We would like to very much thank the anonymous referee #1 for reviewing our study and her/his constructive comments. Please find below the referee's comments in black font and the authors' response in blue font.

The paper by Plach et al. addresses two topics of interest. First, it simulates the frequency of surface melt over Greenland during the Eemian from ~130ka to 115ka. The authors use the surface mass balance output from the Norwegian Earth System Model with time slices at 125 and 115ka in combination with the Modele Atmospherique to attain regional climates over Greenland. To test the viability of their approach, the models were validated by comparing them to preindustrial conditions. The authors conclude from the preindustrial comparison that their model is likely conservative in estimating the percentage of melt. They find that at 125ka the percentage of melt could exceed 25% of the annual accumulation at GRIP and up to 90% in less central locations such as Dye-3. These are impressive results and could be important for understanding seasonality effects on surface melt and on ice sheet mass balance.
Secondly Plach et al. addresses how surface melt can affect ice core records, particularly TAC. The authors point out that the interpretation of TAC as a unique proxy for elevation is complicated by the influence of surface melt during warm periods especially the Eemian where these layers cannot be visually identified due to thinning. Melt layers are generally bubble free with the amount of air in the melt layer being primarily dictated by Henry's law. The result is that melt layers have significantly lower TAC. Plach et al. use the results of their melt simulations to calculate theoretical Eemian TAC values which they call TACred and then compare these values to published data. The results of the model derived TAC is consistently lower than the measured data at 125ka but similar at 115ka and the preindustrial.

General comments, suggestions and edits

Both the extent of melt over Greenland, and how melt can affect TAC during warm periods are important topics and of value to the paleoclimate community. The approach of the authors to account for melt in TAC is novel and could help explain some of the anonymously low TAC values we see during the Eemian in some ice core records. I find that the subject matter fits well within the scope of Climate of the Past. However, the paper could use substantial revision, as noted below.

First, I wonder if it would be better to split this into two papers, one on the Greenland surface melt simulations and a second on the potential effects of melt on TAC records and their interpretation. This would enable a more detailed analysis of the surface melt simulations and the interpretation of them, as well as a more robust comparison between the derived or simulated TAC and the measured data. On both the melt simulation results and the derived TAC, I would like to see a more robust interpretation of the results. Assuming the authors choose to keep this as a single paper the following are my suggestions.
We agree that it would be interesting to perform further comparisons and more detailed analysis. However, since melt and TAC are strongly related, we prefer to keep the manuscript as a single paper. We address the reviewers concerns below.

Major Suggestions
Title: The title makes no mention of total air content but yet this is a major component of the

paper. I suggest changing the title to include total air content.
We agree, the total air content should also be represented in the title. Therefore, we will change the title to: “Greenland climate simulations show high Eemian surface melt explaining reduced total air content in ice cores”

Abstract: In contrast to the title the abstract is excessively focused on the TAC results. I suggest adding a few sentences about the melt simulations.
The current abstract illustrates the strong relation we see between melt and TAC, which is also a reason why we prefer to present both in one paper. However, we agree that the abstract is focused on TAC. We will add a few sentences on the melt simulations in the abstract giving a more consistent picture together with the new title.

Ln 101-120: Calculation of the model-derived total air content (TAC) The derived TAC does not account for insolation. As mentioned earlier in the paper (Eicher et al. 2016) show that TAC at high accumulation sites such as in Greenland have a similar imprint from insolation as in Antarctic records. The implication is that the comparison shown in figure 6 is between TAC records with the effects of insolation and derived values without the effect of insolation. This will bias the results. While this discrepancy is included in the Discussion section, it would be preferable here. Note that (Eicher et al. 2016) provides an insolation sensitivity (5.7 *10-9 mL kg-1 J-1) for the integrated insolation threshold over 390Wm-2. This should provide the framework to approximate how much insolation affects the analysis in this paper.
Eicher et al. (2016) analyzed the NGRIP ice core. To what degree their findings are representative for the entire Greenland Ice Sheet is an open question and goes beyond the scope of this paper. The dominant effect in our analysis is the melt effect not the insolation effect.

Ln 164-170: Results: Total air content (TAC) and Figure 7 In addition to comparing the derived results with data, it would be useful to compare the derived results with and without TACred included. This would help determine the magnitude of the effect on TAC. While the derived TAC may be lower than the measured TAC for a number of reasons including insolation effects and elevation uncertainty, the difference between derived TAC and TACred may still be fairly accurate and informative.
This will indeed be very informative. We will include a TAC-to-TACred comparison in the text and Fig. 6. Furthermore, we will consider also adding the comparison to Fig. 7.

Ln 95-96: and Figures 6 and 7 It is not clear to me why only the lowest 10% of TAC values (20% for GRIP) were used to determine the Eemian measured values for comparison to the derived values at the 125ka time slice. For the derived TAC the melt effect should be applicable to all TAC samples, not just the ones with the lowest TAC values. This may just be a misunderstanding on my part but regardless some clarification would be helpful.
The 125ka simulations represent the warmest part of the Eemian interglacial period in our analysis, we therefore expect the largest melt influence in this period. We choose the 10% (20%) lowest TAC values as a representation of the measurements most likely representing the strongest melt-influenced observations. We will add some clarification in the revised manuscript.

Also note that in addition to the TAC values for GRIP, there is also TAC data for GISP2 in the Eemian. See (Yau, Bender, Robinson, & Brook, 2016).

Thank you for this reference. We will consider adding the GISP2 TAC data to the revised manuscript. Alternatively, we will discuss its characteristics in the analysis.

Minor suggestions

Ln 20 – The integrity of the ice core record is not the issue as much as our ability to interpret the records of CH4, N20 and TAC when they are affected by melt layers. Questioning the integrity of the ice core record makes me think something happened during analysis or storage of the ice core.
Thank you for this note. We will reformulate in the revised manuscript.

Ln 24 . . .only direct proxy for past surface elevation of the interior of an ice sheet.

Ln 25-26 It should also be mentioned that TAC responds on millennial time scales as noted by (Eicher et al., 2016). Their hypothesis is that these effects were due to rapid changes in accumulation. As this is unlikely to occur in the Eemian this can probably be ignored for the rest of the analysis but should still be mentioned here.

Ln 30 . . . TAC is the only direct method . . .

Ln 33 . . . NEEM-derived surface temperature anomaly relative to the last 1000 years…
Thank you, we will address the points above in the revised manuscript.

Ln 115 -117 What assumptions are being made in using Henry's law to calculate air in melt water i.e. is the meltwater saturated with O2 and N2 when it is refrozen and are any bubbles incorporated into the meltwater? I think the assumption of using Henry's law works but the assumptions should be noted.
To calculate TACrefrozen, it is assumed that the meltwater is in equilibrium with air at a temperature of 273K and at the local atmospheric pressure (Eq. 5 and 6 in the discussion paper). No air is occluded in the form of bubbles in the freezing process. We will revise the TAC method section and clarify the assumptions.

Ln 153 -Ln162 Melting and Refreezing and Tbl 1 Add accumulation to table 1. This will be useful when discussing refreeze relative to accumulation rates in the later section

Ln 153-162. Alternatively plot the model accumulation rates.
Thank you for this suggestion. We will add the accumulation to Table 1.

Ln 204-206- This sentence is not clear to me. What part of the simulation would fit better?
We are referring to the large uncertainty of the NEEM temperature reconstructions (warming of 8°C +/-4°C) which is largely related to the uncertain elevation change. The lower end of the NEEM reconstructions would fit better with the simulated warming of ~3-4°C found in our study. We will clarify this sentence in the revised manuscript.

Ln 257-258 – It is worth noting that if the lower TAC values in GRIP and NGRIP are related to surface melt rather than elevation, then CH4 over this period should be elevated with NGRIP being higher than GRIP and GISP2 due to the greater melt percent.
While the referee is correct in the above statement, we are not aware that data to confirm

this is available. However, we will consider adding a note on this in the revised manuscript.

Readability

There are sections of the paper that could use a revision for readability. The following are a few examples:

Ln 6 can not -> cannot

Ln 20 . . . the presence of surface melt during ice formation can be a problem -> the presence of surface melt can be a problem

Ln 25: However, TAC was also found to have an insolation signal-> However, TAC is also affected by insolation at both Greenland and Antarctic sites (Eicher et al., 2016; Raynaud et al., 2007)

Ln 36 – unclear antecedent- Despite these concerns

Ln 62 moderate -> moderately

Ln 62? smaller Eemian ice sheet equivalent to ∼0.5 m of sea level rise.-> smaller Eemian ice sheet with the difference equivalent to ∼0.5 m of sea level rise

Ln 260 have an ensemble of climate to explore-> have an ensemble of climate models to explore

We will address the named readability issues and give the manuscript another round of proofreading to improve the readability.

Final thoughts

I found this paper thought provoking. While I think there is work left to do, I look forward to seeing the next iteration.

Yau, A. M., Bender, M. L., Robinson, A., & Brook, E. J. (2016). Reconstructing the last interglacial at Summit, Greenland: Insights from GISP2. Proceedings of the National Academy of Sciences of the United States of America, 113(35), 9710-9715. doi:10.1073/pnas.1524766113

Thank you very much for your overall positive feedback. Your comments and suggestions will help to significantly improve our manuscript.

We would like to very much thank the anonymous referee #2 for reviewing our study and her/his constructive comments. Please find below the referee's comments in black font and the authors' response in blue font.

Review "Greenland climate simulations show high Eemian surface melt" by Plach et al.

The authors compare modeled and measured Eemian (130-115 ka) total air content (TAC) extracted from seven ice cores drilled in Greenland and the Canadian Arctic. TAC is a proxy commonly used to infer past changes in surface elevation since the density of air trapped in the ice declines with altitude. The authors show that low TAC values observed in Greenland Eemian ice are affected by high melt rates and subsequent refreezing that reduce TAC through the formation of ice layers (referred to as melt layers). Therefore, high Eemian melt rates could explain the low measured TAC in ice cores, a process that should be considered when estimating surface elevation changes in past warm periods.

The paper is well-written and provides important insights on the impact of Eemian high melt rates on measured TAC that should be accounted for to accurately estimate surface elevation changes in past warm periods. The paper would benefit from additional clarifications/details regarding the methods, model evaluation and study limitations. The reviewer deems that **minor revisions** are required before publication in Climate of the Past. The reviewer's comments are summarized hereunder.

General comments

1. The authors use the climate model MAR to dynamically downscale two Eemian time slices from the Earth System Model NorESM1-F (125 and 115 ka) as well as a pre-industrial control run. Modeled melt, refreezing and temperature are the core of the study as these are used to estimate modeled TAC that are compared with Eemian ice cores observations. The description of the MAR model is however not sufficient. The authors should mention which model version is used, and at what spatial resolution (i.e. 25 km in **L67** appears too late in the text). The authors should also briefly describe in Section 2 how surface melt (SEB-derived) and subsequent refreezing are calculated in MAR.
   Thank you. We will extend the description of the MAR model and address your suggestions in the revised manuscript.

2. The authors prescribe a fixed contemporary Greenland ice sheet geometry in MAR to simulate the surface mass balance (SMB) components over the warmer than present Eemian period. This is acceptable given the lack of an accurate estimate of Eemian ice sheet geometry and the high computational costs of an offline coupling with an ice dynamics model (e.g. Le clec'h et al., 2019). However, the authors should discuss the limitations and uncertainties introduced by the use of a fixed modern ice sheet geometry. For instance, Van de Berg et al. (2011) and references therein suggest a 30-60% ice sheet volume reduction in the Eemian relative to present-day. Consequently, simulating melt and SMB on a more extensive, modern ice sheet may artificially cause high melt rates over larger ablation zones than expected if using a more accurate Eemian ice sheet geometry. Could the authors elaborate on this matter? Figure 1 could also show MAR melt rates averaged for the Eemian period

125 ka as a background.

We agree that there is a large uncertainty in the Eemian ice sheet geometry and that a model ice sheet geometry, which is too large during the melt simulations, could cause artificially high melt rates. However, such artificially high melt rates will influence regions on the margins much stronger than sites in the ice sheet center which are the main focus of our study. Ideally, a more systematic evaluation of Eemian melt at the ice cores sites should also investigate different possible ice sheet geometries. However, this is, as you mention, difficult due to high computational costs and not within the scope of our initial investigation in this study. We will include a discussion of these points in the revised manuscript with a focus on the uncertainty in using a given ice sheet geometry.

Furthermore, we will consider adding the 125k melt as a background of Fig. 1.

3. The Eemian period is characterized by a climate significantly warmer than today, however in Fig. 2, annual mean near-surface temperature from the pre-industrial, 125 ka and 115 ka Eemian periods are almost systematically colder than or roughly equal to present-day observations. This is confusing especially since summer temperatures in the Eemian shown in Fig. 3 are considerably higher than present-day (3-4 K). Is this the result of a more pronounced seasonality of the Eemian climate, i.e. with colder winters and warmer summers, making the average annual temperature comparable to present-day but with markedly warmer summers? Could the authors further comment on this?

