Authors response on Referee Comment tc-2021-63-RC2

May 21, 2021

1 General comments

Specifically, I find that the methods section is difficult for non-experts to follow, and in particular I find that the current version of the manuscript lacks a description of the authors' logic behind the overall analysis and modeling strategy. This could probably be solved by some rework of each of the method sections to be organized in a logical way as to clearly lead the reader through the authors' reasoning. For example, the addition of a summary paragraph with an introduction of the method steps at the beginning of section 2 and a few sentences at the beginning of each section indicating the purpose of the described methods step would really help ground the reader for each part of the study. Overall, I find that the data and methods section is the most difficult to comprehend, since it seems to lack logical flow. Either adding some more context to lead the reader, or adding something like a flow chart for reference to show the methods graphically, would improve the manuscript greatly. Many of my questions and suggestions stem from vagueness within and my confusion about the written description of the methods.

Author response: Thank you for this valuable feedback on the lacking guidance and logical flow throughout the methods section. We will follow your suggestions in the revised version of our manuscript by incorporating a flow-chart to provide an overview of the work-flow leading to our results. We will further introduce a summarizing paragraph in the beginning of section 2 where we intend to outline why the individual steps are necessary and provide the context for the following sections. As you also suggested, we will make the transitions between the subsections smoother and more logic by adding a few sentences providing the context. We hope that this will improve the reading flow and guidance through the text and ultimately improve the quality of the paper.

2 Specific comments

- Line 30: Please specify "snow" or "source" deposition

  Author response: We will change it to "snow deposition".

- Line 32: "where" → "so" or "therefore" or something similar

  Author response: We will replace "where" with "so".

- Line 38: Can you define here what you mean by "non-climatic" within the text? As is, the sentence is confusing since you describe variability in climatic variables as "non-climatic". I think you are technically referring to non "local" climate effects.

Author response: Thank you for pointing out the lack of clarity here. We will rephrase this section as follows:

original:

The spatial variation in accumulation rate, surface temperature and atmospheric pressure in the upstream area can introduce non-climatic imprints in the ice core (e.g. Koutnik et al., 2016; Fudge et al., 2020).

revised:

The spatial variation in accumulation rate, surface temperature and atmospheric pressure in the upstream area can introduce climatic imprints in the ice core record which stem from the advection of ice deposited under different atmospheric conditions. The ice core signal is thus a combination of temporal and spatial variations in climatic components (Koutnik et al., 2016; Fudge et al., 2020) and information on the source characteristics is necessary to interpret ice core measurements within the climatic context.

- Line 40: "parameter" sounds like something from a model instead of the physical characteristic of the ice. Maybe "measurement" or "properties" or something similar?

  Author response: Yes, we agree. We will replace 'parameter' with 'quantity' here and make sure that 'parameter' is only used if related to the model throughout the manuscript.

- Line 57: "upstream effects... quantities". It is not clear to me what this sentence means. It would be more impactful if you clearly spelled out and expanded upon for the reader how your results can inform future studies.

  Author response: Thank you for pointing out that this is not clear enough. We will rephrase this part as follows:

  original:

  The results presented here serve as a basis for corrections of upstream effects in various chemical and physical quantities.

  revised:

  The source characteristics presented here form a basis to correct for upstream effects in various chemical and physical quantities of the EastGRIP ice core. These corrections are important to remove any climatic bias in ice-core measurements which are currently analyzed and will become available in the future.

- Line 60: As mentioned above, a brief upper-level description of your methods/strategy would help bring all the below sections together for the reader. In addition, every section in part 2 might also benefit from an introductory sentence or two to describe the motivation for the methods described in the given section and to give context to how it follows from the previously described method steps. Or, even something like a methods flow chart with inputs and outputs as well as the order of your method steps could help convey the information I feel is missing in this section.

Author response: Thanks a lot for this input. We will follow your suggestions and implement a flow chart which shows the work flow and guides the reader through this section. We will also add a summarizing paragraph in the beginning of Section 2. The rest of the methods section will be restructured as follows: 2.1) Description of the flow line derivation and the selection of RES images approximating the flow line derived from satellite based surface velocities. 2.2) Extension of the EastGRIP chronology. 2.3) Tracing and dating of the isochrones. 2.4) Full description of the ice flow model, including the climate model. 2.5) Expanded description on the Monte Carlo method.

