stuiver, 1997), Summit (Fischer, 2003), SE-Dome (Furukawa et al., 2017)). The station numbers assigned to the respective samples within this study, as well as their locations and $\delta^{18}O$ values are summarized in Table 2. Since all snow pit samples cover different time periods, the present-day $\delta^{18}O$ values (black numbers in Table 2) are calculated as an average of all available $\delta^{18}O$ values measured between 1940 and 2014. With this procedure uncertainties in snow pit samples and top ice core samples, associated with post depositional diffusion and wind erosion and the resulting constraints in analysing annual and interannual top ice core data (e.g. Johnson et al., 2000), can be neglected. However, further uncertainties in snow pit samples and ice core data remain, regarding the timescale assignment (Steig et al., 2005) and the spatial variability (Weißbach et al., 2016b).

Since both, snow pit samples and top core samples from ice cores represent an integrated signal of the isotopic composition in precipitation, the observed isotope ratios are compared with simulated yearly mean $\delta^{18}O$ values in precipitation. For the calculation of this yearly mean values, the modelled $\delta^{18}O$ 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.

Table 1: List of GNIP stations used in this study.

No.	Station Name	Longitude	Latitude	Time period
1	Danmarkshavn	-18.66	76.76	2008-2014
2	Ny Alesund	-11.93	78.91	2008-2014
3	Reykjavik	-21.93	64.13	2008-2014
4	Espoo	24.83	60.18	2008-2010
5	Kuopio	27.62	62.89	2008-2010
6	Rovaniemi	25.75	66.49	2008-2010
7	Snare Rapids	-116.00	63.52	2008-2010
8	Tartu	26.46	58.26	2013-2014
9	Vilsandi	21.81	58.38	2013-2014

Table 2: Description of the snow pit and ice core samples used in this study. The present-day $\delta^{18}O$ values are calculated as an average of all available $\delta^{18}O$ values measured in snow pit samples between 1940-2014. The mid-Holocene $\delta^{18}O$ values are calculated as an average of the measured $\delta^{18}O$ values in ice cores over the period 5.5 ka – 6.5 ka. Black numbers indicate present-day $\delta^{18}O$ values, blue numbers mid-Holocene values.

No.	Name	Sample	Longitude	Latitude	$\delta^{18}O$	Reference
1	Renland	top core	-26.73	71.27	-27.38 (-26.44)	Vinther et al., 2008
2	NEEM	top core	-51.06	77.45	-33.24	Masson-Delmotte et al., 2015
3	GISP2	top core	-38.48	72.58	-34.95 (-34.83)	Grootes & Stuiver, 1997
4	Summit	top core	-37.64	73.03	-36.46	Fischer, 2003
5	B27_B28	snow pit	-46.48	76.65	-34.05	Weißbach et al., 2016a
6	NGT03C93	snow pit	-37.62	73.94	-37.02	Weißbach et al., 2016a
7	NGT06C93	snow pit	-37.62	75.25	-36.89	Weißbach et al., 2016a
8	NGT14C93	snow pit	-36.4	76.61	-36.18	Weißbach et al., 2016a
9	NGT23C94	snow pit	-36.5	78.83	-35.18	Weißbach et al., 2016a
10	NGT27C94	snow pit	-41.13	80	-34.01	Weißbach et al., 2016a
11	NGT30C94	snow pit	-45.91	79.34	-34.19	Weißbach et al., 2016a
12	NGT33C94	snow pit	-44	78	-36.13	Weißbach et al., 2016a
13	NGT37C95	snow pit	-49.21	77.25	-33,81	Weißbach et al., 2016a
14	NGT39C95	snow pit	-46.48	76.65	-34.95	Weißbach et al., 2016a
15	NGT42C95	snow pit	-43.49	76	-35.53	Weißbach et al., 2016a
16	NGT45C95	snow pit	-42	75	-35.33	Weißbach et al., 2016a
17	GRIP	top core	-37.64	72.58	-35.23 (-34.73)	Vinther et al., 2006
18	NGRIP	top core	-42.32	75.1	-35.15 (-34.69)	Vinther et al., 2006
19	SE-Dome	top core	-36.37	67.18	- 27.26	Furukawa et al., 2017

Ice core samples are also used to evaluate the simulated isotopic ratios for the mid-Holocene. Beside the already mentioned Renland and GISP2 samples, two more ice core samples, namely GRIP and NGRIP (Vinther et al., 2006), are used for the model evaluation. The mid-Holocene $\delta^{18}O$ values (blue numbers in Table 2) are calculated as an average of the measured $\delta^{18}O$ values in ice cores over the period 5.5 ka – 6.5 ka.

3 Results

3.1 Present-Day

3.1.1 Standard climatological parameter

In a first step, the general capability of the COSMO model to reproduce observed standard climatological parameters in present-day simulations for Greenland is assessed. For this purpose, the results of an ERA-Interim reanalysis (Dee et al., 2011) driven simulation with the standard COSMO model (without isotope application) are compared with observations, collected by the Danish Meteorological Institute (DMI). Evaluated are the yearly mean 2 m temperatures (Figure 2a) and the yearly mean precipitation sums (Figure 2b) over the period 1995 – 2015. Both, simulated 2 m temperatures as well as simulated precipitation amounts are in good agreement with the DMI observations. Especially the simulated 2 m temperatures coincide well with the observed values. For the precipitation sums, the spread of simulated and observed values is higher than for the 2 m temperatures, a feature generally occurring in weather and climate simulations. Thus, the COSMO model is generally able to simulate reasonable climate conditions in Greenland and can therefore be used for isotope applications in this region. A detailed analysis of the standard COSMO model performance in the Arctic region is presented in Karremann et al., (2020).

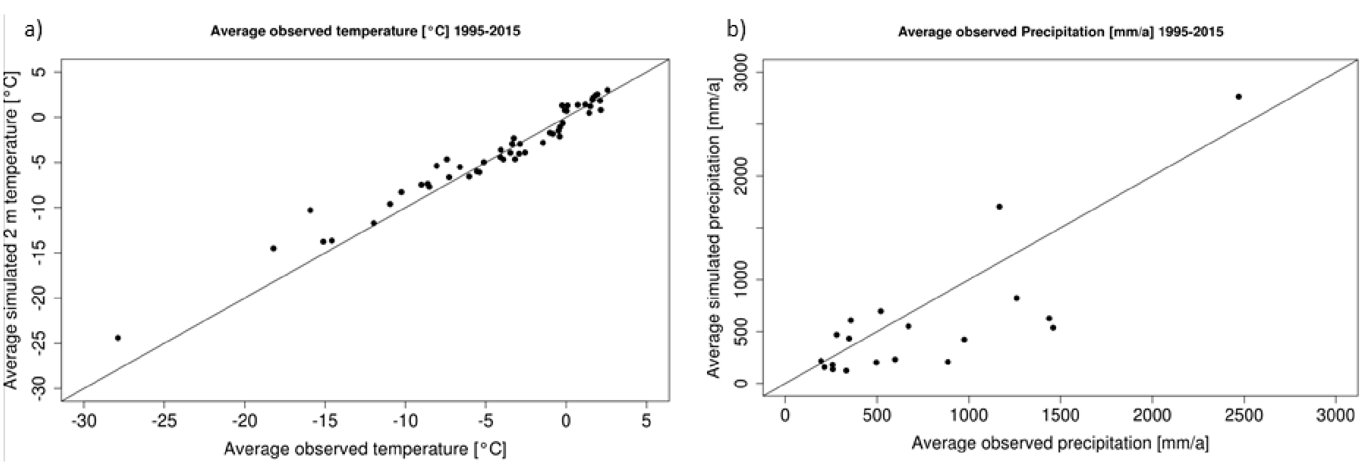

Figure 2: Simulated yearly mean (a) 2 m temperatures and (b) precipitation sums of a standard COSMO simulation, driven with ERA-Interim, for Greenland over the period 1995-2015 compared to DMI observations.