   You are absolutely right, the Eemian interglacial period was characterized by a more pronounced seasonality due to the difference in the Earth's orbital parameters (larger obliquity and eccentricity; Yin and Berger, 2010): giving a positive summer insolation anomaly and warmer-than-present summers in the Northern Hemisphere, as also recorded in Greenland ice cores and elsewhere in the Arctic (CAPE Last Interglacial Project Members, 2006). We will clarify this point in the revised manuscript.

Yin, Q. Z. and Berger, A.: Insolation and CO2 contribution to the interglacial climate before and after the Mid-Brunhes Event, Nature Geoscience, 3, 243–246, https://doi.org/10.1038/ngeo771, 2010.

CAPE Last Interglacial Project Members: Last Interglacial Arctic warmth confirms polar amplification of climate change, Quaternary Science Reviews, 25, 1383–1400, https://doi.org/10.1016/j.quascirev.2006.01.033, 2006.

Point comments

L6: The reviewer suggests reformulating as: “Therefore, simulating high Eemian melt rates and associated melt layers is beneficial to improve the representation of past surface elevation.”

L23: The authors could reformulate as: “However, refrozen melt has the potential to form impermeable ice layers (melt layers henceforth) that alter the diffusion of ice core signals.”

We will modify the two sentences above accordingly.

L33-35: With respect to which period are these temperature anomalies estimated?

The cited temperature anomalies are relative to the mean of the past millennium. We will add this in the text.

L39: The site GISP2 is not shown in Fig. 1 nor referred to elsewhere in the manuscript. The authors could remove "(used synonymous ... proximity)."
We will revisit the discussion of GISP2 as referee #1 pointed out existing Eemian TAC data for GISP2.

L40: The authors could mention that Agassiz ice cap is situated in the northern Canadian Arctic.
We will add this information.

L42: "evaluated" instead of "validated", same comment in **L50**. The authors should stress that present-day measurements are used as a reference for comparison with a warmer Eemian and colder pre-industrial climate rather than for model "evaluation". Strictly speaking, present-day observations cannot be used to "validate" nor "evaluate" Eemian or pre-industrial climate.
We will reformulate this section. We think that the word "validated" is used correctly in L50, as the MAR model has been shown to be able to represent the present-day climate well over Greenland in several studies. We will clarify that we refer to a validation under present-day climate conditions by modifying L50 to "which was extensively validated over Greenland under present-day climate conditions".

L47: The reviewer suggests: "based on **two** Eemian time slice simulations ... conditions and one preindustrial (PI; **YYYY-YYYY**) control simulation." Later on in the text (**L52**) "four" Eemian experiments are mentioned while only two (125 and 115 ka) are described in the text. Please, mention the period spanned by the pre-industrial control run (e.g. 1850-1949?) as well as the 125 and 115 ka runs (i.e. number of thin lines in e.g. Fig. 2).
The global NorESM-F runs are started with a 1000 year equilibrium pre-industrial run (pre-industrial refers to constant 1850 forcing; GHG and orbital parameters). After this the pre-industrial run was continued for another 1000 years (with constant 1850 forcing). Additionally, after the first 1000 year equilibrium run the Eemian runs are branched off and run for 1000 years with constant Eemian forcing (115 and 125ka, respectively; changed GHG and orbital parameters). The downscaling with MAR is done with the last 30 years of the NorESM simulations, while the first 4 years are used as a spin-up for MAR and not used in the analysis. Therefore, the analysis of the pre-industrial (constant 1850 forcing) and Eemian melt simulations (constant 115 and 125ka forcing) are based on 26 years of MAR simulations.
We will include this information in the revised manuscript.

L51: Maybe "All climate simulations use a fixed, modern ice sheet geometry, in lack ..." See also general comment #2, i.e. a too large ice sheet extent are likely to artificially increase surface melt.

L54: To clarify, the reviewer strongly suggests to replace "SEB-derived SMB" by "MAR SMB" across the manuscript.
Yes, we will do that.

L56: The authors could reformulate as: "Additionally, while providing the most complete representation of physical surface processes in the pool of investigated models, MAR shows lower Eemian melt rates (**XX**%) than intermediate complexity SMB models.".

L62: "Eemian ice sheet volume equivalent to ~0.5 m ..."

L71: "SMB simulations are compared to present-day satellite ...", see also comment in **L42**.

L76: The authors could reformulate as: "covers the whole MAR grid at 25 km from May to September for most years between 1979-2010".

L93-100: This paragraph describing the data sets presented in Figs. 6 and 7 should be moved to **P9** under Subsection *Total air content (TAC).*

L119: In Eq. 6 "$C_{a,O2}$" instead of "$C_{a,N2}$".
Thank you, we will change the manuscript according to the suggestions above.

L124-126: To the reviewer's knowledge, average pre-industrial temperatures should be colder than present-day observations. Could the authors elaborate on this?
The observations from weather stations used for the comparisons of observed and simulated annual mean temperature (Fig. 2, long black bold line) cover the period 1890 to 2014. You are right that we would expect the present-day annual mean temperatures to be higher than pre-industrial temperatures (at least for the last few decades). However, the long averaging period from 1890 to 2014 should reduce the influence of recent global warming. Furthermore, the warmer-than-present simulated pre-industrial temperatures indicate that the climate simulations are conservative in terms of temperature, or at least not particularly warm, and therefore should not result in extreme melt.
In the revised manuscript we will clarify the difference between the temperatures presented in Figs. 2. and 3 (averaged over the period 1890-2014) and the pre-industrial and present day temperatures.

L128-129: "The lower borehole ... than near-surface temperature". The sentence is unclear, could the authors reformulate?
We will reformulate this sentence.

L131-133: This is confusing as temperature in the Eemian should be warmer and pre-industrial temperature colder than present-day. For instance, how should readers interpret the fact that near-surface temperatures at NGRIP are systematically warmer in the pre-industrial period than in present-day? See also general comment #2
You are right, this is confusing. We will clarify this section in the revised manuscript. We don't expect the annual mean temperatures for pre-industrial and Eemian to be very different (since the total amount of solar insolation didn't differ much). However, since the Eemian seasonality was much more pronounced the Eemian summer temperatures should be higher than the pre-industrial ones as seen in Fig. 3 (shown the simulated JJA temperatures).

L132: "(Fig. 2; blue and orange)", there is no red data in Fig. 2.
The red color is a remainder of a previous manuscript version. We will remove this reference.

L134-135: How come that the 3-4 K warming only appears in summer temperature, see also general comment #2.
Due to the higher Eemian seasonality. Also see our response to general comment #3.

L138: What do the authors mean by "precipitation-weighted temperatures"? How is this calculated? Why do annual precipitation-weighted temperatures show a warming similar to that of summer temperatures? What is the difference with the annual data shown in Fig. 2?
For the calculation of the precipitation-weighted temperature, daily temperatures are multiplied by the precipitation (snowfall+rainfall) at the individual days, summed up over the year and then divided by the sum of the annual precipitation. Precipitation is used as a weight, instead of time in the usual averages where each time step is equally represented in the average. In the precipitation-weighted temperature, days with a lot of precipitation are weighted stronger than days with low precipitation, and days with no precipitation are not represented. The precipitation-weighted temperature is sometimes used in the interpretation of ice core temperature reconstructions, since ice cores can only record temperatures if there is some kind of precipitation deposited. Since most precipitation in Greenland falls in summer, the precipitation-weighted temperature is more similar to summer temperatures than it is to annual mean temperature. We will clarify this in the revised manuscript.

L161: The reviewer suggests: "~3,200 m elevation, refreezing surpasses 25% of the annual accumulation under 125 ka conditions. [...] where refreezing percentages can reach 80-90%." It is much clearer to mention period averages (thick lines in Fig. 5) rather than single year values (thin lines).

L167-168: The authors should consider mentioning period averages as: "... 45-70 ml kg-1 on average, whereas ... between 75-100 ml kg-1. At Dye-3 ... is about 25 ml kg-1 on average for the warm ..."
We will adapt the two sections above accordingly in the revised manuscript.

L173: The authors should consider removing Dye-3 data in Fig. 7 as the ice core does not include Eemian ice.
Although, there are no Eemian TAC measurements for Dye-3. The ice at the bottom of Dye-3 has been found to be much older than the Eemian interglacial period (Willerslev et al., 2007). Furthermore, Dye-3 illustrates how our melt/TAC calculations play out at a more marginal site. Therefore, we prefer to include the TAC observations at this site.

Willerslev E, Cappellini E, Boomsma W, et al. (2007): Ancient biomolecules from deep ice cores reveal a forested southern Greenland. Science. 317(5834):111-114. doi:10.1126/science.1141758

L196: The reviewer suggests "the lowering and retreat of the Eemian ice sheet", see also general comment #2.

L204-206: This is unclear, could the authors reformulate?
We will reformulate the two sections above accordingly in the revised manuscript.

L214: What do the authors mean by "100% melt"?

This should actually refer to a refreezing percentage of 100%. We will revise this sentence.

L260-261: Eemian melt derived from the regional climate model RACMO2 should be available from Van de Berg et al. (2011).
This is a very good point, that other melt data from other Eemian simulations might be available. However, we see our analysis as an initial study investigating the relationship between melt and TAC during the Eemian interglacial period. A more systematic analysis comparing the output of different climate models is a possible work for the future.

L264-267: Such analysis has been conducted in e.g. Fettweis et al. (2013) or Tedesco et al. (2020).
Thank you, we will mention this in the revised discussion.

L272: The reviewer suggests: “The simulated air pressure ... are used to estimate Eemian total air content (TAC). Simulated high melt rates could explain the low corresponding ice core TAC observations.”
Thank you, we will change this sentence accordingly.

Style

L3: The reviewer suggests “affect” instead of “influence”. Same in **L21** and **L44**.
L5: Do the authors mean “high surface melt” or “enhanced surface melt relative to present-day”?
L9-10: Replace “elevated levels of surface melt” by “high melt rates”.
L10: “when interpreting measured Greenland TAC fluctuations as surface elevation changes.”
L19: “favorable for high melt rates across the Greenland ice sheet.”
L20: “alter” instead of “be a problem for”.
L26: Replace “can be applied on” by “can be estimated for”.
L37: “limited” instead of “small”.
L60: “larger” instead of “bigger”.
L201: “that the climate simulations might include a cold bias.”
L244: “air content to estimate ice surface elevation changes”.
L259: “obtain” instead of “accomplish”.
Thank you, we will revise the corresponding lines.

Figures

Fig. 1: The authors could consider showing MAR Eemian melt as a background (125 ka).
Figs. 2, 3, 5, 6 and A1-3: Data should be shown in chronological order: PI (pre-industrial), 115 ka (late Eemian), and then 125 ka (early-Eemian).
Fig. 4: Replace “nan” by e.g. “NA” for “Not Available” and explain the acronym in the caption. NAN commonly means “Not A Number” while the authors certainly mean “unavailable data”. How should readers interpret the fact that the number of melt days is higher in the present-day climate than in the warmer Eemian period at Agassiz site?
Fig. 6 caption: “almost completely overlaps with ...”.
We will consider your suggestions for the adaptation of the figures in the revised manuscript. Furthermore, we will adapt the discussion of the observed vs. Eemian melt at the Agassiz

site.

References

Le clec'h et al. (2019): https://tc.copernicus.org/articles/13/373/2019/
Van de Berg et al. (2011): https://www.nature.com/articles/ngeo1245#Sec7
Fettweis et al. (2013): https://tc.copernicus.org/articles/7/241/2013/
Tedesco et al. (2020): https://tc.copernicus.org/articles/14/1209/2020/

Thank you very much for your overall positive feedback. Your comments and suggestions will help to significantly improve our manuscript.