- Line 72: I suggest that the information in paragraph 3 of this section (line 3) introducing the radar data be placed before paragraph 2 here, to add context to the flightline discussion.

  Author response: Thank you for this suggestion. We will move the information from line 119-126 to section 2.1.

- Lines 83 and 86: References to paper in preparation are not appropriate.

  Author response: The referenced paper is available as preprint now and will be cited accordingly.

- Lines 94-96: I think you are saying here that the Mojtabavi et al. (2020) paper is motivating and informing this work, and for this study you extend the analysis through the depth reached by 2019 (which is from 49.ka b2k). But it took me many times reading these sentences to understand that relationship. Please try to rephrase so that the relationship between the past work and what is done is this study is clear to the reader (especially readers who might not be experts in ice core analysis).

  Author response: Thank you for pointing out that this relationship is unclear. We have built up on the work by Mojtabavi et al. (2020) and extended their timescale to the current EastGRIP depth in order to date the isochrones observed in the radargrams. We will rephrase this section as follows:

  original:

  Mojtabavi et al. (2020) synchronized the EastGRIP and NorthGRIP ice cores for the last 15 kyr in order to apply the Greenland Ice Core Chronology 2005 (GICC05 Andersen et al., 2006) to EastGRIP. By 2019, the ice-core drilling progressed down to 2,122.45 m, allowing us to extend the time scale to 49.2 ka b2k (thousands of years before 2000 CE).

  revised:

  The validation of our modeling results and the correct dating of isochrones requires a reliable depth-age scale. The Greenland Ice Core Chronology 2005 (GICC05 Vinther et al., 2006; Rasmussen et al., 2006; Andersen et al., 2006; Svensson et al., 2006) is based on annual layer counting in various Greenland ice cores. It has been transferred to GRIP and other deep drilling sites in Greenland by synchronizing the ice cores with each other using horizons of e.g. volcanic origin (Rasmussen et al., 2008; Seierstad et al., 2014). The upper 1,383.84 m of the EastGRIP ice core were drilled between 2015 and 2018, and synchronized with the NorthGRIP ice core in previous work by Mojtabavi et al. (2020) to transfer the GICC05 chronology to EastGRIP.

By 2019, the ice-core drilling progressed down to 2,122.45 m, allowing us to extend the existing time scale from 15 ka to 49.9 ka b2k (thousands of years before 2000 CE). As part of the present study we identified common isochrones between EastGRIP, NorthGRIP and NEEM to transfer the GICC05 chronology to the part of the EastGRIP record which is not yet synchronized. This involved the same methods applied to NEEM by Rasmussen et al. (2013) and to the upper 1,383.84 m of EastGRIP by Mojtabavi et al. (2020).

- Line 104: "termination of the Greenland Stadial (GS) 2"

  Author response: We will introduce the missing abbreviation here, thank you for noticing it.

- Line 118: As for the other sections, some summary sentences motivating why you need to do this step and the context of how it informs the following steps would be highly appreciated. The way it is written now, that knowledge is assumed and the transition from the previous section to this section is very abrupt.

  Author response: Thanks again for this input. We agree that this section requires some restructuring and smoother transitions to ensure the reading flow and guidance of readers outside of the ice-core community. We will add the following information in the beginning of the section:

  The depth-age relationship from ice core chronologies can be extended in the lateral plane by tracing and dating of isochrones in RES images. The depth of these isochrones along the EastGRIP flow lines is part of the observed data used to tune the ice flow model parameters in the Monte Carlo inversion.

- Line 127: Which Matlab program is used?

  Author response: The Matlab program we used is called "picking tool" and was developed by Aslak Grinsted. It is not publicly available and we will mention it in the revised version of the manuscript. Thank you for pointing it out.

- Lines 129: "subsequent" → "subsequently"

  Author response: We agree.

- Lines 128-130: I am not sure what this sentence means. Please try to rephrase it so that it more clearly describes the method used.

  Author response: We agree that the description is not the clearest and will rephrase it as follows:

  original:

  The algorithm is based on calculating the local slope in each pixel of the RES image by minimizing the variance along a local line segment. Layers are traced automatically between two user-defined points by following the steepest slope from both ends and subsequent weighting of the two lines by distance to the end points. The number of picks required for thorough tracing depends on the data quality and reflector strength.

  revised:

The program is based on calculating the local slope in each pixel of the RES image, and layers are traced automatically between two user-defined points. Starting from each of these points the algorithm walks along the steepest slope towards the other point. Subsequently, the two lines are weighted by distance to their starting point and combined to one layer. The number of picks required for thorough tracing depends on the data quality and reflector strength.