3.1.2 Comparison of simulated $\delta^{18}O$ data to station data

Figure 3 shows the yearly mean $\delta^{18}O$ values for the period 2008-2014 for Greenland, simulated with COSMO_iso_50km (a) and ECHAM5-wiso (b). Additionally, the locations and the observed $\delta^{18}O$ values of the 19 snow pit samples, used to assess the models' capability to reproduce observed $\delta^{18}O$ ratios in Greenland, are illustrated. In general, COSMO_iso in a 50 km x 50 km spatial resolution is able to reflect the observed isotopic ratios at the snow pit samples and improves the simulation results of ECHAM5-wiso. In both simulations, the $\delta^{18}O$ ratios are high near the coastline and low in Central Greenland. But in COSMO_iso_50km, the $\delta^{18}O$ ratios decline more rapidly from the coastline to the inland plateau than in ECHAM5-wiso. The spatial $\delta^{18}O$ differences are consequently more pronounced and the general overestimation of $\delta^{18}O$ ratios, which occurs in ECHAM5-wiso, is reduced in COSMO_iso_50km. As a consequence, the regional simulation reaches a better agreement with the observations. The average bias reduction of COSMO_iso_50km over all snow pit samples is 0.7 ‰. Especially for the snow pit samples for which ECHAM5-wiso exhibits strong deviations from the observed $\delta^{18}O$ values (1,3,4,6,7,8,9,10,16,17,19; see Table 2), a regional downscaling with COSMO_iso_50km reduces the bias considerably (Figure 4). But for snow pit samples at which ECHAM5-wiso has already a high agreement with the observations (2,5,11,13,14), COSMO_iso_50km tends to increase the bias.

Figure 5 shows that these annual biases of the COSMO_iso_50km simulation are not caused by systematic seasonal biases, as for example reported by Sjolte et al., (2011) for RCM simulations in Greenland. Shown are the simulated monthly $\delta^{18}O$ values with COSMO_iso_50km compared to observed monthly $\delta^{18}O$ values in precipitation for the period 2008-2014, collected at arctic stations of the GNIP dataset (Table 1). In general, the modelled $\delta^{18}O$ values in precipitation are in good agreement with the monthly GNIP data. But in the COSMO_iso_50km simulation no systematic over- or underestimation of observed isotope ratios is simulated with the RCM. This is true for each season. Neither in winter (low $\delta^{18}O$ values), nor in summer (high $\delta^{18}O$ values), systematic deviations to the observations are simulated. Thus, the seasonal variability in the COSMO_iso_50km results has no systematic impact on the yearly mean $\delta^{18}O$ values and is therefore not the reason for systematic differences between the coarse model results and observations.

As visible in Figure 3, these systematic differences are rather caused by a southward shift of the area of low yearly mean $\delta^{18}O$ values in central Northern Greenland in COSMO_iso_50km relative to ECHAM5-wiso. As a result, the simulated $\delta^{18}O$ values in central Northern Greenland in COSMO_iso_50km are higher than in ECHAM5-wiso. Since there, ECHAM5-wiso has already a high agreement with the observed $\delta^{18}O$ values, a model bias is introduced in COSMO_iso_50km, causing the deviations relative to the observations in Northern Greenland.

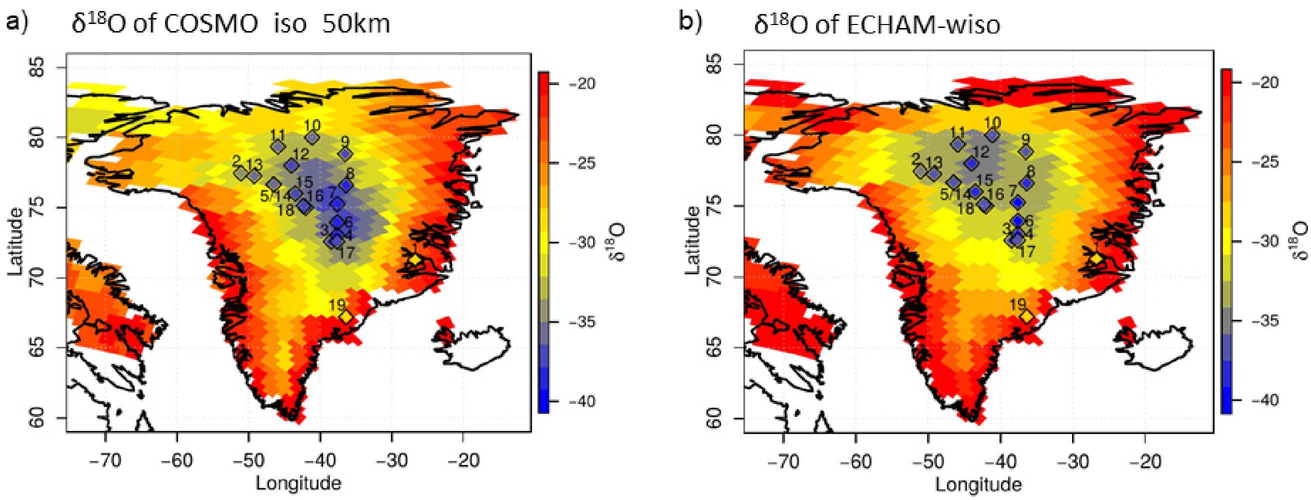

Figure 3: Yearly mean δ^{18}O values of COSMO_iso_50km (a) and ECHAM5-wiso (b, interpolated to the COSMO_iso_50km grid) for the period 2008 - 2014 and the corresponding observations for the 19 snow pit samples (Table 2).

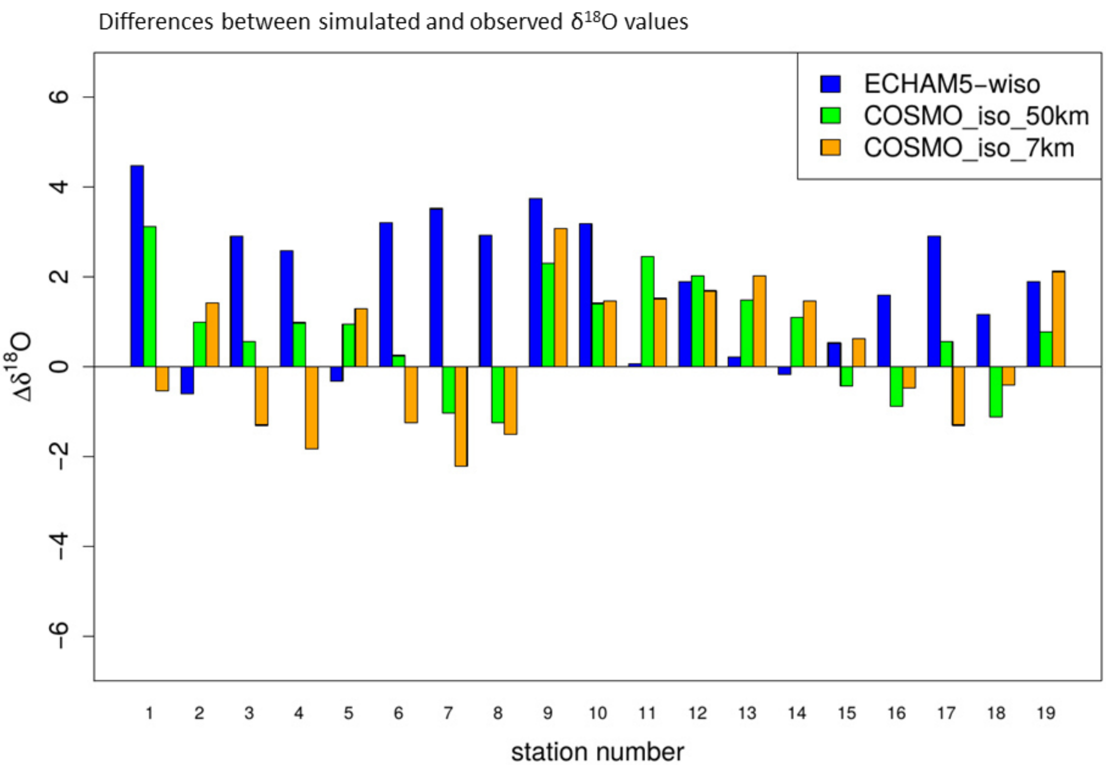

Figure 4: Differences (Δ) between simulated and observed δ^{18}O values (model minus observation) for the model results of ECHAM5-wiso, COSMO_iso_50km, and COSMO_iso_7km, and snow pit samples / top core samples from ice cores from Greenland (simulation: 2011, observation: mean present values). Numbers refer to the different snow pit locations shown in Figure 3.