Greenland climate simulations show high Eemian surface melt which could explain reduced total air content in ice cores

Andreas Plach[1, 2, 3], Bo M. Vinther[4], Kerim H. Nisancioglu[1, 5], Sindhu Vudayagiri[4], and Thomas Blunier[4]

[1]Department of Earth Science, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway
[2]Department of Meteorology and Geophysics, University of Vienna, Austria
[3]Climate and Environmental Physics, Physics Institute, University of Bern, Switzerland
[4]Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Denmark
[5]Centre for Earth Evolution and Dynamics, University of Oslo, Oslo, Norway

Correspondence: Andreas Plach (andreas.plach@gmail.com)

Abstract. This study presents simulations of Greenland surface melt for the Eemian interglacial period (~130000 to 115000 years ago) derived from regional climate simulations with a coupled surface energy balance model. Surface melt is of high relevance ~~for ice core records because it can influence~~ due to its potential effect on ice core observations, e.g., ~~lower~~ lowering the preserved total air content (TAC) used to infer past surface elevation. An investigation of surface melt is particularly interesting for warm periods with high surface melt, such as the Eemian interglacial period~~, with enhanced surface melt~~. Furthermore, Eemian ice is the deepest and most compressed ice preserved on Greenland, ~~which means that melt layers can not be identified~~ resulting in our inability to identify melt layers visually. Therefore, ~~a knowledge of potential melt layers would be advantageous. The simulations presented here show Eemian surface melt at all deep Greenland ice core locations~~simulating Eemian melt rates and associated melt layers is beneficial to improve the reconstruction of past surface elevation. Estimated TAC, based on simulated melt during the Eemian, could explain the lower TAC observations~~: at~~. The simulations show Eemian surface melt at all deep Greenland ice core locations and an average of up to ~30 melt days year^{-1} at Dye-3, corresponding to more than 600 mm water equivalent (w.e.) of annual melt. For higher ice sheet locations between 60 to 150 mm w.e. year^{-1} on average are simulated. At the summit of Greenland ~~(GRIP)~~ this yields a refreezing ratio of more than 25 % of the annual accumulation~~is simulated~~. As a consequence, ~~elevated levels of surface melt~~ high melt rates during warm periods should be considered when interpreting Greenland TAC ~~measurements~~ fluctuations as surface elevation changes. Additionally to estimating the influence of melt on past TAC in ice cores, the simulated surface melt could ~~also~~ potentially be used to identify ~~potential~~ coring locations where Greenland ice ~~might be~~ is best preserved.

1 Introduction

The Eemian interglacial period (~130000 to 115000 years ago; thereafter ~130 to 115 ka) was the last period with a warmer-than-present summer climate on Greenland (CAPE Last Interglacial Project Members, 2006; Otto-Bliesner et al., 2013; Capron et al., 2014). Favourable orbital parameters (higher obliquity and eccentricity compared to today) during the early Eemian period caused a positive Northern summer insolation anomaly (and negative winter anomaly) at high latitudes, which led to a stronger seasonality (Yin and Berger, 2010). ~~A~~ This stronger seasonality with relatively warm summer seasons is favourable for ~~surface melt of~~ high melt rates across the Greenland ice sheet.

Unfortunately, the presence of surface melt ~~during ice formation can be a problem for the integrity of~~ can influence our ability to interpret ice core records. Measurements of CH_4, N_2O, and total air content (TAC) can be ~~influenced if the ice core contains melt layers~~ affected if melt layers are present. Other ice core measurements such as δ^{18}O, δD, and deuterium excess appear to be only marginally affected (NEEM community members, 2013). However, ~~melt layers have~~ refrozen melt has the potential to form impermeable ~~layers and also influence~~ ice layers (melt layers henceforth) that alter the diffusion of ice core signals.

The observed TAC of ice core records is the only direct proxy for past surface elevation of the interior of an ice sheet, i.e., the TAC is governed by the density of air which mainly decreases with elevation. However, TAC ~~was also found to have an insolation signal in East Antarctica (Raynaud et al., 2007) and Greenland (Eicher et al., 2016)~~is also affected by low-frequency insolation variations (changing orbital parameters) at both Antarctic and Greenlandic sites (Raynaud et al., 2007; Eicher et al., 2016) . Furthermore, Eicher et al. (2016) find a TAC response on millennial time scales (during Dansgaard-Oeschger-Events) which is hypothesed to be related to rapid changes in accumulation. While TAC can be ~~applied on~~ estimated for each individual ice core without the need for other reference ice cores, another indirect method which has been applied to infer Holocene thinning of the Greenland ice sheet (Vinther et al., 2009) requires several ice cores. Vinther et al. (2009) compare the changes of δ^{18}O at coastal ice caps (stable surface elevation due to confined topography) with Greenland deep ice cores, and infer elevation changes. Unfortunately, Eemian ice core records are sparse, and therefore TAC is the only direct method available to estimate surface elevation changes this far back in time. Since the assumed surface elevation also influences the actual Eemian temperature reconstructions and its uncertainty range, an accurate TAC record is of high importance. The following example illustrates this importance: the NEEM-derived surface temperature anomaly (NEEM community members, 2013) at 126 ka is 7.5 ± 1.8 °C (relative to the last 1000 years) without accounting for elevation changes; including the elevation change based on TAC measurements, the temperature estimate becomes 8 ± 4 °C. This means that more than half of the uncertainty of this temperature estimate is related to the uncertainty of past surface elevation. ~~Despite these concerns~~

Despite the importance that melt can have for the interpretation of TAC and other variables of ice core records, the number of studies ~~investigating~~ analyzing the frequency of melt layers in Greenland ice cores is ~~small~~ limited (Alley and Koci, 1988; Alley and Anandakrishnan, 1995).

This study investigates regional climate simulations and observations at ~~six~~ seven deep Greenland ice core sites — Camp Century, Dye-3, EGRIP, ~~NEEM, NGRIP, GRIP (used synonymous with~~ GRIP, GISP2~~due to their close proximity). Furthermore~~, NEEM, and NGRIP. Additionally, an ice cap in the vicinity of the ~~Greenland~~ ice sheet is ~~investigated~~ examined — the Agassiz ice cap, located in the northern Canadian Arctic. TAC is derived from ~~the regional climate~~ regional climate and melt simulations at these ~~seven~~ locations of interest ~~also considering the simulated melt~~ (Sec. 2). Furthermore, the simulated local temperature and melt ~~at the locations is validated~~is evaluated, and the impact on TAC is estimated and compared with ice core observations (Sec. 3 and 4). The results indicate that Greenland ice core records from warm periods, such as the Eemian interglacial period, might be more ~~influenced~~ affected by surface melt than previously considered (Sec. 5).

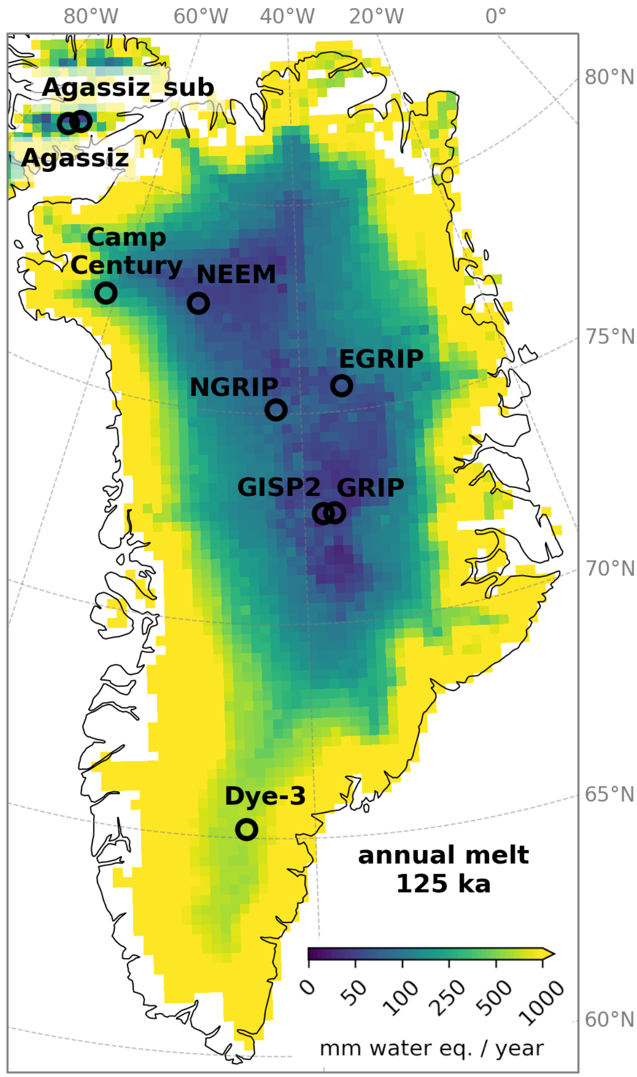

Figure 1. Overview map of Greenland ice core locations ~~discussed~~ considered in this study. The gridded data shows the simulated annual melt rate under 125 ka conditions. Note: Agassiz_sub refers to a substitute location ~~of the Agassiz ice cap used~~ necessary due to the model topography misrepresentation (see Sec. 2).

2 Methodology

Climate and surface mass balance (SMB) simulations

This study uses climate and surface mass balance (SMB) based on two Eemian time slice simulations with a fast version of the Norwegian Earth System Model (NorESM1-F; Guo et al., 2018) representing (constant) 125 and 115 ka conditions ~~(and a~~ and one pre-industrial ~~control simulation)~~(PI; constant 1850 forcing) control simulation. These global simulations are dynamically downscaled over Greenland with the regional climate model Modèle Atmosphérique Régional (MAR, v3.6, 25 x 25 km), which was extensively validated over Greenland under present-day climate conditions (Fettweis, 2007; Fettweis et al., 2013a, 2017).

MAR employs a land surface model (SISVAT; Soil Ice Snow Vegetation Atmosphere Transfer) with a detailed snow energy balance (Gallée and Duynkerke, 1997) fully coupled to the model atmosphere. MAR's atmosphere uses the solar radiation scheme of (Morcrette et al., 2008) and accounts for the atmospheric hydrological cycle (including cloud microphysics) based on Kessler (1969) and Lin et al. (1983). The snow-ice component of MAR is derived from the snowpack model Crocus (Brun et al., 1992) simulating mass and energy fluxes between snow layers, and reproducing snow grain properties as well as their effect on surface albedo. The MAR model has 24 atmospheric layers (up to 16 km above ground) and SISVAT 30 snowpack layers.

The NorESM-F experiments are spun up for 1000 years with constant 1850 forcing (greenhouse gas (GHG) concentrations and orbital parameters) to a quasi-equilibrium state. The PI simulation is run for another 1000 years with constant forcing. The two Eemian time slice simulations are branched off from the initial 1000-year spin-up and run for another 1000 years each with constant 125 ka and 115 ka forcing, respectively (changed GHG concentrations and orbital parameters compared to PI). For the MAR experiments, NorESM is run for another 30 years for each of the three experiments and the output is saved 6-hourly. These 30 years are used as boundary forcing for MAR. After disregarding the first four years as spin-up, the final 26 years are used for the analysis (thin lines in Figs. 2, 3, 4, 5, 6, A1, A2, A3). All climate simulations use ~~an offline~~a fixed, modern ice sheet ~~, in lack~~ geometry, in the absence of a reliable Eemian ice sheet estimate ~~. However, the orbital forcing and the greenhouse gas concentrations are changed in the four Eemian experiments. The SMB used in this study is derived from a full surface energy balance (SEB) model coupled to MAR~~and high computational costs of a coupling with an ice flow model (e.g., Clec'h et al., 2019).

~~This SEB-derived SMB is also~~ The MAR SMB is analyzed in a study investigating the influence of climate model resolution and SMB model selection on ~~the simulation of the Eemian SMB~~ Eemian SMB simulations (Plach et al., 2018a) which amongst other things shows the high importance of ~~considering~~ solar insolation in Eemian simulations. Additionally, ~~the SEB-derived SMB shows less extensive Eemian melt than an intermediate complexity SMB model while using~~ while providing the most complete representation of physical surface processes in the ~~investigated model pool~~pool of investigated models, MAR shows a less negative SMB than an intermediate complexity model during the warmest Eemian simulations (mainly due to a higher ratio of refreezing).

Furthermore, the discussed SMB is ~~also~~ used in a study investigating the Eemian Greenland ice sheet ~~with an~~ volume with a higher-order ice sheet model (Plach et al., 2019). Plach et al. (2019) shows that different external SMB forcings show a ~~bigger~~ larger influence on the Eemian ice volume minimum than sensitivity ~~tests~~ experiments performed with internal ice ~~dynamical parameters like basal friction~~dynamics (like changed basal friction). The ice sheet simulations with the ~~SEB-derived SMB showed a moderate~~ MAR SMB show a moderately smaller Eemian ice sheet with the difference equivalent to ~0.5 m of sea level rise (with respect to the modern ice sheet).