- Line 156: "propagation" and also their evolution (i.e. thickness)?

  Author response: We prefer to use 'deformation' instead of 'evolution' and will rephrase the sentence as follows:

  original:

  Here, we use a two-dimensional Dansgaard–Johnsen model (Dansgaard and Johnsen, 1969) to simulate the propagation of internal layers along approximated flow lines between the ice-sheet summit (GRIP) and EastGRIP.

  revised:

  Here, we use a two-dimensional Dansgaard–Johnsen model (Dansgaard and Johnsen, 1969) to simulate the propagation **and deformation** of internal layers along approximated flow lines between the ice-sheet summit (GRIP) and EastGRIP.

- Line 164: Use of "B" for base is confusing because it was previously used in eq. 2 as radar bandwidth.

  Author response: Many thanks for pointing this out. We will revise the notation throughout the manuscript and use subscript 'bed' instead of 'B'.

- Line 172: Please define w within the text, e.g. "vertical velocities (w)"

  Author response: We agree and will make the suggested adjustment.

- Line 175: Please define S and B in the text (e.g. "surface (S) and bedrock (B) are:"

  Author response: We agree and will define the parameters in the text. To avoid confusion with the misfit (S) and radar bandwidth (B) we will use E_{sur} and E_{bed} for surface and bed elevation instead.

- Line 183: I suggest adding → age of the isochrones "above the bed, respectively".

  Author response: We agree and will add 'above the bed' for clarification.

- Line 199: Please define what is mean by the "slope" of the accumulation

  Author response: The 'slope' comes from the parameter definition, which is the relative slopes of the accumulation rate in warm and cold climate, i.e. they describe how sensitive the accumulation is towards changes in the $\delta^{18}O$ record. We agree that the word 'slope' is confusing and will rephrase the sentence. We also realized that a reference towards the previous studies of Grinsted and Dahl-Jensen (2002) and Buchardt and Dahl-Jensen (2007) which used a similar model is appropriate here. We will revise this part as follows:

  original:

The unknown parameters c_w and c_c are defined as the relative slopes of the accumulation rates in warm (c_w) and cold (c_c) periods:

revised:

The parameters c_w and c_c determine the sensitivity of the accumulation rate with varying $\delta^{18}O$ in warm (c_w) and cold (c_c) periods and are defined as (Grinsted and Dahl-Jensen, 2002; Buchardt and Dahl-Jensen, 2007):

- Line 202: Please quantify or more clearly describe what is considered a "good" approximation

  Author response: We evaluated the parameters c_w and c_c by trial and error of the initial model and found that the isochrone misfit was smallest for $c_w = 0.1$ and $c_c = 0.15$. To better constrain these parameters in the revised version of the manuscript, we used $c_w = 0.1$ and $c_c = 0.15$ as initial parameters and further tuned them with the Monte Carlo method, together with the other model parameters.

- Line 203: This methods section is the most difficult to understand. It would improve the manuscript if it were expanded and reworked to be clearer (and reproducible by future studies).

  Author response: We agree that this section should be elaborated more and we will expand it in the revised version of the manuscript. Specifically, we will add more information on the Monte Carlo method and why it is used in this context, describe more precisely the initial model assumptions and parameter regularization, and elaborate in detail how the model parameters are perturbed. The individual steps of the Monte Carlo iterations will be displayed in the flow-chart for additional guidance.

- Line 204: How are your parameters initialized?

  Author response: We described the initialization of the model parameters in section 2.3, line 184–190, but we agree that it would make more sense here. We will thus move the description of the parameter initialization from Sect. 2.3 to Sect. 2.5.

- Line 205: Please specify here how the eight are selected (e.g. reference to Table 3, equally spaced for computational efficiency, etc)

  Author response: We agree that a reference to Table 3 would be appropriate here and will incorporate this in the revised version. We will also move the reasoning of why only eight isochrones are used from line 240 to this section. The reason for choosing the specific layers is a mixture between achieving approximately equal vertical spacing and good agreement between the ages obtained at the GRIP and EastGRIP sites. We will also mention this in the revised version of the manuscript.

- Eq. 18: The use of S is confusing because it was used to mean surface in earlier equations. Also, please define in the text (i.e. "The misfit (S)").