A further downscaling with COSMO_iso to a spatial resolution of 7 km x 7 km does not improve the simulation results further. The average bias reduction in comparison to ECHAM5-wiso is 0.6 ‰. The only exception constitutes the snow pit sample from Renland (1). Here, a considerable model bias in ECHAM5-wiso and COSMO_iso_50km is strongly reduced in COSMO_iso_7km. The coastal area of Renland is characterized by complex terrain and constitutes a special case for isotope-enabled modeling in Greenland. The snow pit sample is located in a transition zone from the homogeneous inland glaciation to the rugged coastline, where the glaciers calve into the sea. Thus, within short distances large differences in altitude and land surface characteristics occur in this region. The isotopic ratios in the snow pit sample are therefore strongly affected by these heterogeneous local conditions, which are insufficiently represented in the coarse model resolution of ECHAM5-wiso. By increasing the spatial resolution with regional climate modelling, also the representation of the associated small-scale processes is improved. This leads generally to an improved agreement of the simulation results with observations, as seen for the COSMO_iso_7km run for Renland (Figure 4).

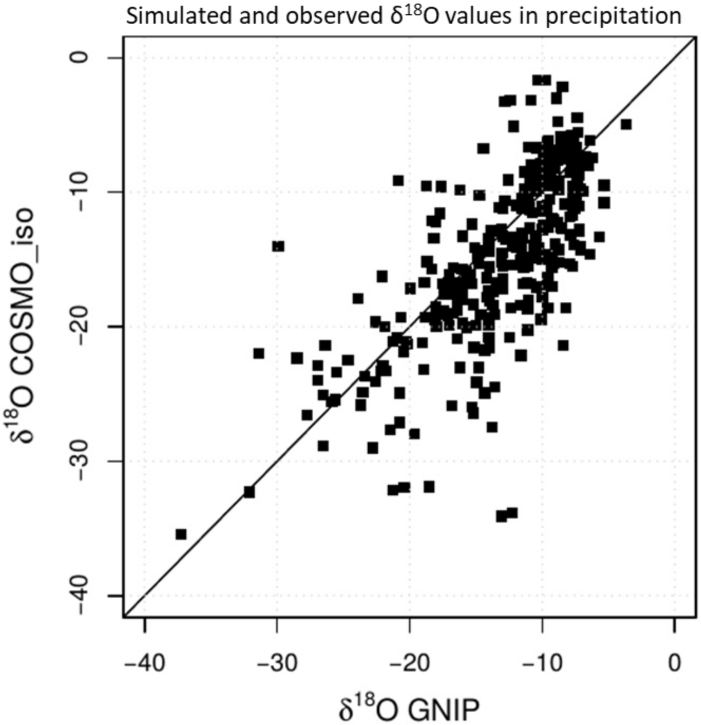

Figure 5: Monthly $\delta^{18}O$ simulated with COSMO_iso_50km for the period 2008 - 2014 and the corresponding observations for 9 GNIP stations (Table 1).

However, an increase in spatial resolution is also associated with an increased heterogeneity of the surface characteristics and the related small-scale processes, especially in complex terrains. This is because the GCM grid boxes are further divided in smaller RCM grid boxes and consequently higher as well as lower values (for e.g. altitude) are now included in the respective GCM grid boxes. As a consequence, an additional spatial variability is introduced in the RCM simulations in comparison to the GCM results. Due to uncertainties accompanied by model simulations, this can potentially increase the RCM bias with respect to in situ point measurements, which may actually be closer to the spatially averaged values simulated by the coarse GCM model. This effect can be observed for the SE-Dome ice core (19) in southeastern Greenland. Comparable to the Renland ice core, SE-Dome is located near the coastline. But in contrast to the Renland ice core, an increase in the spatial resolution to 7 km does not further improve the RCM results for SE-Dome. On the contrary, the $\delta^{18}O$ bias is even higher than in the ECHAM5-wiso simulation.

However, by performing higher resolved RCM simulations, the subgrid-scale variability of $\delta^{18}O$ within GCM grid boxes can be simulated and compared to observed $\delta^{18}O$ values. In this way, the inherent uncertainty of in situ measurements, associated with a local micrometeorological variability, can be considered. Thus, in the following, snow pit samples are not anymore solely compared to the model grid boxes covering the samples location. Instead, it is investigated whether the $\delta^{18}O$ range of all adjacent RCM grid boxes to a snow pit location is consistent with the observed $\delta^{18}O$ value of the same site. For this, all RCM grid boxes located within the corresponding GCM grid box are included in the comparison with the observations.

3.1.3 $\delta^{18}O$ variability

The spatial isotopic ratio variability of the COSMO_iso_50km grid boxes surrounding the 19 snow pit samples is shown as a Box-Whiskers-plot in Figure 6a. The spatial isotopic ratio variability of the COSMO_iso_7km is shown in Figure 6b. In this spatial isotopic ratio variability, the $\delta^{18}O$ values of all COSMO_iso (50 km) and COSMO_iso (7 km) grid boxes within the ECHAM5_wiso grid box closest to the snow pit sample, are included. For 14 of the 19 snow pit samples (1,2,3,4,5,6,7,8,14,15,16,17,18,19) the observed $\delta^{18}O$ values are within the range of the spatial COSMO_iso_50km grid box variability. But for 5 of the 19 snow pit samples (9-13) the spatial isotope range of the COSMO_iso_50km simulation does not fit with the observations. Since these stations are all located in the north of Greenland (Figure 3), this is most likely associated with the southward shift of the area of low yearly mean $\delta^{18}O$ values in central Northern Greenland in COSMO_iso_50km in comparison to ECHAM5-wiso, as already described in section 3.1.2.

A downscaling to 7 km does slightly increase the spread of the COSMO_iso results. But still, the observed $\delta^{18}O$ values from 5 of 19 snow pit samples are not covered within the modelled COSMO_iso_7km grid box variability (Figure 6b). Thus, a further downscaling to a spatial resolution of 7 km does not increase the accuracy of the simulated isotopic ratio spread within an ECHAM5-wiso grid box. In accordance with the missing benefits of the COSMO_iso_7km simulation and its increased computing time costs, only a COSMO_iso_50km simulation is performed for the mid-Holocene (section 3.2).