In this study, the ~~SEB-derived~~ MAR SMB simulations are analyzed at ~~six~~ seven deep Greenland ice core locations — Camp Century, Dye-3, EGRIP, GRIP, GISP2, NEEM, NGRIP ~~, GRIP~~ — and an adjacent ice cap — the Agassiz ice cap (Fig. 1). Due to model topography misrepresentation at the ice sheet margins, i.e., the model topography is lower than in reality at the

Table 1. Greenland ice core locations.

location	latitude (°N)	longitude (°W)	observed elevation (m)	model elevation (m)	model accumulation (m w.e./yr) PI | 115 ka | 125 ka
Agassiz	~~80.81~~ 80.7	~~72.89~~ 73.1	~~1760~~ 1730	~~1354~~ 1575	0.22 | 0.18 | 0.26
Agassiz_sub	~~80.53~~ 80.5	~~74.45~~ 74.5	~~1760~~ 1730	1741	0.29 | 0.24 | 0.34
Camp Century	~~77.16~~ 77.2	~~61.13~~ 61.1	~~1885~~ 1890	~~1776~~ 1849	0.63 | 0.52 | 0.76
Dye-3	~~65.18~~ 65.2	~~43.81~~ 43.8	~~2489~~ 2490	2444	0.65 | 0.61 | 0.74
EGRIP	~~75.63~~ 75.6	~~35.99~~ 36.0	~~2708~~ 2710	2684	0.13 | 0.11 | 0.14
~~NGRIP~~ GISP2	~~75.10~~ 72.6	~~42.32~~ 38.5	~~2917~~ 3200	~~2906~~ 3198	0.20 | 0.18 | 0.22
~~NEEM~~ GRIP	~~77.45~~ 72.6	~~55.06~~ 37.6	~~2450~~ 3230	~~2253~~ 3221	0.19 | 0.18 | 0.21
~~GRIP~~ NGRIP	~~72.58~~ 75.1	~~38.63~~ 42.3	~~3230~~ 2920	~~3198~~ 2906	0.18 | 0.16 | 0.22
NEEM	77.5	51.0	2450	2429	0.26 | 0.23 | 0.34

Agassiz_sub refers to a substitute location used due model topography misrepresentation. Details see Sec. 2

Agassiz ice cap location (model resolution 25 km), a substitute location (Agassiz_sub) in the vicinity of the ice cap, with a model elevation similar to the observed elevations, is chosen (Tab. 1).

Observed surface melt

The ~~pre-industrial regional~~ PI climate and SMB simulations are ~~validated against~~ compared to present-day satellite and temperature observations at the locations of interest. The two observational melt day data sets are both derived from satellite-borne passive microwave radiometers — Scanning Multichannel Microwave Radiometer (SMMR), the Special Sensor Microwave/Imager (SSM/I), and the Special Sensor Microwave Imager/Sounder (SSMIS). The first data set, *MEaSUREs (Greenland Surface Melt Daily 25km EASE-Grid 2.0, Version 1)*, covers the years 1979 to 2012 and is available for the entire Northern Hemisphere. The melt onset is identified by comparing 37 GHz, horizontally polarized (37 GHz H-Pol) brightness temperatures with dynamic thresholds associated with a melting snowpack (Mote, 2014). Unfortunately, the Agassiz ice cap is not covered by this data set. The second data set, $T19H_{melt}$, covers ~~May through~~ the whole MAR grid at 25 km from May to September for most years between 1979 ~~to 2010 on the 25 km MAR grid.~~ and 2010. It uses data collected at K-band horizontal polarization (T19H) with a constant brightness temperature threshold of 227.5 K (Fettweis et al., 2011). Both satellite data sets are discussed to show their different sensitivities and to illustrate the uncertainty of these satellite-based melt observations.

The seasonal temperature observations at weather stations and 10 m borehole temperatures (representing annual mean temperatures from 1890 to 2014) are taken from a collection of shallow ice core records and weather station data (Faber, 2016). Finally, the bore hole temperatures from the Agassiz ice cap are taken from Vinther et al. (2008).

Observed total air content (TAC)

Firstly, the Dye-3 TAC for the ice core depth range of ~240 to 1920 m was extracted from Herron and Langway (1987, Fig. 4 therein). Since Souchez et al. (1998) indicate that ice from warmer periods (higher δO^{18} values), likely Eemian, is located below 2000 m at Dye-3, the presented Dye-3 TAC record does not represent Eemian conditions. Secondly, the GRIP TAC data set (Raynaud, 1999) covers depths from ~120 to 2300 m and ~2780 to 2909 m, while an age mode is only provided for the upper part (oldest ice 41 ka). For the deeper sections of the core, a published unfolding of the GRIP core (Landais et al., 2003, age bands in Fig. 3 therein) is used to assign an age to the observations. Thirdly, the GISP2 TAC data was extracted from a supplement table of Yau et al. (2016) and covers the period from 127.6 to 115.4 ka. Fourthly, the NEEM TAC observations (NEEM community members, 2013) cover the deepest section of the NEEM ice core from ~2200 to 2500 m depth (corresponding to an age of ~75 to 128 ka; not continuous) and an example for Holocene conditions from depths between ~100 to 1400 m (no age provided). ThirdlyFinally, the NGRIP TAC record (Eicher et al., 2016) includes the entire core from ~130 to 3080 m, however the sampling resolution varies. An age model is provided for the entire data set with an oldest a maximum age of ~120 ka. Finally, the GRIP TAC data set (Raynaud, 1999) covers depths from ~120 to 2300 m and ~2780 to 2909 m, while an age mode is only provided for the upper part (oldest ice 41 ka). For the deeper sections of the core, a published unfolding of the GRIP core (Landais et al., 2003, age bands in Fig. 3 therein) is used to assign an age to the observations. Note that only the Eemian sections for NEEM, GRIP, GRIP, GISP2, NEEM, and NGRIP are shown in Fig. 7.

The Eemian ranges in Fig. 6 are calculated as the mean (plus/minus two standard deviations) of the lowest 10 % of observed Eemian TAC (Fig. 7; used observations are indicated in orange) for NEEM and NGRIP. Due to the low number of Eemian observations at GRIP, a different threshold of 20 % is used for this core. For the calculation of the late Holocene ranges in Fig. 6, observations younger than 1000, 2000, and 4000 years, are used for GRIP, Dye-3, and NGRIP, respectively. The late Holocene range for NEEM is calculated from the entire Holocene example provided in the NEEM community members (2013) data (nine data points; no age provided).

Calculation of the model-derived total air content (TAC)

The model-derived TAC is calculated with the annual mean surface pressure and the annual mean near-surface temperature from the MAR regional climate simulations at every location of interest (Martinerie et al., 1992; Raynaud et al., 1997):

$$TAC = V_c \frac{P_c}{T_c} \frac{T_0}{P_0} \tag{1}$$

where V_c is the pore volume at close-off in cm^3/g of ice, P_c the mean atmospheric pressure at the elevation of the close-off depth interval in $mbar$, T_c the firn temperature prevailing at the same depth interval in K, P_0 the standard pressure

(1013 $mbar$), and T_0 the standard temperature (273 K). V_c is calculated as a function of T_c following an empirical relation (Martinerie et al., 1994; Raynaud et al., 1997):

$$V_c = (6.95 \times 10^{-4} T_c) - 0.043 \tag{2}$$

This theoretical TAC is then reduced (TAC_{red}) depending on the percentage of refreezing of the annual accumulation (RZ_{per}):

$$TAC_{red} = TAC \times \left(1 - \frac{RZ_{per}}{100}\right) + TAC_{refrozen} \times \left(\frac{RZ_{per}}{100}\right) \tag{3}$$

where $TAC_{refrozen}$ is calculated using Henry's solubility law (Sander, 2015) for N_2 and O_2 (neglecting other atmospheric gases) to account for air that is dissolved in the meltwater before refreezing:

$$TAC_{refrozen} = C_{a,N2} + C_{a,O2}, \tag{4}$$

with $C_{a,N2}$, and $C_{a,O2}$ being the aqueous-phase concentration of N_2 and O_2, respectively:

$$C_{a,N2} = P_c * C_{atm,N2} * H^{cp,N2} \tag{5}$$

and

$$C_{a,N2a,O2} = P_c * C_{atm,O2} * H^{cp,O2} \tag{6}$$

where $C_{atm,N2}$ and $C_{atm,O2}$ are the atmospheric concentration ratio ratios (0.79 and 0.21) and $H^{cp,N2}$, $H^{cp,O2}$ are Henry's solubility constants (10.49×10^{-6} and 2.1982×10^{-5}) for N_2 and O_2, respectively.

Henry's law assumes that the meltwater is in equilibrium with the ambient air at a temperature of 273 K and at the local atmospheric pressure (Eqs. 5 and 6). No air is occluded in the form of bubbles in the freezing process.

3 Results

Temperatures

The simulated pre-industrial The simulated PI annual mean (near-surface) temperatures at the seven (1850 climate forcing) at the eight locations of interest (Fig. 2; black columns; short bold lines - ensemble means; short thin lines - individual model years) generally fit well with annual mean temperature observations from weather stations (Fig. 2; long bold lines in black;

standard deviation in gray shading). However, the annual means inferred from 10 m borehole temperatures (Fig. 2; long bold lines in gray; average of the years 1980 to 2014) are consistently colder than the simulated ~~pre-industrial~~ PI means. The lower borehole temperatures ~~are probably related to the fact that they represent surface~~ represent snow temperatures which are typically ~~lower than near-surface~~ cooler than the ambient air temperatures. Only at the Agassiz site, the borehole temperatures are higher~~than the simulated temperatures~~. This exception is likely related to the usage of a substitute location (see Sec. 2).

The annual mean temperatures at most locations only vary by 0.5 °C between the time slice simulations, i.e., ~~a strong difference between the pre-industrial~~ no large difference between PI (Fig. 2; black) and ~~warm~~ warmest Eemian simulations (Fig. 2; ~~red and orange)is absent in the climate simulations~~orange). This is to be excepted since the annually integrated solar irradiance is similar in all time slices.

~~The simulated pre-industrial JJA (~~However, the varying Eemian seasonality (Yin and Berger, 2010) results in consistently ~3-4 °C (with respect to PI; black) warmer summer (JJA; June-July-August) temperatures at all locations for mid Eemian conditions (125 ka: orange) and cooler temperatures for late Eemian conditions (115 ka: blue). The simulated PI summer temperatures (Fig. 3; black columns; short bold lines - ensemble means; short thin lines - individual model years) ~~also~~ show good agreement with observations from weather stations (Fig. 3, long bold lines in black). ~~The climate simulations show consistently ~3-4 °C warmer temperatures (compared to pre-industrial; black) at all locations for mid Eemian conditions (125 ka: orange) and cooler temperatures for late Eemian conditions (115 ka: blue).~~

The precipitation-weighted temperatures (Fig. A1) ~~, which is arguably closer to what is recorded in an ice core,~~ show a similar pattern as the JJA temperatures (Fig. 3). ~~However, the precipitation-weighted~~ This is understandable since most precipitation in Greenland falls around the summer month and these temperatures are calculated by multiplying daily temperatures with daily precipitation, summing up the results over the year and then dividing by the sum of the annual precipitation, i.e., precipitation is used as a weight, instead of time in annual mean temperatures. Precipitation-weighted temperatures are arguably closer to what is recorded in an ice core (temperature at the time of deposition) and these temperatures show a less pronounced warming for mid Eemian conditions (125 ka: orange), i.e., maximum 3 °C warmer compared to ~~pre-industrial~~ PI (black).

Number of melt days

Passive microwave satellite data shows a strong difference in observed melt days per year (~~i.e.,~~ presence of surface water) (Fig. 4; first three columns from the left; brown and green) between central ice core locations (~~NEEM, EGRIP~~GRIP, GISP2, NGRIP, ~~GRIP~~NEEM, EGRIP), where surface melt is sparse, and locations closer to the margins (Camp Century, Dye-3) and ice caps (Agassiz), where melt is much more frequent. Central locations show between 0 and ~1 melt days year^{-1} in the last ~30 years for which satellite data ~~are~~ is available. The exact values vary depending on the location, satellite data set, and whether the extreme melt event of 2012 is included.

The simulated ~~pre-industrial~~ PI melt day frequency (Fig. 4, black columns) shows good agreement with the observations (Fig. 4; brown and green columns), i.e., low melt frequencies at the central locations and higher melt frequencies at locations at the margins. However, the simulated ~~pre-industrial~~ PI melt frequencies are ~~in general~~ generally lower than present-day observations (especially at the Agassiz location), with the exception of Dye-3 which shows a higher simulated melt frequency.