  Author response: Thank you for pointing this out. As mentioned in a previous comment we will look over the notations to make sure that the symbols are unique and we will define the quantities in the text.

- Line 208: Please define in this context what is meant by uncertainty. Is it the standard deviation or a defined uniform error spread? How is it determined?

  Author response: Thank you for this feedback. The data uncertainty is assumed to be the standard deviation of a gaussian distribution. The uncertainty of the isochrone depth is 13 m, equivalent to the maximum depth uncertainty related to the picking process and radar range resolution. We will add this information and describe the definition of the misfit more thoroughly in the revised version of the manuscript.

- Line 209: Please quantify "a large number"

  Author response: This is very difficult to quantify because the probability density in the model space is not known. In theory, there is an infinite amount of solutions and, hence, the probability density can contain an infinite amount of local maxima. The advantage of the Monte Carlo method over local search methods is that it is less likely to get trapped in one of the local maxima. We have rewritten this entire section to be more clear on the reasoning behind the used method.

- Line 214: "mcurr is perturbed" → Please specify how the parameters themselves are perturbed. For example, are they all perturbed independently from each other?

  Author response: Thank you for pointing out this missing explanation. We perturb one (randomly selected) parameter per iteration, independent from each other. We will elaborate this further in the revised version of the manuscript by adding a paragraph describing in detail how this is done.

- Line 218: What is meant by a "burn-in phase"? Please specify in the text.

  Author response: The term 'burn-in phase' is commonly used in Markov Chain Monte Carlo methods and refers to the initial phase of the sampling process, where the model moves from the initial state to a high-probability area. Models sampled during this initial phase should be discarded to ensure the sampling of the target probability. We will formulate this more explicitly in the revised version of the manuscript.

- Line 219: Please specify in the text how the thresholds (or maximum deviations) are determined?

  Author response: Thanks for pointing out the lack of information here. We defined the threshold as follows:

  - The kink height is allowed to vary within the ice thickness, i.e. $0 < h < H$. Anything outside this range would physically not make sense. We did not regulate this parameter further because we do not have any prior knowledge on the vertical velocity distribution along the flow line.

  - The accumulation rate was set to vary within ± 2 cm from the initial accumulation rate, i.e. $\lambda_{H,0} - 0.02 < \lambda_H < \lambda_{H,0} + 0.02$. The initial accumulation rate obtained from Eq. (12) fits quite well with field observations at GRIP and EastGRIP. Nevertheless, small deviations can be expected because the local layer approximation is not valid in the study area. We estimate that this deviation should be within ± 2 cm from the initial guess.

- The basal sliding was allowed to vary ± 15 % from the initial parameterization, i.e. $f_{B,0} - 0.15 < f_B < f_{B,0} + 0.15$, resulting in a maximum sliding fraction of 95 % in the vicinity of EastGRIP.
- The threshold for the basal melt rate was set to 0.03 m a^{-1}, i.e. $\lambda_{B,0} - 0.03 < \lambda_B < \lambda_{B,0} + 0.03$ which allows a maximum melt rate of 0.06 m a^{-1} at EastGRIP. The choice of this upper limit is based on preliminary modeling results which showed that much higher basal melt rates lead to erosion of the deepest observed isochrones.

As pointed out by Referee # 1, the basal melt rates are reaching the limits at EastGRIP for flow line A and B, and the upper threshold is lower than values suggested in this area in previous studies (e.g. Fahnestock et al., 2001; Keisling et al., 2014; Zeising and Humbert, 2021). We will thus repeat our model runs allowing the parameters to be more free in the revised version of the Manuscript.

- Figure 3 (caption), Line 5: "(a,e,j)" → "(a,e,i)" ?

  Author response: Yes, this is correct. Many thanks for pointing this out.

- Figure 3 (caption): The particle trajectories should probably be described earlier in the caption when panels a,e, and i are first described. At this point, please distinguish that they are illustrated by the solid lines and that the IRHs are represented by broken lines of the same color to indicate age of deposition.

  Author response: Thank you for this valuable suggestion. We will move the description of particle trajectories further up in the caption. We will also add clarification on what the different line styles and the colors indicate.

- Figure 5: Please add a label for the y axis (i.e. number of model scenarios/samples/runs or something more appropriate).

  Author response: Thank you for pointing this out. We have revised this figure and added '# of samples' on the y-axes.

- Table 4: Could uncertainties also be included in this table?