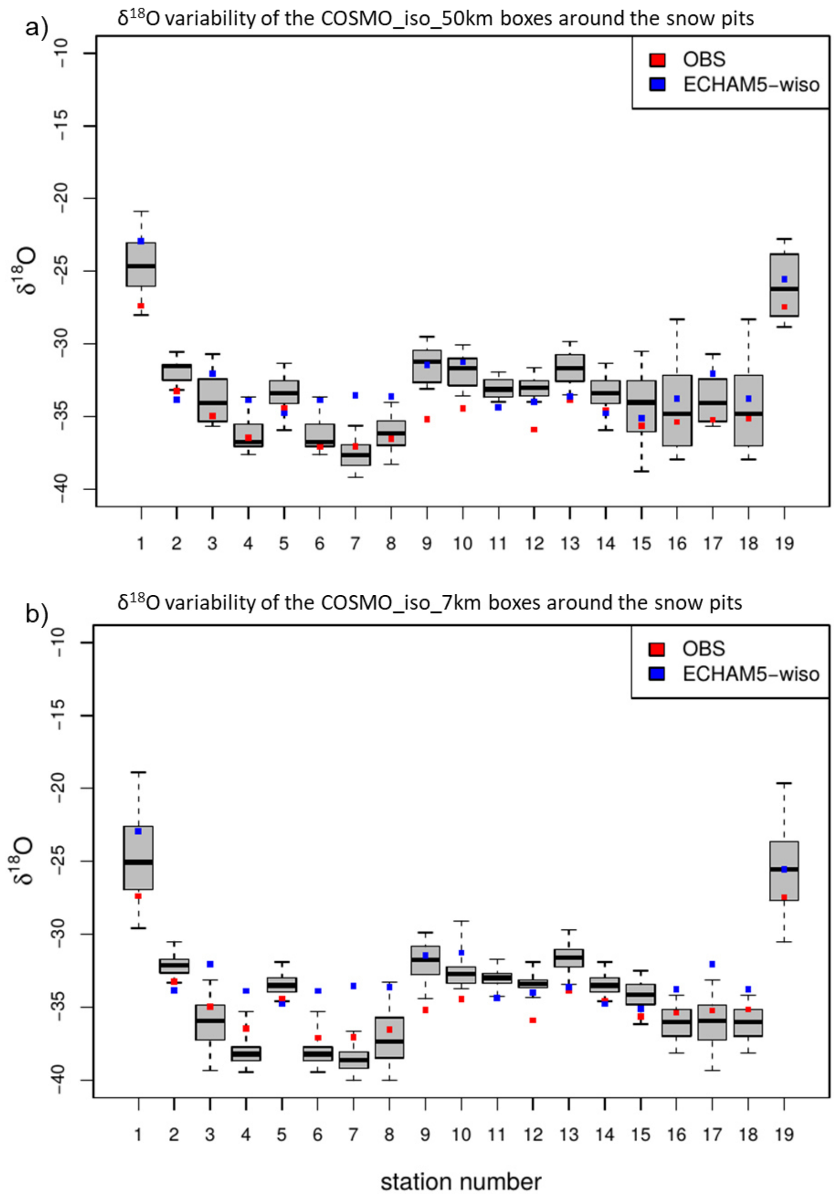

Figure 6: Present-day isotopic ratio variability of the COSMO_iso grid boxes, surrounding the 16 snow pit samples for the (a) 50 km and (b) 7 km simulation. The black bar in the Box-Whiskers-plot represents the median of the isotope ratio distribution. The box comprises the upper and lower quartile, the whiskers the whole distribution. The MPI-ESM-wiso results are shown by the blue dots and the observed $\delta^{18}O$ values are shown by the red dots.

The high spatial $\delta^{18}O$ variability in COSMO_iso simulations is also reflected in the spatial $\delta^{18}O$-temperature slope of the COSMO_iso_50km run (Figure 7c), a measure that is frequently used to analyze how strong isotope ratios and surface temperatures are interrelated. The spatial isotope-temperature slope constitutes a linear fit between the simulated $\delta^{18}O$ ratios and the surface temperatures at all COSMO_iso_50km grid boxes within the respective ECHAM5-wiso grid box. The spatial δ¹⁸O-temperature slope is high in Central Greenland and low at the coastline. In order to better understand these spatial δ¹⁸O-temperature patterns, both quantities affecting the spatial δ¹⁸O-temperature slope, i.e. the spatial δ¹⁸O variability and the spatial temperature variability, are explicitly analyzed in Figure 7a and Figure 7b. These spatial variabilities are calculated as the standard deviation of all COSMO_iso_50km grid boxes within the respective ECHAM5-wiso grid boxes.

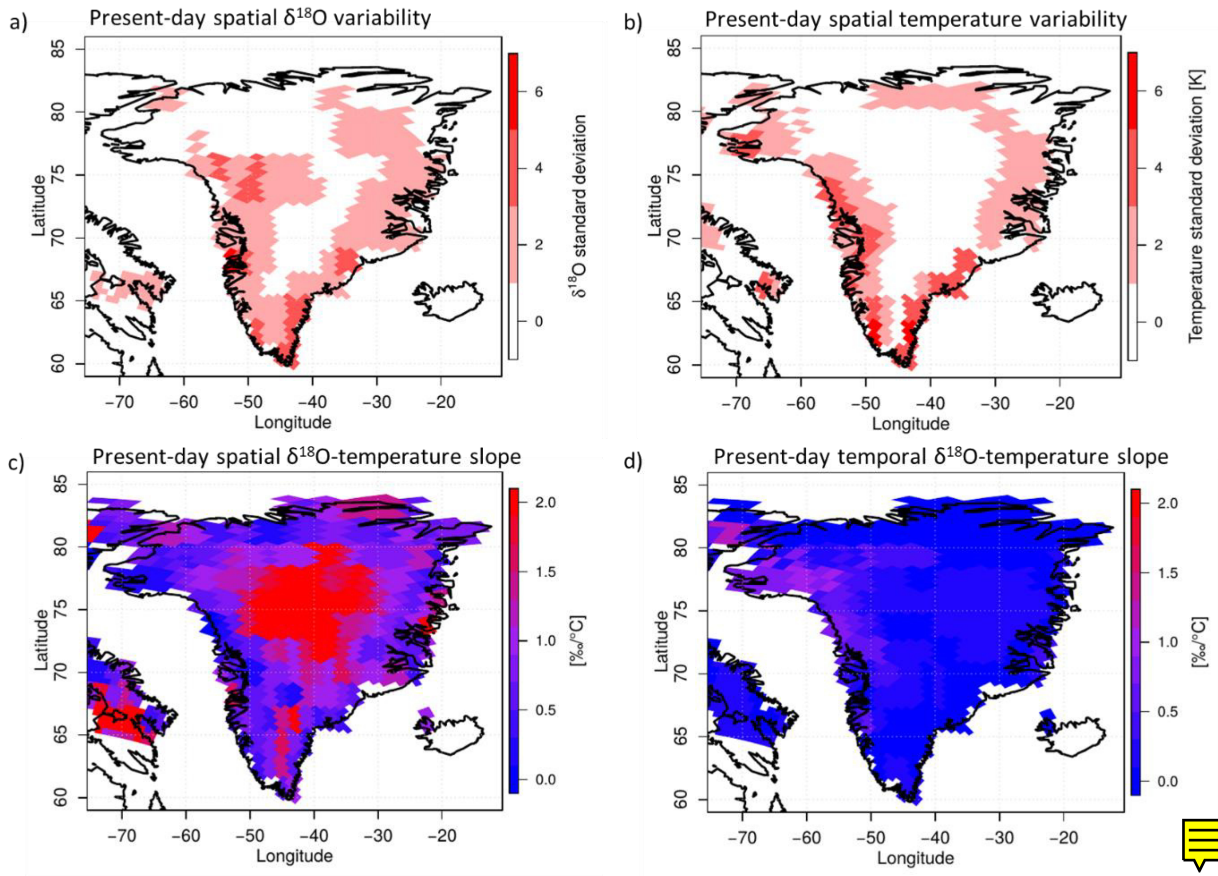

Figure 7: Present-day spatial subgrid-scale variability (calculated as standard deviation) of (a) δ¹⁸O and (b) surface temperature, derived from the COSMO_iso_50km grid boxes within the respective ECHAM5-wiso grid boxes for whole Greenland. Present-day (c) spatial and (d) interannual temporal δ¹⁸O-temperature slope for Greenland, based on yearly mean values.

Figure 7a shows that at the coastline, the spatial δ¹⁸O variability of COSMO_iso_50km is considerably increased within the ECHAM5-wiso grid boxes. In Central Greenland the increase in the spatial isotopic ratio variability is lower. Thus, the simulated spatial δ¹⁸O variability is high in regions where large orographic differences occur within short distances, like the coastal areas of Greenland, and lower for homogeneous terrain like the inland plateau. Nevertheless, widespread areas with higher spatial isotopic variability occur also in the inland plateau of Greenland. This is not the case for the spatial surface temperature variability. In Central Greenland almost no surface temperature variability occurs (Figure 7b). But near the coastline the spatial surface temperature variability is also high, highlighting how important the land surface characteristics are for the regional temperature variability. The low spatial $\delta^{18}O$-temperature slope at the coastline (Figure 7c) is therefore a result of a high surface temperature variability in this region counteracting the high $\delta^{18}O$ variability in the slope calculation. On the contrary, the $\delta^{18}O$-temperature slope is high in Central Greenland due to an increased $\delta^{18}O$ variability there, while the surface temperature variability is low. The spatial distribution of $\delta^{18}O$ consequently not only depends on land surface processes, but also on dynamic atmospheric processes. In this way, isotopic ratios based on atmospheric fractionation processes along the trajectory of an air mass, are transported to Central Greenland and increase there the isotopic variability.