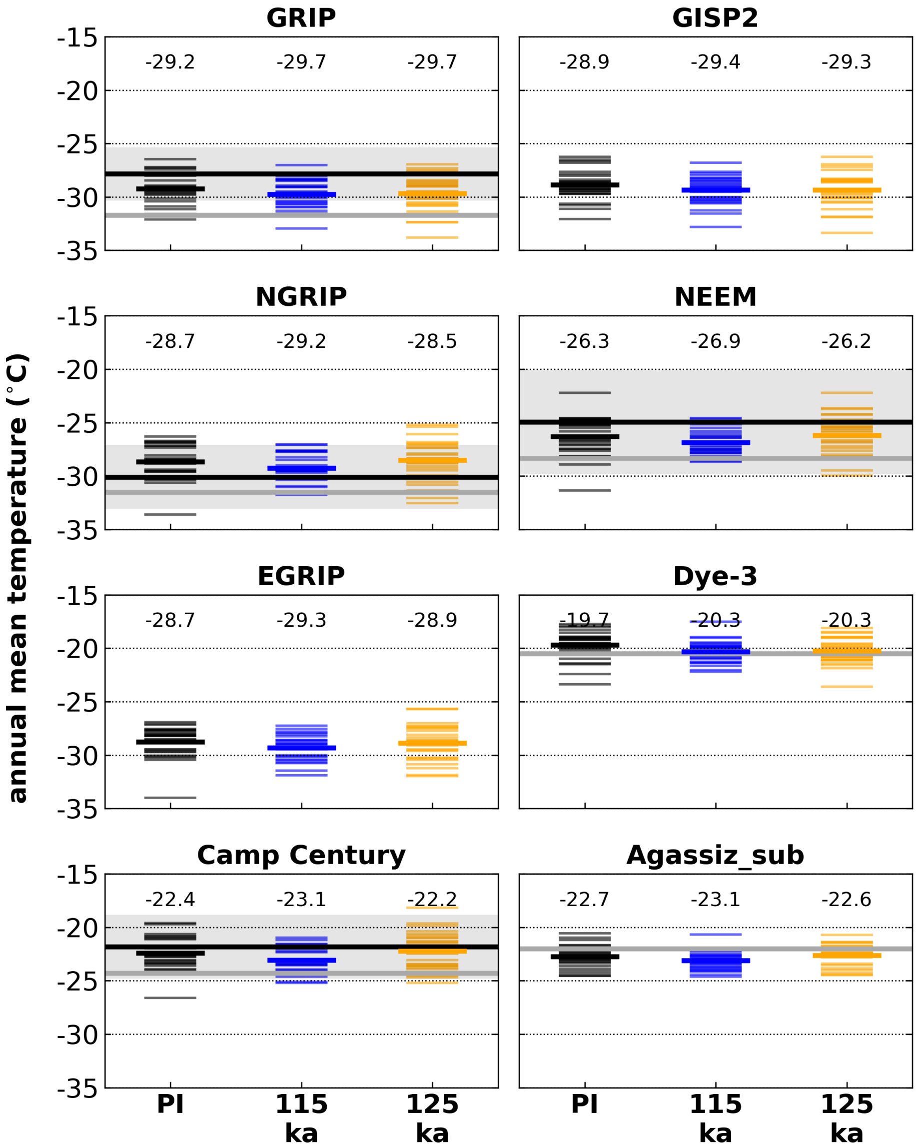

Figure 2. Annual mean (near-surface) temperature at Greenland ice core locations simulated by the climate model MAR for three time slices. Individual model years (short thin lines) and their mean (short bold lines, numerical values on top of columns) are compared to mean observations from weather stations (long bold lines in black), their corresponding standard deviation (gray shading), and 10 m borehole temperatures (annual mean; long bold lines in gray).

Melt and refreezing

The 125 ka simulations (Fig. 4; orange columns) show a significantly higher melt frequency at all locations (more than 30 melt days year^{-1} at Dye-3), compared to the ~~pre-industrial~~ PI simulations (Fig. 4; black columns) and observations

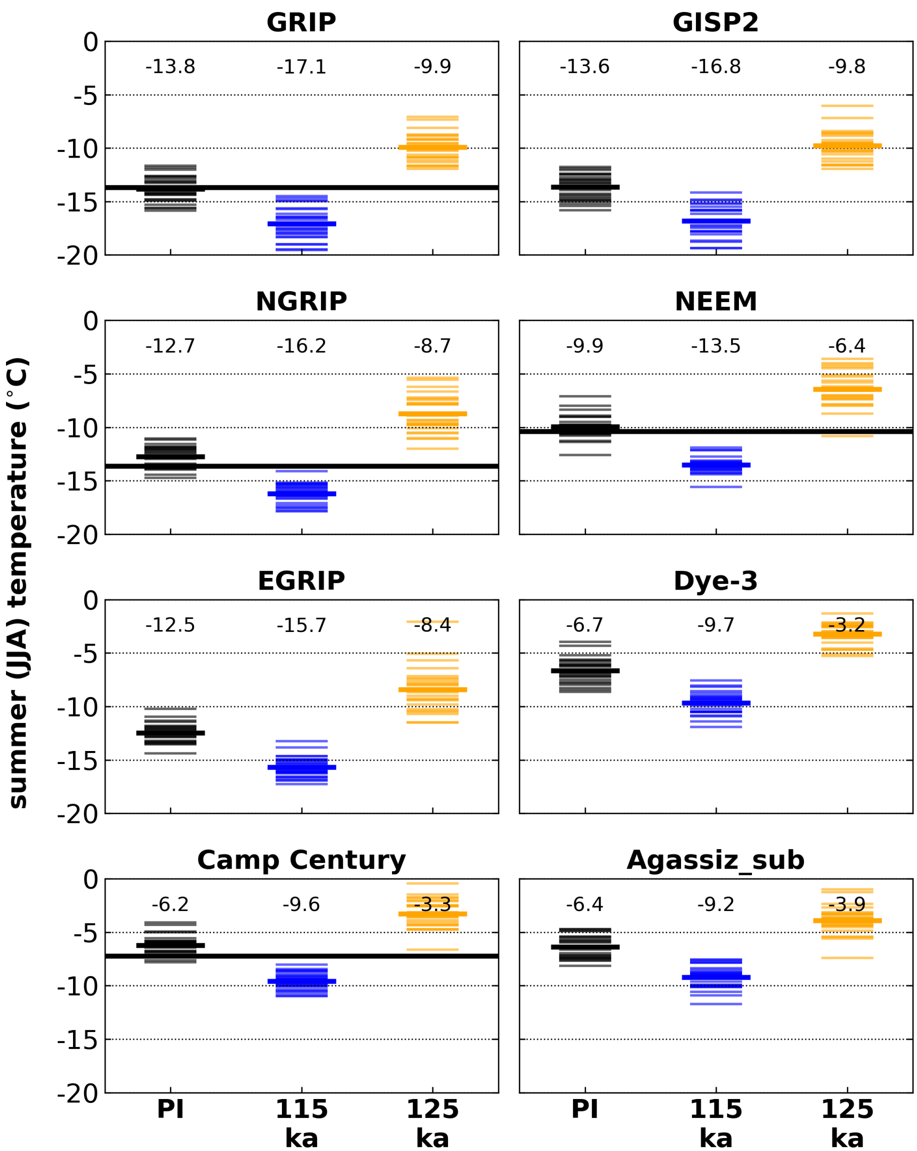

Figure 3. Mean (near-surface) JJA (June-July-August) temperature at Greenland ice core locations simulated by the climate model MAR for three time slices. Individual model years (short thin lines) and the mean (short bold lines, numerical value on top of columns) are compared to mean observations from weather stations (long bold lines in black).

(Fig. 4; brown/green columns). The SMB simulations show surface melt at all ice core locations during the warm mid Eemian with an annual melt water production (Fig. A2) for warmer locations of ~~~300-400~~300 mm w.e. year^{-1} (Camp Century) and ~~~600-700~~600 mm w.e. year^{-1} (Dye-3). However, even modern dry, high altitude locations show an annual surface melt of ~~~100~~60 (GRIP, GISP2), 80 (NGRIP) and up to 120 mm w.e. year^{-1} (~~GRIP, NGRIP,~~ EGRIP). NEEM shows ~~~200~~150 mm w.e. year^{-1} for the warmest Eemian simulations.

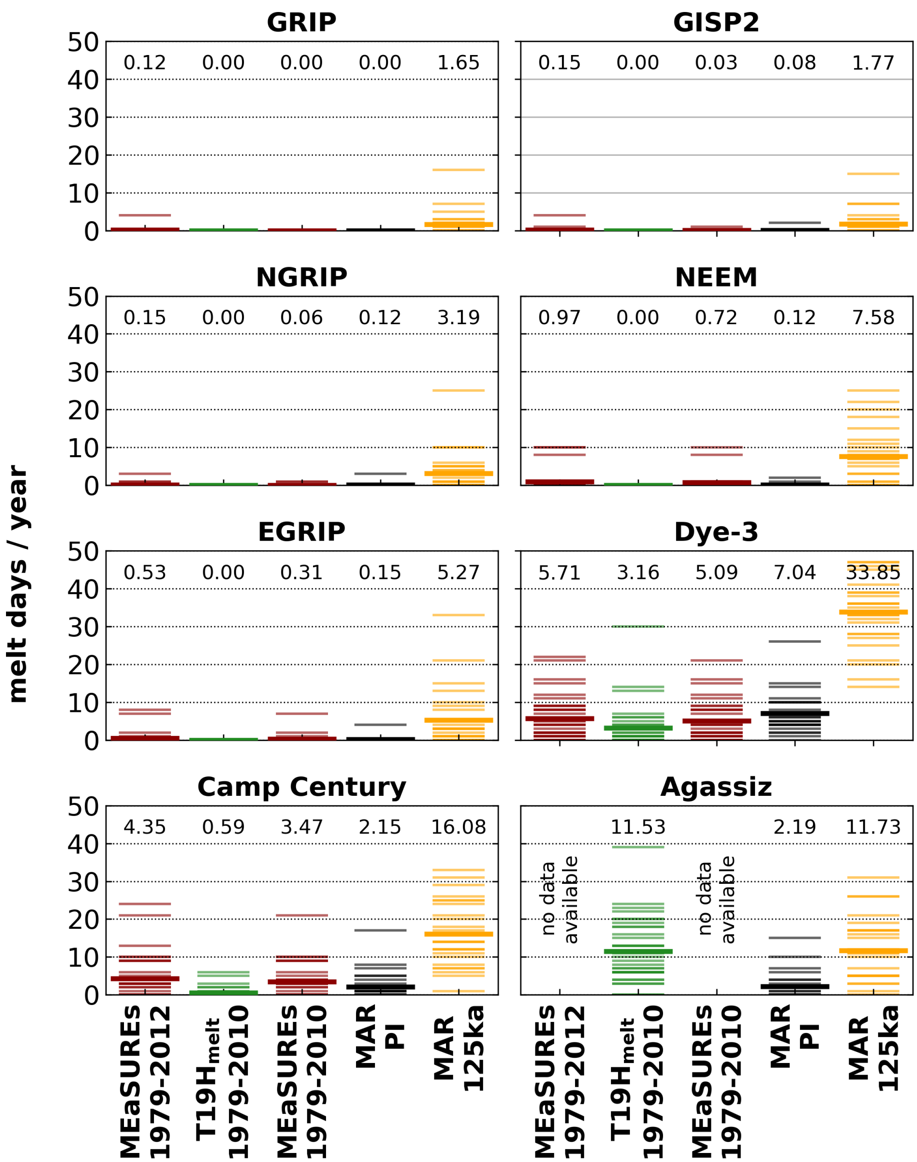

Figure 4. Annual melt days at Greenland ice core locations derived from satellite data and simulated by the climate model MAR. Observations in the first three columns from the left are compared with simulations in the fourth and fifth column. Columns from the left: (1) Passive microwave data from MEaSUREs (1979 to 2012); (2) The same data as in (1) but with a different processing (T19H$_{melt}$; Fettweis et al., 2011) (1979 to 2010); (3) the MEaSUREs data set excluding the extreme melt year 2012 (1979 to 2010); (4) Simulated melt for pre-industrial (PI) and (5) 125 ka conditions. Individual model years (thin lines) and the ensemble means (bold lines, numerical values on top of columns) are shown. For Agassiz, simulation results for the substitute location are shown; as discussed in Sec. 2.