  Author response: This is a good idea, thank you for this suggestion. We will include the maximum spread between the different flow lines in the table.

- Figure 6: It appears that the colored lines for panel f are colored with the same scheme as the lines in Fig. 3 and Fig. 4. This is a very nice feature and connection between the figures, and I don't remember this being strongly noted in the text. I may have missed it, but if was not, please make sure to point out to the reader that you made this effort, since it is a definitely a helpful tool. For example, in Fig. 3 and Fig. 4 captions you could reference Fig. 6f as to where one could see where the lines fall within the core. It would also be helpful if this nice connection was pointed out clearly in the text. In addition, for Fig. 6, maybe you could highlight in the panel f somehow the 8 chosen isochrones or connect them with their layer number as noted in Table 3.

  Author response: Thank you for this great input. We did not mention it in the text but will

do so in the revised version of the manuscript. We will also follow your suggestion of referring to this figure in Fig. 3 and Fig. 4.

- Line 298: Please reference a figure (i.e. Fig. 3c,g,k). Also, add directionality to this statement for clarity. i.e. "increasing accumulation along the flow line with distance upstream" or something similar

  Author response: Thank you for pointing this out. We will refer to Fig 3 and 4 in the revised version of the manuscript. We will also add the directionality and will make sure that it is clear in all similar statements throughout the manuscript.

- Line 300: It would be helpful to directly specify what exactly the climatic reasons are for this.

  Author response: Yes, indeed. We will mention here that this is related to the colder and dryer atmospheric conditions (Cuffey and Clow, 1997).

- Lines 301-302: This sentence is awkward and could be rephrased to be clearer as to lead the reader more directly. Please also reference the figures and panels that support your argument.

  Author response: We agree that this part should be rephrased. We will also refer to the corresponding figure panels in the revised version of the manuscript. The planned adjustments look as follows:

  original:

  Older ice was, due to climatic reasons, deposited under lower accumulation rates between 0.05 m a^{-1} in the stadials and 0.14 m a^{-1} in interstadials.
  The accumulation-rate variations between the three flow lines are a combination of the varying along-flow accumulation pattern and upstream distance of the source area, and the model spread provides important uncertainty estimates.

  revised:

  The accumulation rate at the deposition site for older ice varies between 0.05 m a^{-1} (GS) and 0.14 m a^{-1} (GI). The atmosphere in the glacial period was in general colder and dryer, and hence, accumulation rates were generally lower than today (Cuffey and Clow, 1997). However, due to the upstream flow effects, the ice from the interstadials was deposited under higher accumulation rates than observed at the EastGRIP site today. The variations in the past accumulation-rates between the three flow lines result from both, the varying along-flow accumulation pattern and different upstream distance of the source location. The spread between the three models provides important uncertainty estimates.

- Line 333: Please be clearer about what is meant by "out-of-plane effects" and why this means that the core is not affected.

  Author response: It means that the way these isochrones are deformed is not directly related to the ice flow along the flow-line since this area deviates considerably from the surface flow direction. The undulations observed here could for instance be related to features of the bed topography east of this flight line as that's where the ice most likely originates. The ice we find in the EastGRIP ice core is unlikely to have passed this area and therefore it is not so important

that these undulations can not be reproduced by our model. We will try to specify this more clearly in the revised version of the manuscript.

original:

We argue that these strongly deformed isochrones are out-of-the-plane effects since they predominantly appear in parts of the flow lines which deviate from the observed surface velocity direction by more than 15 degrees. Accordingly, the ice in the EastGRIP ice core is presumably not affected by them, and the fact that they are not reproduced by the model does not put any constraints on the usefulness of our results for upstream corrections.

revised:

These strongly deformed isochrones predominantly appear in parts of the flow lines which deviate from the observed surface velocity direction by more than 15 degrees. We thus argue that they are out-off-the-plane effects and that the isochrones parallel to the ice flow direction are not as strongly deformed. Accordingly, the ice in the EastGRIP ice core has not experienced such deformation, and the fact that they are not reproduced by the model does not put any constraints on the usefulness of our results for upstream corrections.

- Line 429: our model allowed "us" to invert for

  Author response: We agree and will adjust this in the revised version of the manuscript.

- Line 436: As for line 298 comment above please be specific about directionality of the increase in accumulation.

  Author response: Again, a very important point, thanks for making us aware of it. As mentioned above we will address this and check the entire manuscript for similar unclear statements in terms of directionality.

References

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