In order to investigate the temporal interrelations between the isotope ratios and the surface temperature, the interannual temporal $\delta^{18}O$-temperature slope is calculated for the COSMO_iso_50km simulation, based on the yearly mean $\delta^{18}O$ and surface temperature values (Figure 7d). The interannual temporal $\delta^{18}O$-temperature slope is, in contrast to the spatial $\delta^{18}O$-temperature slope, very small all over Greenland, which is in accordance with the results of Sjolte et al., (2011). That means that the interannual $\delta^{18}O$ variability is less pronounced than the interannual surface temperature variability and both quantities are lowly correlated. The impact of interannual surface temperature variations on the temporal $\delta^{18}O$ variability is therefore small in Greenland.

3.2 Mid-Holocene

3.2.1 Comparison of simulated $\delta^{18}O$ data to ice core data

In contrast to the present-day simulations, for the mid-Holocene, COSMO_iso_50km is not anymore driven by ECHAM5-wiso, but by MPI-ESM-wiso. While in ECHAM5-wiso oceanic boundary conditions are prescribed by monthly varying sea surface temperatures and sea ice cover, ocean states are calculated internally in the fully-coupled atmosphere-ocean Earth-System-Model MPI-ESM-wiso. Systematic deviations between the COSMO_iso_50km simulations for mid-Holocene and present-day, caused by these different forcing approaches, therefore, cannot be excluded. For this reason, a comparison of the mid-Holocene $\delta^{18}O$ anomalies to the present-day conditions is omitted and an analysis is performed for simulated absolute $\delta^{18}O$ ratios and their differences to observed $\delta^{18}O$ values.

In Figure 8a the absolute differences of the simulated MPI-ESM-wiso (blue) and COSMO_iso_50km (green) grid box results to the observed $\delta^{18}O$ ratios at the corresponding ice cores are presented for the mid-Holocene. As in Figure 6, the spatial isotopic ratio variability of the COSMO_iso_50km grid boxes surrounding four Greenland ice core samples is shown as a Box-Whiskers-plot. MPI-ESM-wiso properly reflects the isotopic ratios of the mid-Holocene from ice core data. For the inland ice cores (GRIP, GISP2, NGRIP), the simulated $\delta^{18}O$ deviates only about 1 ‰ to the observations, at Renland the deviation is about 3 ‰. For GRIP and GISP2 the MPI-ESM-wiso simulations slightly underestimate the $\delta^{18}O$ ratios, for NGRIP and Renland, the $\delta^{18}O$ values are slightly overestimated.

COSMO_iso_50km simulates the opposite sign of MPI-ESM-wiso for the deviation of the $\delta^{18}O$ values to the observations at the inland ice cores. That means that in GRIP and GISP2, the underestimated $\delta^{18}O$ values in MPI-ESM-wiso are turned into overestimated $\delta^{18}O$ values in COSMO_iso_50km, at NGRIP the overestimation is turned into an underestimation, but the net bias is not reduced. At Renland, the bias is even increased. Thus, by just looking at the absolute biases, the downscaling does not seem to bring an added value to the MPI-ESM-wiso results for mid-Holocene conditions. But taking also into account the spatial isotopic ratio variability in the COSMO_iso_50km simulation, the model results are in agreement with the isotopic ratios of the ice core samples.

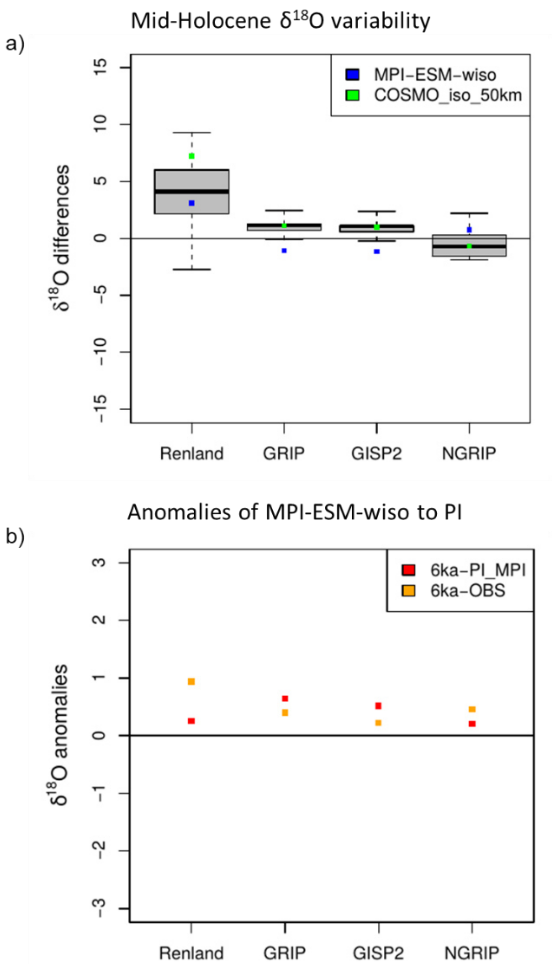

Figure 8: (a) mid-Holocene isotopic ratio variability of the COSMO_iso_50km grid boxes surrounding four Greenland ice core samples. In each grid box, the simulated δ^{18}O ratios are subtracted by the observed ratios in the ice cores. The black bar in the Box-Whiskers-plot represents the median of the isotope ratio distribution. The box comprises the upper and lower quartile, the whiskers the whole distribution. The MPI-ESM-wiso (blue dots) and COSMO_iso_50km (green dots) results for the grid points closest to the ice cores are also shown as differences to the observed δ^{18}O ratios. (b) the anomalies of the MPI-ESM-wiso simulation to the pre-industrial (PI) conditions, based on an MPI-ESM-wiso PI-reference simulation (Cauquoin et al., 2019) are shown in red dots, the observed mid-Holocene-PI anomalies in orange dots.

In Figure 8b, the MPI-ESM-wiso model anomalies with reference to the pre-industrial period (PI) conditions, which are based on an MPI-ESM-wiso PI-reference simulation performed by Cauquoin et al. (2019), are compared to the measured mid-Holocene-PI $\delta^{18}O$ anomalies of the ice cores. The positive $\delta^{18}O$ anomalies between mid-Holocene and PI for both ice core data and MPI-ESM-wiso model results are associated with higher temperatures, especially during the summer and a reduction in Arctic sea-ice during mid-Holocene (Cauquoin et al., 2019). In Renland and NGRIP simulated anomalies are slightly underestimated, in GRIP and GISP2 anomalies are slightly overestimated. But overall, the biases of the MPI-ESM-wiso mid-Holocene-PI model anomalies to the observed mid-Holocene-PI anomalies are for all ice cores very small.

3.2.2 $\delta^{18}O$ variability

The fact that, in contrast to the present-day simulations, only four observational data sets are available for the mid-Holocene, makes the assessment of the simulation results difficult. Moreover, the GRIP and GISP2 ice cores being located very close to each other (Figure 9), only three local isotope distributions clearly different from each other are available. Therefore, in Figure 9a, the spatial $\delta^{18}O$ variability of the COSMO_iso_50km simulation is illustrated for whole Greenland, which is, in accordance to the analysis of the present-day simulation, again calculated as the standard deviation of all COSMO_iso_50km grid boxes within the respective GCM grid boxes. In general, the $\delta^{18}O$ variability of COSMO_iso_50km in the mid-Holocene is high at the coastline, while it is lower in Central Greenland. The Renland ice core is consequently located in an area of a high isotopic variability, the GRIP and GISP2 ice cores in an area of low isotopic variability. But regions with increased isotopic variability occur also in the inland plateau of Greenland. The NGRIP ice core, for instance, is located in such an area of a moderate isotopic ratio variability. The four ice core drill sites are therefore located in three regions of Greenland with substantially different sub-grid isotopic ratio variabilities.