The ~~simulated mean~~ mean simulated amount of refreezing exceeds 40 % of the annual accumulation at most ice core locations under warm mid Eemian conditions (Fig. 5; ~~red and orange columns~~thick orange lines). Even ~~the highest location, GRIP~~

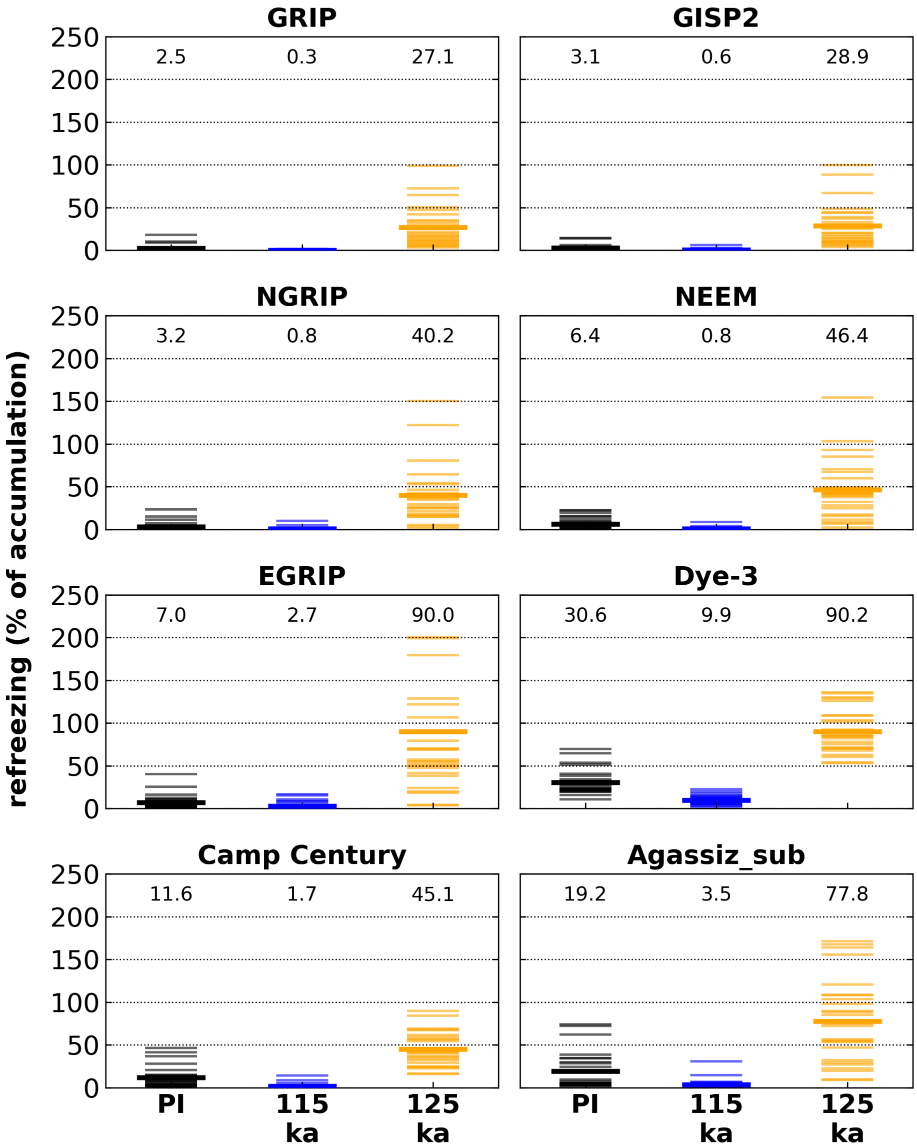

Figure 5. Annual refreezing percentage (of accumulation) at Greenland ice core locations simulated by the climate model MAR for three time slices. Individual model year percentages (thin lines) and the simulation ensemble mean percentages (bold lines, numerical values on top of columns) are shown.

at the highest locations, GRIP and GISP2 at ~3200 m elevation, ~~shows more than~~ refreezing surpasses 25% ~~refreezing~~ of the annual accumulation under 125 ka conditions. The largest amount of refreezing is simulated at ~~Dye-3~~Agassiz_sub, EGRIP, and ~~Agassiz_sub where refreezing percentage reaches~~ Dye-3 where refreezing percentages reach 80 to 90%~~and more~~.

Total air content (TAC)

Theoretical TAC derived from simulated surface pressure and annual mean temperature (Raynaud et al., 1997) and reduced according to the amount of simulated refreezing (Fig. 6 and Sec. 2) shows significantly lower values for the 125 ka simulations. Most of the higher ice core locations (GRIP, GISP2, NGRIP, NEEM, EGRIP and Camp Century) show simulated TAC values between ~~50~~45 and ~~60~~70 ml kg^{-1} on average, whereas the respective ~~pre-industrial~~ PI values are between 90 and 100 ml kg^{-1}. At Dye-3 the simulated TAC is ~~lower than 20~~about 25 ml kg^{-1} on average for the warm 125 ka Eemian simulations compared to 75 ml kg^{-1} during PI. Observed Holocene TAC from ice core records (Fig. 6; horizontal gray shading) fit well with the ~~pre-industrial~~ PI simulations, while observed Eemian TAC (Fig. 6; horizontal orange shading) is not as low as the simulated values.

The Eemian ranges in Fig. 6 are calculated as the average (plus/minus two standard deviations) of the lowest 10 % of observed Eemian TAC (Fig. 7; used observations are indicated in orange) for NEEM and NGRIP. Due to the low number of Eemian observations at GRIP and GISP2, a different threshold of 20 % is used for this core. For the calculation of the late Holocene ranges in Fig. 6, observations younger than 1000, 2000, and 4000 years, are used for GRIP, Dye-3, and NGRIP, respectively. The late Holocene range for NEEM is calculated from the entire Holocene example provided in the NEEM community members (2013) data (nine data points; no age provided).

Finally, TAC observations from the deeper ice core sections (i.e., possibly Eemian; Fig. 7; NEEM, GRIP, GISP2, NGRIP; circles; inverted y-axes) are compared with mean simulated TAC for 115 ka (Fig. 7; blue line) and 125 ka conditions (Fig. 7; orange line). For Dye-3 the entire TAC record is shown due to the lack of Eemian observations. ~~Note:~~ However, the ice at the bottom of Dye-3 has been shown to contain pre-Eemian ice (Willerslev et al., 2007). Note that NEEM and GRIP are shown against age based on a more robust chronology involving "unfolding the ice" (NEEM community members, 2013; Landais et al., 2003), while NGRIP and Dye-3 are shown against core depth.

The 115 ka simulations generally fit well with the late Eemian (NEEM, GRIP, GISP2, NGRIP) and Holocene (Dye-3) observations~~. While~~ , while the 125 ka simulations are lower than the observations. For ~~the NEEMdata~~NEEM, the lowest TAC ~~observation~~ observations are within the ~~gray shading which indicates the influence of melt at the ice core site (NEEM community members, 2013)~~ice core section influenced by melt (gray shading in Fig. 7; NEEM community members, 2013)
.

4 Discussion

The enhanced Eemian seasonality (Yin and Berger, 2010) and warmer Eemian summers (CAPE Last Interglacial Project Members, 2006; Otto-Bliesner et al., 2013; Capron et al., 2014) are indicators of elevated melt during this period. The recent extreme melt event in Greenland in 2012 and a similar event in 1889 (Nghiem et al., 2012) demonstrate that surface melt on the entire Greenland ice sheet, even at the summit of Greenland, is possible under recent climate conditions. Even though these extreme Greenland-wide melt events were caused by a rare large-scale atmospheric pattern (Neff et al., 2014) and were further

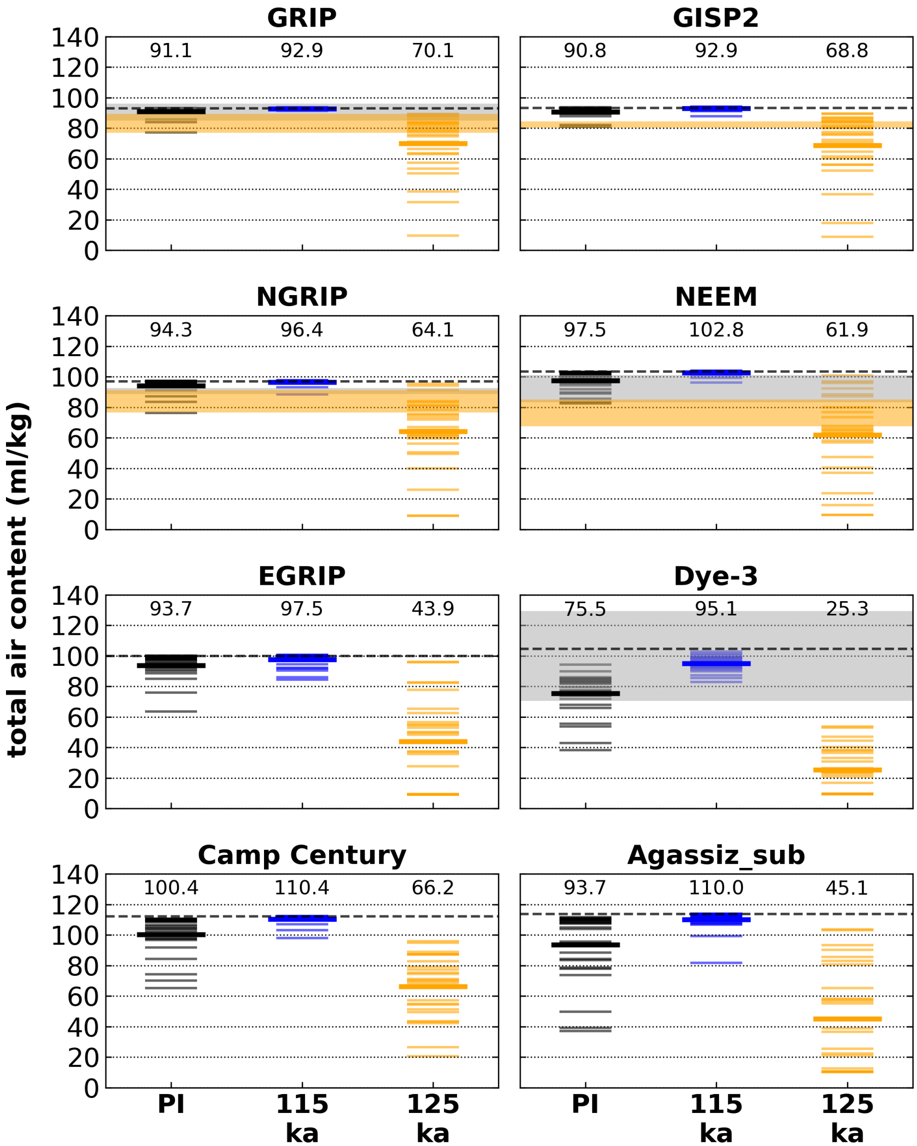

Figure 6. Calculated total air content (TAC) at Greenland ice core locations derived from simulations with the climate model MAR for three time slices (see method in Sec. 2). Individual model years (thin lines) and the simulation ensemble means (bold lines, numerical values on top of columns) are compared to observed late Holocene and Eemian ranges (horizontal gray and orange shading, respectively; two standard deviations). Dashed lines illustrate the model-derived TAC before reducing it by the refreezing percentage (not distinguishable for the respective time slices; see Sec. 2). Note: The Holocene range at NGRIP is very narrow and almost completely ~~overlapping~~ overlaps with the ~~respective~~ Eemian range and there is no Holocene range for GISP2 and no Eemian range for Dye-3.

enhanced by an externally caused albedo lowering (ash deposition from forest fires; Keegan et al., 2014), it is likely that such events are more frequent in a warmer climate such as the Eemian interglacial period.

The simulations discussed in this study (regional climate plus a full surface energy balance) indicate surface melt and refreezing (Fig. 4 and 5) at all deep Greenland ice core locations. Even central Greenland locations close to Summit (GRIP, GISP2) show a melt of ~~100~~~60 mm year^{-1} (Fig. A2). Due to this high surface melt, TAC derived from these simulations are between ~25 % (GRIP, GISP2) and ~80 % (Dye-3, EGRIP) lower than modern (~~pre-industrial~~PI) values (Fig. 6). Even though the presented climate simulations show such extensive melt, there are several reasons why these simulations can be interpreted as conservative estimates: (1) The simulated ~~pre-industrial~~ PI melt frequency is mostly lower than satellite observations (Fig. 4; black versus brown/green columns). However, the observation of higher melt frequencies can likely also be related to the effects of recent global warming which are not represented in the ~~pre-industrial~~ PI climate simulations. (2) Processes like ash deposition which were partly responsible for the extreme Greenland melt events of 2012 and 1889 (Keegan et al., 2014) are not simulated. (3) The climate simulations ~~do not include a lowering~~ use a fixed, modern ice sheet geometry and including the neglected lowering and retreat of the Eemian ice sheet ~~surface which would likely enhance the simulated warming~~ would likely increase the simulate warming in many regions.

Many studies suggest a substantial Eemian ice volume reduction (e.g, Van de Berg et al., 2011) particularly in the marginal regions — an overview of previous Eemian studies can be found in Plach et al. (2018a). The use of a fixed ice sheet undoubtedly adds additional uncertainties to the presented melt simulations — e.g., neglecting modifications of local wind patterns and surface albedo as regions become deglaciated impacting local near-surface temperature (Merz et al., 2014a), local orographic precipitation following the slopes of the ice sheet (Merz et al., 2014b), or increased katabatic winds caused by steeper ice sheet slopes (Gallée and Pettré, 1998; Clec'h et al., 2019). However, these uncertainties are much stronger in marginal than in high altitude regions where the ice elevation changes were more limited. After all, a future, more exhaustive evaluation of Eemian melt at the ice cores sites should investigate different possible ice sheet geometries.

