

We would like to thank the reviewer for taking the time to consider the manuscript in details and for the great suggestions that will improve the coming version of the manuscript. Detailed replies are given in the following.

On behalf of the co-authors
Helle Kjær

Comment on cp-2021-99

Anonymous Referee #1

General comments

The manuscript is focused on the analysis of the chemical records obtained by CFA from 6 shallow firn cores retrieved along the NEEM - EastGRIP Scientific Traverse. The Authors present a study of both spatial variability along the 6 sites spanning West to East

Greenland and temporal variability, after yielding an ice core chronology, basing on annual layer counting. As regarding the latter, dust concentration of size-sorted particles was used to spot possible local dust sources, free acidity and conductivity were employed to detect volcanic eruptions and a stacked ammonium record was found as a valuable proxy of forest fires in Northern America.

The paper presents an ample set of new data which can be useful to a broad community of scientists involved in recent climate reconstructions from ice core records and I find it apt to be published on Climate of the Past eventually.

We thank the reviewer for recognizing the ample work put into this manuscript as well as its usefulness for the community.

However, I find that the manuscript should go through some consistent revisions.

Some parts of the text, e.g. ice core chronology (see Specific Comments) should be better detailed and deserve a further short discussion.

We have extended this section to further elaborate the methods used to date the cores and added Figures to the supplementary that illustrates the dating better.

A general English revision is also suggested: the text is usually easy to read but sometimes sentences look as broken or dashed off hurriedly and should be rephrased. Furthermore, there are many basic format and punctuation issues which can be easily fixed.

We will carefully go through each sentence for a next version.

Here below I am listing some specific remarks to help in this process.

Specific comments

Abstract

Line 18 page 1 (and related Table 2). "Annual mean and quartiles of the...": the sentence is not immediately clear upon reading if one has not gone through the text We will revise the sentence

And Table 2 could be accompanied by a figure showing the overlap of data distributions to better appreciate it. For instance, a box and whiskers plot could be helpful, but any other solution is welcome. We thank the reviewer for this great suggestion and will add a whiskers plot of the data also presented in Table 2 and Figure 1, to better illustrate the data distributions.

■ Materials and methods

Lines 14-16 page 4. Melting a firn core is always a critical issue and certainly deserves some more precautions with respect to ice core sections. A melt rate of 4 cm/min sounds fine but probably even a higher rate would work. The addition of a metal coin is interesting, and I guess it is to separate the melting section from the head so that the produced water stays in contact with the firn section as little as possible, but the authors are invited to add some details about the metal coin addition. It could be better shown also in Figure S1 (here metal coin is not visible).

Indeed, the coin works to limit contact of water on the melt head with that of the snow/firn. Especially it limits the percolation into the firn by limiting contact between pores and water.

We will revise supplementary Figure 1 to illustrate better the coin and add a few sentences more on the effect of such a coin and its benefits for melting firn.

A higher melt rate could perhaps also work, but we found this low melt rate in balance with our pumping setting made the optimal amount of water available, so that water on the melt head was at all times limited to a minimum amount thus also minimizing the percolation into the firn, that is unavoidable despite the coin minimizing it.

Section 2.1. Core chronology. As a general remark on the section, I would invite the Authors to complete it because it lacks some details in my view.

We have chosen to split the datasets presented here into two publications. An extensive discussion of the dating, the peroxide and the subsequent accumulation is part of another paper, currently under preparation. We had hoped that this paper by now would have been finalized, but unfortunately that is not the case. We realize that this other paper is not clearly mentioned in this section. Thus we will revise the section "Core chronology" to add more details as requested.

In particular, the Authors should find a way to better show the seasonal pattern of the chosen marker, maybe making lines thinner in Figure 2 and possibly adding a figure with a close-up on a few years. It would be also interesting to read a brief discussion on the stability/loss of H₂O₂ seasonality as depth increases. It cannot be appreciated from Figure 2. We will revise Figure 2 to make it a full page figure, we will further add to the supplementary for each core a plot of the Ca²⁺ and peroxide on a depth scale including vertical lines illustrating the individual years. We note that the combined seasonality of the marker chosen is shown also in Figure 3 top and second left plots (H₂O₂ and insoluble dust).