The spatial surface temperature variability in the COSMO_iso_50km mid-Holocene simulation is shown in Figure 9b. The mid-Holocene simulation shows a high spatial surface temperature variability near the coastline and almost no variability in Central Greenland. As a consequence, the spatial $\delta^{18}O$-temperature slope is low at the coastline and high in Central Greenland (Figure 9c). Moreover, the interannual $\delta^{18}O$-temperature slope is very small over Greenland in the mid-Holocene, although in some regions high temporal slopes are simulated (Figure 9d). But in principle, the influence of interannual surface temperature variations on the temporal $\delta^{18}O$ variability in the mid-Holocene is small.

In general, the results of the COSMO_iso_50km mid-Holocene simulation exhibit the same spatial characteristics as for the present-day simulation (Figure 7 and Figure 9). Comparable spatial patterns are simulated for the surface temperature variability (Figure 7b and Figure 9b) as well as the $\delta^{18}O$ variability (Figure 7a and Figure 9a) within a GCM grid box, although regions of increased $\delta^{18}O$ variability in Central Greenland are more widely present in the mid-Holocene run than in the present-day one. The contrast in the spatial $\delta^{18}O$-temperature slope between the coastal regions and the inland plateau is therefore in the mid-Holocene less clearly pronounced than under present-day conditions (Figure 7c and Figure 9c). Nevertheless, the spatial $\delta^{18}O$-temperature interrelations are in both periods comparable. This is also the case for the temporal variabilities of $\delta^{18}O$ and the surface temperature (Figure 7d and Figure 9d). This broad consistency in the

COSMO_iso_50km simulation results for the mid-Holocene and the present-day is remarkable, considering that both simulations are driven by two different forcing approaches (ECHAM5-wiso nudged to ERA-Interim reanalysis with prescribed monthly varying oceanic boundary conditions vs. the fully-coupled atmosphere-ocean Earth-System-Model MPI-ESM-wiso). This finding indicates that the spatial and interannual $\delta^{18}O$ variability of COSMO_iso_50km within a GCM grid box over Greenland is independent of the oceanic boundary conditions.

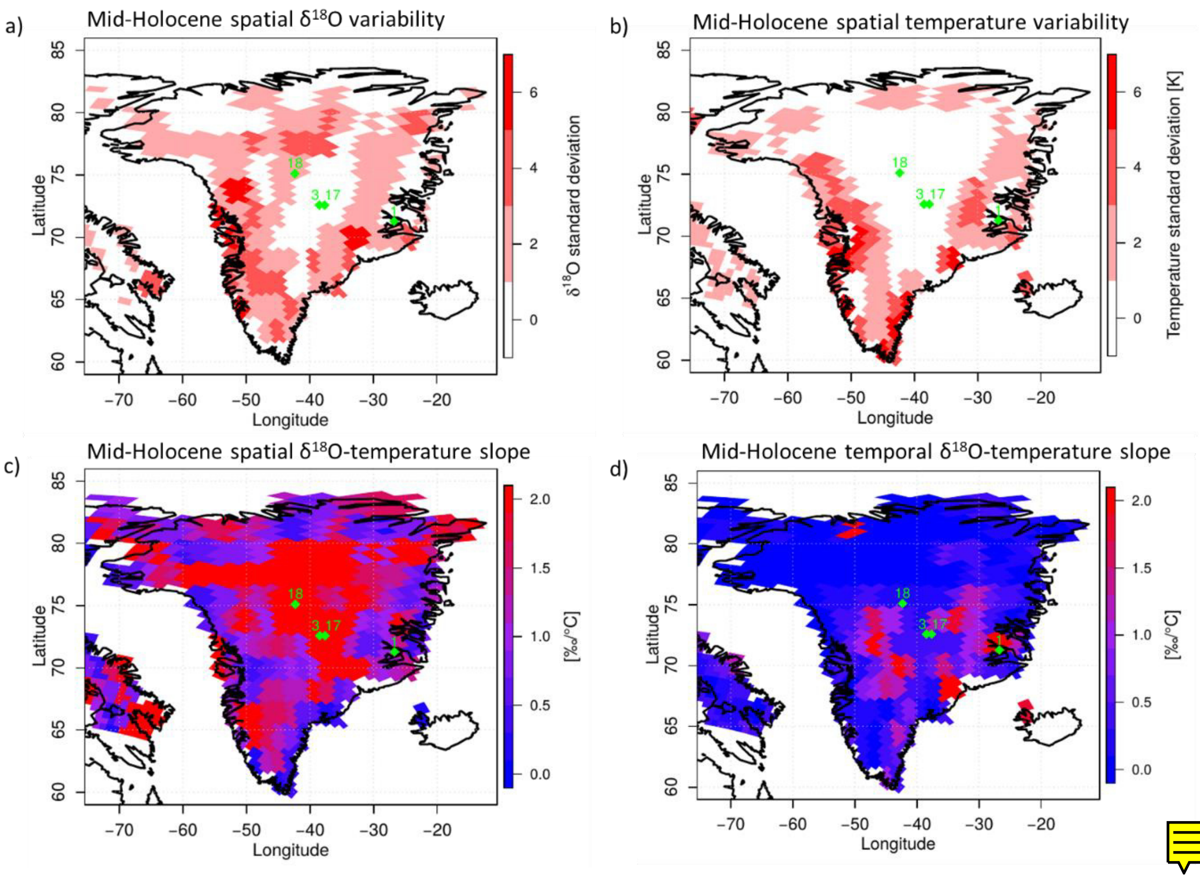

Figure 9: As Figure 7, but for the Mid-Holocene. The locations of the ice core samples are shown in blue.

4 Discussion and Conclusions

The results of several global paleo-climate simulations exhibit considerable deviations to the observed regional climate patterns during the Holocene (Braconnot et al., 2012). In the presented study, for the first time, regional climate simulations with an isotope-enabled RCM are performed for Greenland to potentially improve the agreement with climate observations in this region for the mid-Holocene. In a first step, the capability of the isotope-enabled RCM COSMO_iso to reproduce observed isotopic ratios for Greenland is demonstrated.

The COSMO_iso simulation results show that a spatial resolution of 50 km already leads to reasonable $\delta^{18}O$ values. Especially in regions where the global ECHAM5-wiso model, which has been used to derive necessary forcing fields for the COSMO_iso simulations, deviates strongly from the observed $\delta^{18}O$ values, the bias is considerably reduced by the regional climate simulation with COSMO_iso. In complex terrain like the coastal areas of Greenland, the results can be further improved with an additional downscaling to a spatial resolution of 7 km. In such simulations with high spatial resolution, small-scale processes are described in more detail (e.g. Torma et al., 2015; Coppola et al., 2018) and thus the local characteristics at ice core sites are better taken into account (Sturm et al., 2005; Werner et al., 2011). But for northern Greenland, regional climate simulations with COSMO_iso increase the bias with respect to observations. A comparison of simulated isotope ratios in precipitation with measured values at GNIP stations shows that such deviations between model results and observations are not caused by systematic seasonal biases in the RCM, as it was simulated by Sjolte et al., (2011) for Greenland. In central northern Greenland, rather a model bias is introduced, due to a southward shift of the area of low yearly mean $\delta^{18}O$ values. But all in all, the results of this study show that COSMO_iso is generally able to provide reasonable isotopic ratios for Greenland and the model can be applied for paleo-climate simulations.

