

Review: The dependency of the $\delta^{18}\text{O}$ 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. 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.
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.

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.
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.
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.

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"
2. **Lines 7-9:** The authors should mention here the motivation and purpose of the study, which is described well in the introduction section.
3. **Line 9:** Change "isotopic ratios in Greenland" to "isotopic ratios in Greenland ice cores".
4. **Line 10:** Explain that ECHAM5-wiso and MPI-ESM-wiso are GCM simulations and spell out acronyms.
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."
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."
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.
8. **Lines 70-75:** The text here repeats some information that was mentioned earlier. Suggest revising to avoid repetition.
9. **Line 92:** It should be first noted here that snow surface albedo is fixed and is not spatially and temporally variable.
10. **Lines 120-144:** How are the ocean boundary conditions specified? Are these from reanalysis data?

11. **Line 111:** What is meant by “the models”? Please clarify.
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.
13. **Lines 123-124:** Note the domain boundaries for the Arctic simulation.
14. **Lines 128-130:** Is this an additional simulation forced by the coarse resolution run, or a nested domain within the larger domain?
15. **Line 130:** What is meant by “technical reasons”? Please clarify.
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.
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.
18. **Line 183:** What is the average reduction in the bias?
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.
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.
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.
22. **Lines 251-257:** This paragraph would more appropriately follow the first paragraph of the section, detailing the mid-Holocene results.
23. **Figure 4:** The y-axis label is confusing. Suggest changing to $\delta^{18}\text{O}$ difference. In the caption labels, suggest replacing with MPI_ESM_wiso – obs. and COSMO_iso_50km – obs.

24. **Line 261:** Is the green point for the 50 km grid cell closest to the measurement location? Please clarify.
25. **Line 263:** Spell out PI.
26. **Lines 266 – 294:** I suggest making this a new section, discussing sub-ESM-grid variability.
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.
28. **Line 294:** Change “the same mechanisms” to “similar mechanisms”.
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 “ $\delta^{18}\text{O}$ standard deviation” and “temperature standard deviation [K]” for clarity.
30. **Line 301:** Change “Simulated variability” to “simulated sub-grid-scale variability”.
31. **Figure 6:** This colormap is likely not suitable for red-green colorblind readers. Suggest using a different colormap.
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.
33. **Line 343:** Suggest changing “The same” to “Similar”.
34. **Line 358:** Change “prove” to “test”.

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,...”
2. **Line 13:** Change “a downscaling” to “dynamical downscaling” for clarity.
3. **Lines 14-15:** Revise to “yields improvements only for coastal areas with complex terrain.”
4. **Line 19:** Change “already on a high level” to “already agrees well with observations”
5. **Line 26:** Change “deviations to” to “deviations relative to”
6. **Line 32:** Change “like past changes of temperature, out of” to “such as past temperature changes using”
7. **Line 37:** Change “was steadily rising” to “steadily rose”
8. **Line 39:** Change “were steadily decreasing” to “steadily decreased”.
9. **Line 40:** Change “took place” to “had taken place”.
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...”
11. **Line 43:** Change “processes, leading to this warming,” to “processes leading to this warming...”

12. **Line 44:** Suggest changing “reflect” to “reproduce”.
13. **Line 46:** Remove “which are” before “documented in”.
14. **Line 51:** Suggest changing “does not meet” to “does not reproduce” or “does not adequately represent”
15. **Line 54:** Change “also often not entirely resolved” to “not well resolved” and “coarsely resolved GCMs” to “coarse resolution GCMs”
16. **Line 56:** Change “deviations to” to “deviations relative to”
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.
18. **Line 67:** Change “separated” to “separate”.
19. **Line 82:** Spell out “COSMO”.
20. **Line 87:** Change “presented” to “present”.
21. **Line 100:** Change “2 m temperature” to “2 m air temperature” for clarity.
22. **Line 114:** Add “the” before “best agreement”
23. **Line 121:** Change “reflect” to “reproduce”.
24. **Line 134:** Change “simulation has been” to “simulation is”
25. **Line 138:** Is the improvement to surface albedo for all surface types or one particular surface type?
26. **Line 147:** Perhaps remove “different” from before “different observational data”.
27. **Line 151:** Remove “used” before “ $\delta^{18}\text{O}$ values”.
28. **Line 172:** Change “models capability” to “models’ capability”.
29. **Line 175:** Change “decline stronger” to “decline more rapidly”.
30. **Line 179:** Change “stronger pronounced” to “more pronounced.
31. **Line 181:** Change “at which” to “for which”.
32. **Line 182:** Change “deviations to” to “deviations from”.
33. **Line 185:** Change “results anymore” to “results further”.
34. **Line 188:** Change “a complex terrain” to “complex terrain”
35. **Line 194:** Change “a higher agreement” to “an improved agreement”.
36. **Line 196:** Change “an enlarged heterogeneity” to “an increased heterogeneity”.
37. **Line 236:** Change “differences for” to “differences between” and “grid box results to the” to “grid box results and the”
38. **Line 238:** Change “shown as Box-Whiskers” to “shown as a Box-Whiskers”.
39. **Lines 277-278:** Change “the three regions...” to “in three regions of Greenland with substantially different sub-pixel isotopic ratio variabilities.”
40. **Line 281:** Change “exhibiting also regional variations” to “which also exhibits regional variations...”
41. **Line 283:** Change “does consequently not only depend” to “consequently not only depends”
42. **Line 313:** Change “agreement to climate” to “agreement with climate”
43. **Lines 322-324:** Revise to “But for northern Greenland, regional climate simulations with COSMO_iso increase the bias with respect to observations and