Furthermore, the absence of a simulated annual warming, and proxy data showing Eemian peak temperatures as high as +7.5 ± 1.8 °C (NEEM community members, 2013, without altitude corrections) and +8.5 ± 2.5 °C (Landais et al., 2016) for NEEM (the North Greenland Eemian Ice Drilling project in northwest Greenland), and +5.2 ± 2.3 °C (Landais et al., 2016, lower bound as the record only starts after the peak Eemian warming) for NGRIP (North Greenland Ice Core Project) indicate that the climate simulations might ~~be cold~~ include a cold bias. The simulated JJA temperatures (Fig. 3) and the simulated precipitation-weighted temperatures (Fig. A1) show a peak warming of only ~3-4 °C and ~3 °C, respectively. However, the fact that NEEM community members (2013) infer an elevation (at the deposition site) of several hundred metres higher than at NEEM today complicates the interpretation of how well the simulated temperatures fit the proxy-derived observations. ~~If the estimated NEEM deposition site was lower than inferred, e.g., stronger influenced by melt, then the warming of ~8 °C at constant elevation would be too high and the simulations would fit better.~~

Focusing again on the comparison of melt observations and simulations (Fig. 4), a strong underestimation of melt at the Agassiz site in the ~~pre-industrial~~ PI simulations becomes apparent. This strong underestimation is likely related to the ~~fact that~~ use of a substitute location ~~for the ice cap is used, i.e., a model location~~ (geographically shifted, with similar model and observed elevation~~is chosen. The selection of the substitute location is necessary , because the~~) necessary due to low model topography at the original core ~~locations causes~~ site causing unrealistically high melt simulations. Furthermore, the Agassiz site is only covered by the satellite data set which appears to be less sensitive to melt (T19H$_{\mathrm{melt}}$ ~~), i.e., T19H$_{\mathrm{melt}}$ shows~~ less melt than MEaSUREs at all ~~investigated locations. And~~ sites) and although Eemian ice is absent at the Agassiz site, the simulated Eemian refreezing percentage (Fig. 5) of approximately 80% is consistent with the Agassiz melt record which indicates ~~100% melt~~ a complete melt of the annual accumulation during the Holocene optimum ~10-11 ka (Fisher et al., 2012; Lecavalier et al., 2017).

Another important aspect for the ~~interpretation of the simulated melt~~ melt interpretation is the formation of melt layers and the amount of meltwater needed to form a (visible) melt layer. While the presented TAC calculations assume Henry's solubility law (Sander, 2015) for the air content of the melt layer, the formation of a melt layer in an ice core is a complicated process, e.g., depending on prevailing snow properties. A higher number of melt layers is not just the result of uniformly higher summer temperatures, but ~~the result~~ a combination of an increased contrast between the pre-melt snow pack temperatures (strongly influenced by winter temperature) and the summer melt rate (a function of summer temperature) (Pfeffer and Humphrey, 1998). Therefore, the enhanced Eemian seasonality might have been favourable for the formation of melt layers.

The simulated ~~TACs for~~ 125 ka ~~conditions are mostly~~ TACs are consistently lower than the observations (Fig. 6 and 7)~~particularly at GRIP, NGRIP, and Dye-3. At NEEM on the other hand~~. However, at NEEM — the ice core with the most complete Eemian record (likely including peak warming) — the simulated 125 ka TAC ~~matches well with~~ seem to be most similar to the lowest observations, indicating that the high amount of simulated melt could explain these observations. The variability of the observed NEEM TAC in the suggested melt zone between 127 and 118.3 ka (gray shading; NEEM community members, 2013) is large, likely due to the varying influence ~~(i.e., number)~~ of melt layers.

The Eemian TAC measurements at GRIP, GISP2, and NGRIP also show reduced values (not as low as at NEEM), which can be interpreted in a similar way as at NEEM — GRIP, GISP2, and NGRIP might have been influenced by Eemian melt as well. The simulated 125 ka TAC for ~~both~~ all three locations are strongly reduced (relative to ~~pre-industrial~~ PI levels), but do not reach levels as low as at NEEM. However, these reduced TAC levels could ~~still~~ indicate significant surface melt.

Overall the lack of a better agreement between observed and simulated Eemian TAC (i.e., few TAC observations as low as the simulations) could be related to the sparse number of Eemian peak warming observations (most ice core records only start after the peak warming; particularly at GRIP, GISP2, NGRIP, and Dye-3). However, another possible explanation could be a shift of the precipitation rates in central Greenland towards much higher values during the Eemian interglacial period. Unfortunately, accumulation rates are unconstrained for the Eemian sections of Greenland ice cores.

Furthermore, another uncertainty to the interpretation of the simulations is the effect of the higher Eemian summer insolation on the TAC. An anti-correlation between local summer insolation and TAC is known in ice core records from East Antarctica during the last 400000 years (Raynaud et al., 2007) and the insolation signal is also found in Greenlandic TAC (NGRIP, Eicher et al., 2016). NEEM community members (2013) estimate (based on data from the Holocene optimum) that the summer insolation could account for 50% of the observed Eemain TAC changes at NEEM.

Nevertheless, the possibility of a melt-induced reduction of TAC should be considered for the interpretation of Eemian air content ~~as~~ to estimate ice surface elevation changes. An early interpretation of the first Greenland ice cores (Camp Century, Dye-3) suggested an extreme scenario for Eemian Greenland with extensive melt ~~of the entire ice sheet~~ and a much smaller ice sheet leading to a sea level rise of 6 m (Koerner, 1989). However, this scenario was rejected by later ice core studies showing evidence of Eemian ice (especially NGRIP and NEEM; North Greenland Ice Core Project members et al., 2004; NEEM community members, 2013). Furthermore, GRIP TAC measurements (Raynaud, 1999) have been interpreted as evidence for the elevation of the summit sites having remained above 3000 m of altitude during the Eemian and GRIP deuterium excess measurements remain in the normal range during the Eemian (Landais et al., 2003). However, this last interpretation can be challenged by measurements of a NEEM Holocene melt layer, suggesting that the melt layer mainly influences TAC and CH_4 observations, while other variables like deuterium excess may be less influenced by melt (NEEM community members, 2013).

The climate simulations show surface melt at all deep ice core locations and at the Agassiz ice cap under 125 ka climate conditions (Fig. 4 and A2; orange column). Even locations near the summit of Greenland (NGRIP and GRIP) show several melt days (i.e., GRIP, GISP2, and NGRIP) show a few melt days year^{-1} on average (defined as >8 mm day^{-1}) during these warm Eemian simulations. NEEM, the ice core location with the longest Eemian record, shows ~108 melt days year^{-1}. While the presence of Eemian surface melt at NEEM was acknowledged previously (NEEM community members, 2013), the lower TAC observations at GRIP, GISP2, and NGRIP could as well be related to Eemian surface melt, rather than stable or higher elevations.

FurthermoreFinally, it should be emphasized that a robust estimate of Eemian Greenland surface melt is challenging to accomplish with the results of obtain with a single climate model. It would be highly advantageous to have Ideally there should be an ensemble of climate models to explore model biases and uncertainties. However, as pointed out earlier in this discussion, there are several reasons why the presented climate simulations could be interpreted as conservative on the lower end of available climate model in terms of the amount of simulated Eemian melt. It is likely that there are other climate models which might show more extensive Eemian surface melt.

In the future, an analysis of individual or ensemble Eemian climate simulations would benefit from a comparison of the observed extreme melt event in 2012 (and similar events in the recent past) with simulated extreme Eemian melt events. Relationships between simulated variables such as surface in the Eemian simulations between air temperature and local wind patterns, and the simulated melt could be analyzed and then be used in order used to identify specific weather patterns leading to the simulated high surface melt on Greenland.

in the simulations (e.g. similar analysis performed by Neff et al. (2014); Keegan et al. (2014); Fettweis et al. (2013b); Tedesco and Fettw
).

5 Conclusions

The Using regional climate simulations (including a full surface energy balance) discussed in this study show this study shows surface melt at all Greenland ice core locations during the Eemian interglacial period (e.g., GRIP, GISP2: ~60 mm w.e. year^{-1}; NGRIP: ~150 mm w.e. year^{-1}). The amount of simulated refreezing exceeds 25 % of the annual accumulation at the summit of Greenland (GRIP, GISP2) and reaches values as high as 90 % at less central locations like Dye-3 and EGRIP. The simulated air pressure, temperature, and refreezing are used to calculate estimates of estimate Eemian total air content which (TAC) and high melt rates could explain the lowest low corresponding ice core TAC observations. This is true even though the discussed simulations could show conservative melt estimates , i.e., the simulations neglect processes which would likely increase the melt(several potentially melt-increasing processes are neglected). Therefore, the possibility of widespread surface melt should be considered for the interpretation of Greenlandic total air content records (as an elevation proxy) from warm periods such as the Eemian interglacial period. In the futureFinally, a robust map of Eemian melt estimates in Greenland could be used in combination with patterns of accumulation accumulation patterns could be used to identify potential sites for future Greenland ice cores . This future ice cores sites on Greenland. Such a procedure would increase the chances of finding well-preserved Eemian ice without or with less influence by Eemian ice influenced by a minimum amount of melt layers. These sites will have relatively high accumulation combined with low surface melt.

6 Code availability

The MAR code is available at: http://mar.cnrs.fr (last access: 25.0527.11.2020)

7 Data availability

The Eemian MAR simulations are available from the corresponding author upon request. *MEaSUREs Greenland Surface Melt Daily 25km EASE-Grid 2.0, Version 1* (Mote, 2014) is freely available at: https://nsidc.org/data/nsidc-0533/versions/1 (last access: 25.0527.11.2020). For more information and to request the $T19H_{\mathrm{melt}}$ data (Fettweis et al., 2011) please contact Xavier Fettweis (xavier.fettweis@uliege.be). For more information and to request the collection of Greenland shallow ice core and weather station data (Faber, 2016) please contact Anne-Katrine Faber (anne-katrine.faber@uib.no). The TAC observations at NEEM (NEEM community members, 2013) are freely available at: http://www.iceandclimate.nbi.ku.dk/data/ (last access: 25.0527.11.2020). The GRIP TAC (Raynaud, 1999) is freely available at: https://doi.pangaea.de/10.1594/PANGAEA.55086 (last access: 25.0527.11.2020). The GISP2 TAC is freely available as a supplement to Yau et al. (2016). The NGRIP TAC (Eicher et al., 2016) is freely available at: https://www.ncdc.noaa.gov/paleo-search/study/20569 (last access: 25.0527.11.2020). For more information and to request the Dye-3 data, please contact Sindhu Vudayagiri (sindhu.v@nbi.ku.dk) or Thomas Blunier (blunier@nbi.ku.dk).

Appendix A: Appenix A

Author contributions. AP and BMV designed the study with contributions from KHN. Dye-3 total air content data was extracted from Fig. 4 in Herron and Langway (1987) by SV. AP made the figures and wrote the text with input from BMV, KHN, SV, and TB.

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

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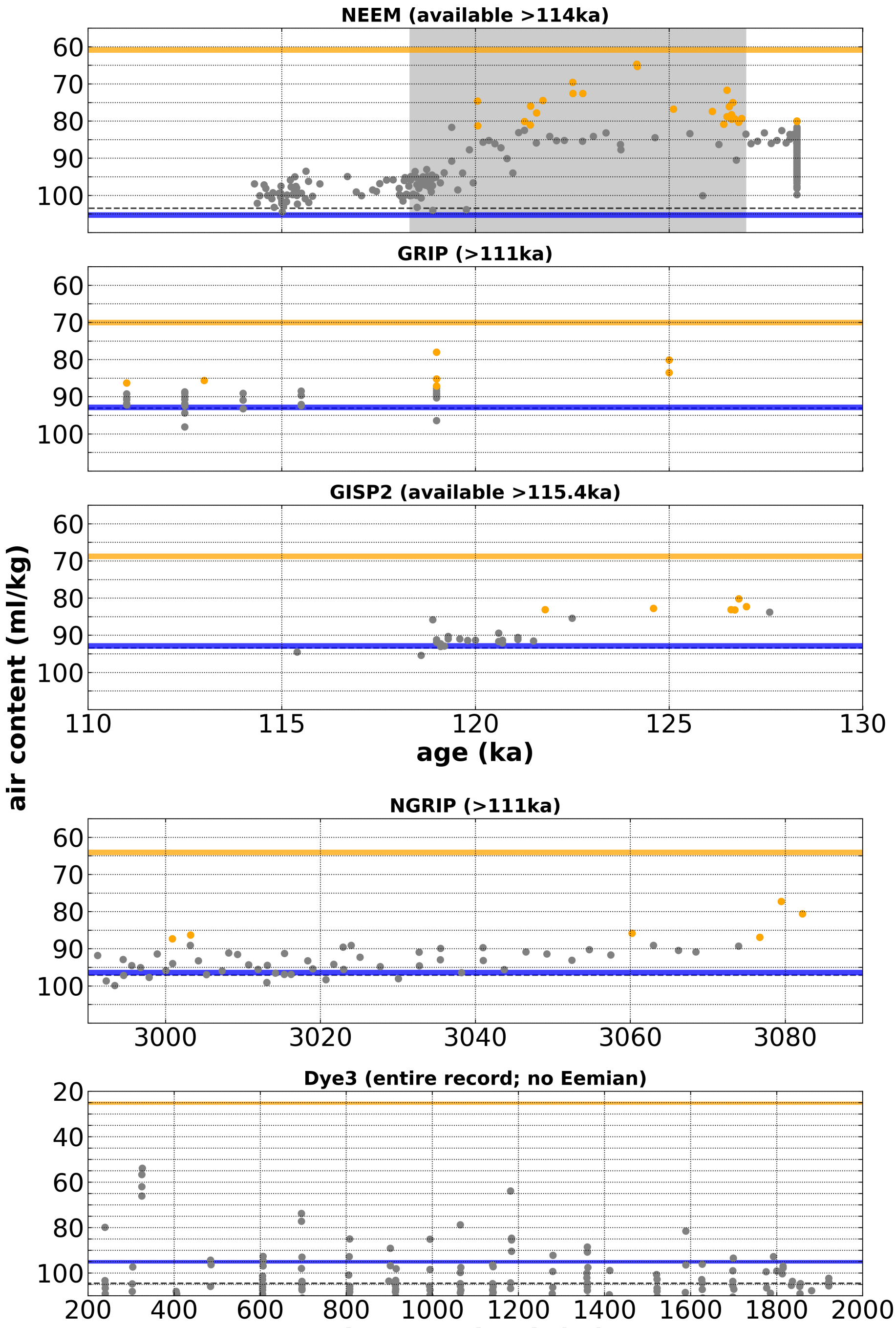