For the mid-Holocene, MPI-ESM-wiso is in good agreement with observed ice core data in Greenland, as already described by Cauquoin et al. (2019). The model bias is, in this context, not further reduced by a downscaling with COSMO_iso. But an increase in the spatial model resolution leads also to an increase in the models' degrees of freedom. This in turn can lead to additional noise and thus, a deviating RCM behaviour with even an increase in the absolute model bias, as seen for the Renland station.

Another consequence of these increased degrees of freedom in the COSMO_iso simulation is that the spatial variability of the simulated $\delta^{18}O$ ratios is enhanced. This enhanced spatial variability represents the subgrid-scale uncertainty of the driving GCM, which can be derived in a physically consistent way by a regional downscaling. Now, by analysing this subgrid-scale variability, the spatial uncertainties in the comparison between GCM data and point measurements can be considered. In this way, it can be demonstrated that most of the observed $\delta^{18}O$ values lie within the local $\delta^{18}O$ uncertainties of the coarse GCM results. This applies for both, the present-day runs and the regional paleo-climate simulations for the mid-Holocene in Greenland. The deviation between the coarser resolved GCM results and the finer resolved observations is therefore potentially caused by the missing representation of important small-scale processes, which are induced by e.g. the surface conditions or orographic effects over Greenland. Shi et al., (2020), for instance, were able to demonstrate that GCM deficiencies to reproduce the observed water isotope variability in the southeastern Tibetan Plateau are associated with the missing representation of such small-scale processes in coarse GCM simulations.

As $\delta^{18}O$ 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 $\delta^{18}O$

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.

Consistent structures over Greenland are also modelled for the interannual temporal δ¹⁸O-temperature slope in the mid-Holocene and the present-day simulation. But in comparison to the spatial δ¹⁸O-temperature slope, the interannual temporal interrelations between the surface temperature and δ¹⁸O are rather small. This weaker interannual δ¹⁸O-temperature slope is again in line with the results of Sjolte et al. (2011).

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. This approach might also be very helpful for other isotope-enabled GCMs and their deviations to observed isotope ratios in different paleo-time periods and regions. Particularly in regions, in which large differences occur between simulated and observed δ¹⁸O ratios, due to small-scale orographic variations, like parts of Europe and North America (Cauquoin et al., 2019; Comas-Bru et al., 2019), an improved representation of small-scale processes can potentially reduce these biases, and consequently, the reconstruction of regional paleo-climate patterns can become more reliable. To test this hypothesis, in follow-up studies, more time slices will be simulated with the presented MPI-ESM-wiso – COSMO_iso model chain for different periods and different regions.

Code availability. The isotope-enabled version COSMO_iso is available upon request from Marcus Breil. The code of the isotopic version MPI-ESM-wiso is available upon request on the AWI's GitLab repository (https://gitlab.awi.de/mwerner/mpi-esm-wiso, Cauquoin et al., 2019).

Author contributions. MB performed the COSMO_iso mid-Holocene simulations, EC the COSMO_iso present-day simulation. The ECHAM5-wiso simulations were performed by MW, the MPI-ESM-wiso simulations by AC. MB analysed the presented model results and wrote the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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References

Aemisegger, F., J. K. Spiegel, S. Pfahl, H. Sodemann, W. Eugster, and H. Wernli: Isotope meteorology of cold front passages: A case study combining observations and modeling, *Geophysical Research Letters*, 42(13), 5652–5660, doi:10.1002/2015GL063988, 2015.

Ambach, W., Dansgaard, W., Eisner, H., and Moller, J.: The altitude effect on the isotopic composition of precipitation and glacier ice in the Alps, Tellus, 20, 595–600, doi:10.1111/j.2153-3490.1968.tb00402.x, 1968.

Baldauf M, Seifert A, Förstner J, Majewski D, Raschendorfer M: Operational convective-scale numerical weather prediction with the COSMO model: description and sensitivities. *Mon Weather Rev,* 139:3887−3905, 2011.

Bonne, J. L., and Coauthors: Resolving the controls of water vapour isotopes in the Atlantic sector. *Nature communications*, *10*(1), 1632, 2019.

Braconnot, P., and Coauthors: Evaluation of climate models using palaeoclimatic data. *Nature Climate Change*, *2*(6), 417, 2012.

Cauquoin, A., Werner, M. and Lohmann, G.: Water isotopes – climate relationships for the mid-Holocene and pre-industrial period simulated with an isotope-enabled version of MPI-ESM, *Clim. Past*, 15, 1913-1937, doi:10.5194/cp-15-1913-2019, 2019.

Comas-Bru, L., Harrison, S. P., Werner, M., Rehfeld, K., Scroxton, N., Veiga-Pires, C., and SISAL working group members: Evaluating model outputs using integrated global speleothem records of climate change since the last glacial, *Clim. Past*, 15, 1557–1579, https://doi.org/10.5194/cp-15-1557-2019, 2019.

Coppola, E., and Coauthors: A first-of-its-kind multi-model convection permitting ensemble for investigating convective phenomena over Europe and the Mediterranean. *Climate Dynamics*, 1-32, 2018.

Craig, H., and Gordon, L. I.: Deuterium and oxygen 18 variations in the ocean and marine atmosphere, Stable isotopes in oceanographic studies and paleotemperatures, 23. Pisa, Italy: Conoglio Nazionale delle Richerche, Labortorio di Geologia Nucleare, 1965.

Christner, E., M. Kohler, and M. Schneider: The influence of snow sublimation and meltwater evaporation on dD of water vapor in the atmospheric boundary layer of central Europe, *Atmospheric Chemistry and Physics*, 17(2), 1207–1225, doi:10.5194/acp-17-1207-2017, 2017.

Christner, E., and Coauthors: The climatological impacts of continental surface evaporation, rainout, and subcloud processes on δD of water vapor and precipitation in Europe. *Journal of Geophysical Research: Atmospheres*, *123*(8), 4390-4409, 2018.

Dansgaard, W.: The abundance of O18 in atmospheric water and water vapour. *Tellus*, *5*(4), 461-469, 1953.

Dansgaard, W.: Stable isotopes in precipitation. *Tellus*, *16*(4), 436-468, 1964.

Dansgaard, W., Johnsen, S. J., Møller, J., and Langway, C. C.: One thousand centuries of climatic record from Camp Century on the Greenland ice sheet. *Science*, *166*(3903), 377-380, 1969.

Dee, D. P., and Coauthors: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the royal meteorological society*, *137*(656), 553-597, 2011.

Dütsch, M.: Stable water isotope fractionation processes in weather systems and their influence on isotopic variability on different time scales. Diss no. 23939, Ph.D. thesis, ETH Zurich, 2017.

Felzer, B., and Thompson, S. L.: Evaluation of a regional climate model for paleoclimate applications in the Arctic. *Journal of Geophysical Research: Atmospheres*, *106*(D21), 27407-27424, 2001.

Fischer, H., and Coauthors: Little ice age clearly recorded in northern Greenland ice cores. *Geophysical Research Letters*, *25*(10), 1749-1752, 1998.

Fischer, H.: Stable oxygen isotopes on snow pit ngt01C93 from the North Greenland Traverse. doi:10.1594/PANGAEA.133399, 2003.

Fischer, N., and Jungclaus, J. H.: Evolution of the seasonal temperature cycle in a transient Holocene simulation: orbital forcing and sea-ice. *Climate of the Past*, *7*, 1139-1148, 2011.

Furukawa, R., Uemura, R., Fujita, K., Sjolte, J., Yoshimura, K., Matoba, S., & Iizuka, Y.: Seasonal-Scale Dating of a Shallow Ice Core From Greenland Using Oxygen Isotope Matching Between Data and Simulation. *Journal of Geophysical Research: Atmospheres*, *122*(20), 10-873, 2017.

Gat, J. R.: Oxygen and hydrogen isotopes in the hydrological cycle. *Annual Review of Earth and Planetary Sciences*,24(1), 225–262.https://doi.org/10.1146/annurev.earth.24.1.225, 1996.

Grootes, P. M., and Stuiver, M.: Oxygen 18/16 variability in Greenland snow and ice with 10− 3-to 105-year time resolution. *Journal of Geophysical Research: Oceans*, *102*(C12), 26455-26470, 1997.

Gurney, S. D., and Lawrence, D. S. L.: Seasonal trends in the stable isotopic composition of snow and meltwater runoff in a subarctic catchment at Okstindan, Norway. *Hydrology Research*, *35*(2), 119-137, 2004.

Harrison, S. P., and Coauthors: Climate model benchmarking with glacial and mid-Holocene climates. *Climate Dynamics*, *43*(3-4), 671-688, 2014.

IAEA/WMO (2016), http://www-naweb.iaea.org/napc/ih/IHS resources gnip.html.

Johnsen, S. J., Clausen, H. B., Cuffey, K. M., Hoffmann, G., Schwander, J., & Creyts, T.: Diffusion of stable isotopes in polar firn and ice: the isotope effect in firn diffusion. In *Physics of ice core records* (pp. 121-140). Hokkaido University Press, 2000.

Jost, A., Lunt, D., Kageyama, M., Abe-Ouchi, A., Peyron, O., Valdes, P. J., and Ramstein, G.: High-resolution simulations of the last glacial maximum climate over Europe: a solution to discrepancies with continental palaeoclimatic reconstructions?. *Climate Dynamics*, *24*(6), 577-590, 2005.

Jouzel, J., and Merlivat, L.: Deuterium and oxygen 18 in precipitation: Modeling of the isotopic effects during snow formation. *Journal of Geophysical Research: Atmospheres*, *89*(D7), 11749-11757, 1984.

Jouzel, J.: A brief history of ice core science over the last 50 yr, *Clim. Past*, 9, 2525–2547, 2013.

Jungclaus, J. H., Fischer, N., Haak, H., Lohmann, K., Marotzke,J., Matei, D., Mikolajewicz, U., Notz, D., and von Storch, J. S.: Characteristics of the ocean simulations in the Max Planck Institute Ocean Model (MPIOM) the ocean component of the MPI-Earth system model, J. Adv. Model. Earth Sy., 5, 422–446,https://doi.org/10.1002/jame.20023, 2013.

Kageyama, M., and Coauthors: The PMIP4 contribution to CMIP6–Part 1: Overview and over-arching analysis plan, *Geosci. Model Dev*., 11, 1033–1057, 2018.

Karremann, M.K., and Schädler, G.: Parametrisation of variables having an impact on the Greenland surface mass balance using regional climate model simulations, to be submitted to Atmosphere.

Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C.: A reconstruction of regional and global temperature for the past 11,300 years. *Science*, *339*(6124), 1198-1201, 2013.

Masson-Delmotte, V., and Coauthors: GRIP deuterium excess reveals rapid and orbital-scale changes in Greenland moisture origin. *Science*, *309*(5731), 118-121, 2005.

Masson-Delmotte, V., and Coauthors: Recent changes in north-west Greenland climate documented by NEEM shallow ice core data and simulations, and implications for past-temperature reconstructions. The Cryosphere Discussions, Copernicus, 2015, pp.1481-1504. 10.5194/tc-9-1481-2015, 2015.

Merlivat, L., and Jouzel, J.: Global climatic interpretation of the deuterium-oxygen 18 relationship for precipitation. *Journal of Geophysical Research: Oceans*, *84*(C8), 5029-5033, 1979.

Moossen, H., Bendle, J., Seki, O., Quillmann, U., and Kawamura, K.: North Atlantic Holocene climate evolution recorded by high-resolution terrestrial and marine biomarker records. *Quaternary Science Reviews*, *129*, 111-127, 2015.

Pfahl, S., Wernli, H., and Yoshimura, K.: The isotopic composition of precipitation from a winter storm–a case study with the limited-area model COSMOiso. *Atmos. Chem. Phys*, *12*(3), 1629-1648, 2012.

Rockel, B., Will, A., and Hense, A.: The regional climate model COSMO-CLM (CCLM). *Meteorologische Zeitschrift*, *17*(4), 347-348, 2008.

Schrodin, R., and E. Heise: The multi-layer version of the DWD soil model TERRA-LM, Consortium for Small-Scale Modelling (COSMO) Tech. Rep., 2, 16, 2001.

Shi, X., and Coauthors: Variability of isotope composition of precipitation in the Southeastern Tibetan Plateau from the synoptic to seasonal time scale. *Journal of Geophysical Research: Atmospheres*, *125*(6), e2019JD031751, 2020.

Sjolte, J., Hoffmann, G., Johnsen, S. J., Vinther, B. M., Masson-Delmotte, V., and Sturm, C.: Modeling the water isotopes in Greenland precipitation 1959–2001 with the meso-scale model REMO-iso. *Journal of Geophysical Research: Atmospheres*, *116*(D18), 2011.

Smith, R. S., and Gregory, J.: The last glacial cycle: transient simulations with an AOGCM. *Climate dynamics*, *38*(7-8), 1545-1559, 2012.

Steen-Larsen, H. C., and Coauthors: What controls the isotopic composition of Greenland surface snow? *Climate of the Past*, 10(1), 377–392, 2014.

Steig, E. J., and Coauthors: High-resolution ice cores from US ITASE (West Antarctica): development and validation of chronologies and determination of precision and accuracy. *Annals of Glaciology*, *41*, 77-84, 2005.

Stevens, B., and Coauthors: Atmospheric component of the MPI-M earth system model: ECHAM6. *Journal of Advances in Modeling Earth Systems*, *5*(2), 146-172, 2013.

Sturm, K., Hoffmann, G., Langmann, B., and Stichler, W.: Simulation of δ18O in precipitation by the regional circulation model REMOiso. *Hydrological Processes: An International Journal*, *19*(17), 3425-3444, 2005.

Sturm, C., Hoffmann, G., and Langmann, B.: Simulation of the stable water isotopes in precipitation over South America: Comparing regional to global circulation models. *Journal of climate*, *20*(15), 3730-3750, 2007.

Timm, O., and Timmermann, A.: Simulation of the last 21 000 years using accelerated transient boundary conditions. *Journal of Climate*, *20*(17), 4377-4401, 2007.

Torma, C., Giorgi, F., and Coppola, E.: Added value of regional climate modeling over areas characterized by complex terrain—Precipitation over the Alps. *Journal of Geophysical Research: Atmospheres*, *120*(9), 3957-3972, 2015.

Vinther, B. M., and Coauthors: A synchronized dating of three Greenland ice cores throughout the Holocene. *Journal of Geophysical Research: Atmospheres*, *111*(D13), 2006.

Vinther, B. M., and Coauthors: Synchronizing ice cores from the Renland and Agassiz ice caps to the Greenland Ice Core Chronology. *Journal of Geophysical Research: Atmospheres*, *113*(D8), 2008.

von Storch, H., H. Langenberg, and F. Feser: A Spectral Nudging Technique for Dynamical Downscaling Purposes, *Monthly Weather Review*, 128(10), 3664–3673, doi:10.1175/1520-0493(2000)128¡3664:ASNTFD¿2.0.CO;2, 2000.

Weißbach, S., A. Wegner, T. Opel, H. Oerter, B. M. Vinther, and S. Kipfstuhl: Accumulation rate and stable oxygen isotope ratios of the ice cores from the North Greenland Traverse, doi:10.1594/PANGAEA.849161, 2016a.

Weißbach, S., Wegner, A., Opel, T., Oerter, H., Vinther, B. M., and Kipfstuhl, S.: Spatial and temporal oxygen isotope variability in northern Greenland–implications for a new climate record over the past millennium. *Climate of the Past*, *12*, 171-188, 2016b.

Werner, M., Langebroek, P. M., Carlsen, T., Herold, M., and Lohmann, G.: Stable water isotopes in the ECHAM5 general circulation model: Toward high-resolution isotope modeling on a global scale. *Journal of Geophysical Research: Atmospheres*, *116*(D15), 2011.

Yoshimori, M., and Suzuki, M.: The relevance of mid-Holocene Arctic warming to the future. *Climate of the Past*, *15*(4), 1375-1394, 2019.