Figure 7. Observed TAC from ~~four~~ five Greenland ice cores — NEEM, GRIP, GISP2, NGRIP, Dye-3. Observations (circles) are compared with mean simulated TAC for 115 ka (blue ~~horizontal~~ lines) and 125 ka simulations (orange ~~horizontal~~ lines). ~~Data~~ Furthermore, data points used to calculate the Eemian range in Fig. 6 ~~are indicated with~~ (orange circles) and the model-derived TAC before reducing it by the refreezing percentage (dashed lines; see Sec. 2) are shown. Note: NEEM~~and~~, GRIP, and GISP2 are shown against age ~~due to their~~ (robust age ~~model~~models), while NGRIP and Dye-3 are shown against ice core depth. The NEEM melt zone (NEEM community members, 2013) is highlighted with a gray shading. The y-axes are reversed.

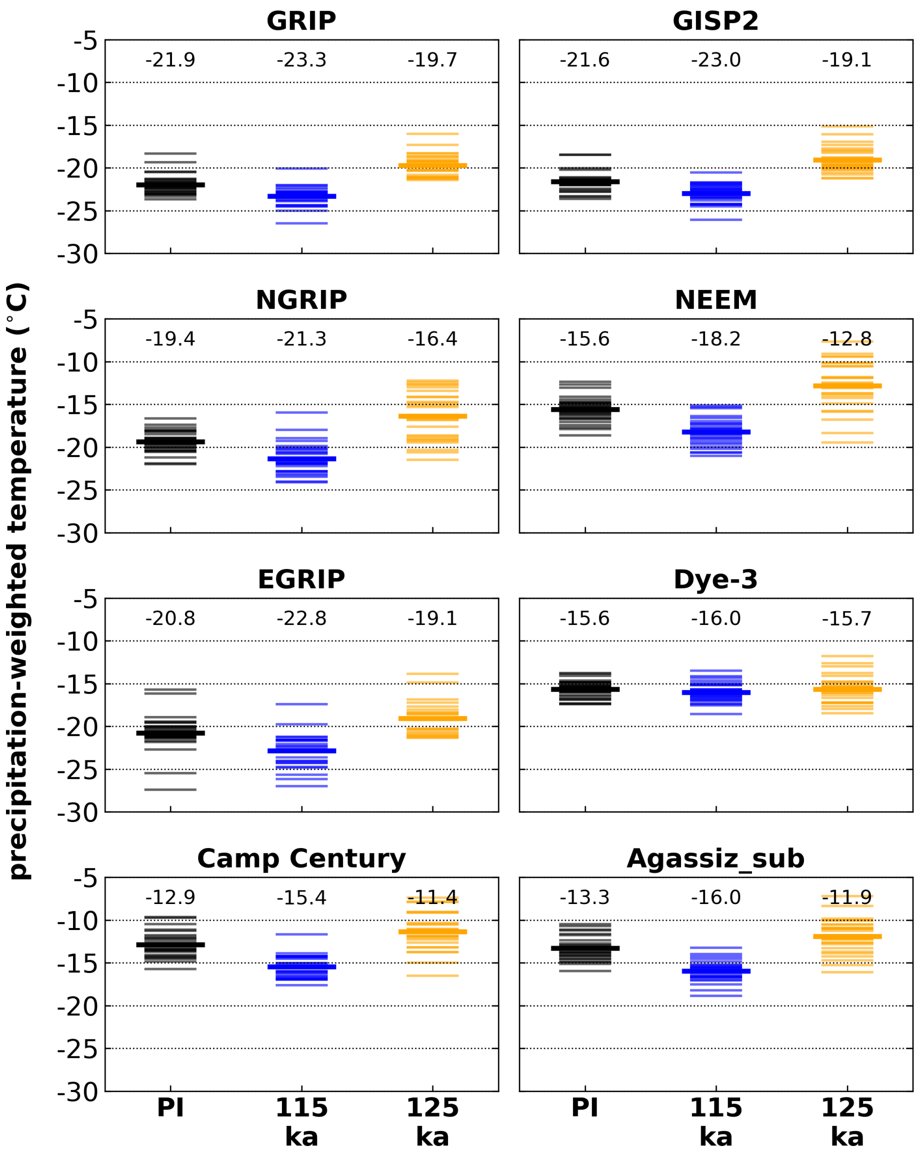

Figure A1. Annual mean precipitation-weighted temperature at Greenland ice core locations simulated by the climate model MAR for three time slices. Individual model years (thin lines) and the mean (bold lines, numerical values on top of columns) are shown.

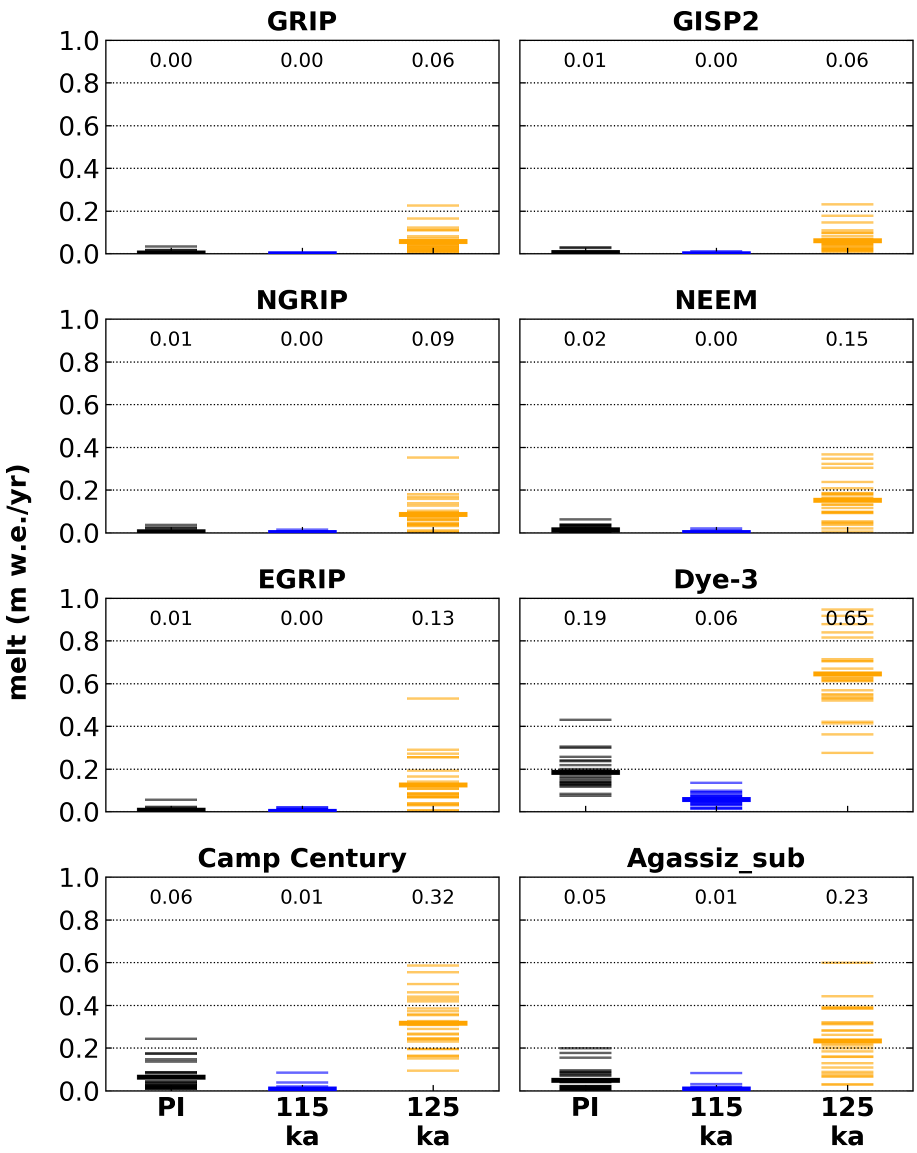

Figure A2. Annual melt at Greenland ice core locations simulated by the climate model MAR for three time slices. Individual model years (thin lines) and the mean (bold lines, numerical values on top of columns) are shown.

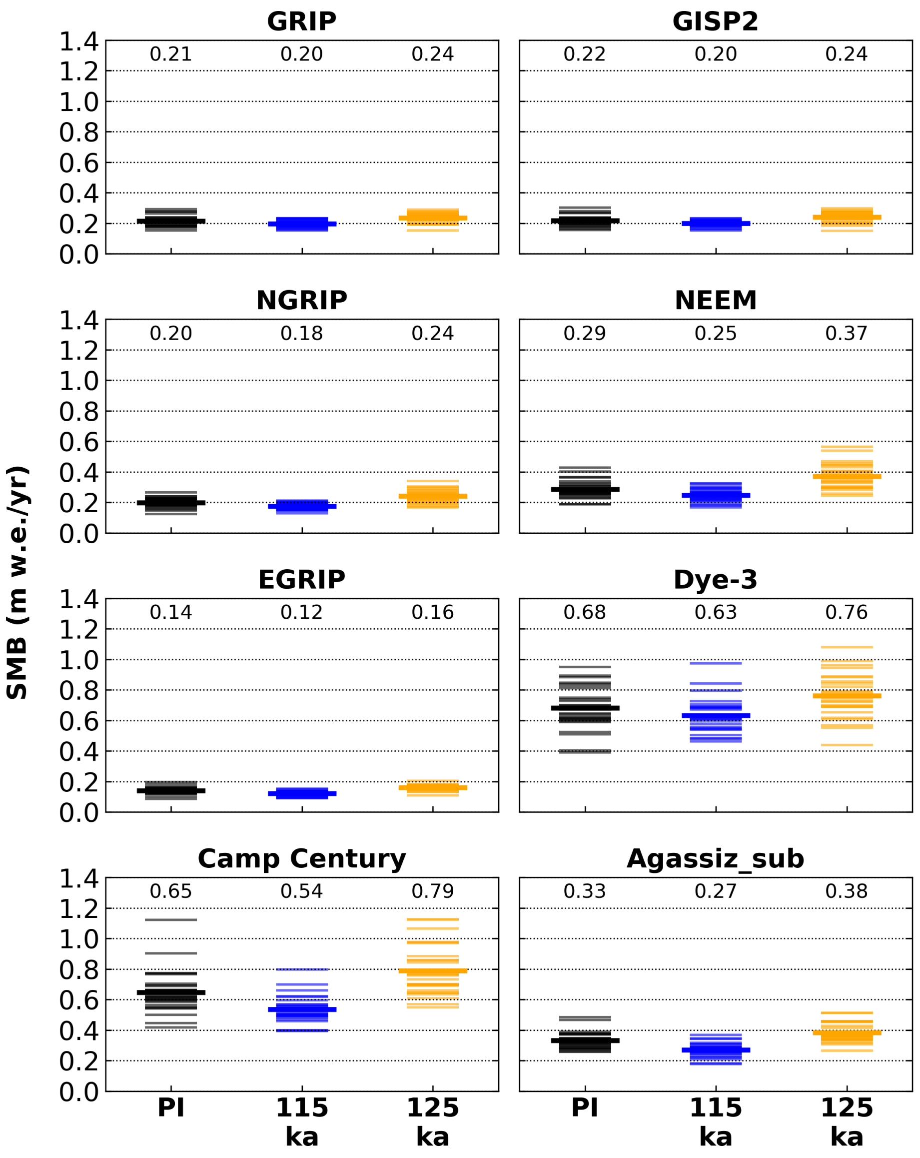

Figure A3. Annual Surface Mass Balance (SMB) at Greenland ice core locations simulated by the climate model MAR for three time slices. Individual model years (thin lines) and the mean (bold lines, numerical values on top of columns) are shown.