Moreover, the Authors are invited to briefly mention the reasons why they have chosen to use only annual layer counting for the dating without using volcanic

signatures of acidity and conductivity, since they have used them to study the spatial variability of volcanic eruptions in section 6.1. We have chosen to use mainly the peroxide for making the timescale, because one of the goals was to see if one could identify spatial shifts in seasonality of the other proxies. Thus by using mainly peroxide to generate the age scale (the only proxy directly related to the annual solar cycle) we hoped to see variability in the other proxies with time. Unfortunately, the signal for the low accumulation sites were not sufficient to keep the annual cycle with depth of peroxide, and in sections where H₂O₂ did not have a clear annual cycle, insoluble dust seemed to be the second most stable in having a clear annual cycle.

When looking into also the reference horizons section 6.1 we have off course also gone back and evaluated if we could argue for more or less years in some of the records to make the reference layers more consistent (e.g., between A1, A2 and A3), however we found no clear years that could be added nor removed, which would make both ammonium layers and acid layers consistent between the three cores west of the ice divide. Thus in the end we went with the simple annual layer counting, not to force layers to be consistent, but to argue in section 6.1 that we cannot rule out them being the same when only 1 yr apart.

We have reformulated in the section "chronology" as follows ". While others of the proxies analysed also show a strong annual cycle (see Figure 3) we stick to a dating based on mainly H₂O₂ (or Ca²⁺). This is because one of the aims of the study is to investigate the seasonal cycle between sites. In addition, we note that acid horizons are commonly used to match ages between cores. However, we have chosen not to do so, as another aim for is to investigate if the acid layers in recent time do deposit between all sites. The total age of each core and the uncertainty was defined as $\pm \frac{1}{2}$ a year for each uncertain year and can be found in Table 1.."

■ Spatial variability

Figure 2 page 6. As mentioned above, Figure 2 is very relevant and necessary to the manuscript but the concentration profiles from all the cores cannot be well appreciated. A simple way to make it all clearer without redrawing completely the figure is to use slightly thinner lines or maybe dashed or dotted lines for one or two cores. Any idea from the Authors in order to make it more readable is welcome.

We will revise Figure 2 to make it more readable and add additional Figures in the supplementary for each core, as well as add a whiskers plot as suggested as a supplement to Table 2.

Lines 13-14 page 7. Is 5 ppb a mean or median or which other reference value? Anyway, one only value as a term of comparison is not sufficient to state that "...no significant recent increase" is observed with respect to the rest of the Holocene. Please, provide a better support to this statement.

We are in this section comparing core medians with the available other published records For the Holocene we are comparing with the NEEM record (Schüpbach et al., 2018, Fig 3). The 5 ppb NH₄⁺ (Schüpbach et al, 2018, Fig3 a) is a median over the Holocene recorded of the deep NEEM record and ours from the NEEM site have a median of 5.8 ppb with 2.2 and 10.8 being the 15 and 85% quantiles respectively. Thus the two datasets are comparable and we find it fair to write the statement. We have however that this relates to the NEEM site only.

Lines 2-4 page 8. More than relative variability (which is lower in the NorthWest than Central and NorthEast – 15% vs. 25%, respectively), absolute values are higher, accordingly with post-depositional processes Authors mention.

We are not certain we understand the reviewer comment. Could the reviewer reformulate the concern?

We write that peroxide concentrations northwest of the ice divide is larger than east of the divide, as a result of photolysis causing loss of the deposited H₂O₂ at low accumulation sites (east~11 cm water equivalent accumulation annual at EastGRIP vs ~25 cm/yr at NEEM).

If the concern is that there is a larger relative variability in the 15 and 85 percentiles compared to the median west of the divide than east, we would explain that by an also more sporadic accumulation scenario east of the divide between years. However, we find it beyond scope to go into that detail in this paper. The issue and others with regards to accumulation and peroxide is discussed in another paper under preparation on accumulation and peroxide covering this same 6 firn cores.

Lines 5-6 page 8. Are 2 mS and 5 mS average values? Which is the associated variability? This can be important to know to evaluate if the two values are significantly different. The 15 and 85% quantiles are shown in Figure 2, as referenced in the text, but we will add a whiskers plot to further make it easier for the reader to appreciate the variation in the records.

■ Seasonal cycles

As a general remark for this section and for Figure 3, I don't find text and figure consistent: Figure 3 displays "formal season" instead of "formal month". The Figures are made based on formal months as described in the text. However, to appreciate the fact that such formal months are likely not true months, we have chosen to label the Figure with seasons only rather than months. In the discussion of section 4, we however often refer to the formal months as some proxies peak in eg. Formal month april-june, which is something between spring and summer. We acknowledge that it can make it hard to compare the text with the Figure and will therefor add also to the Figure the formal months and make the text more consistent so it refers to both seasons and formal months throughout.

Besides, seasons are reported from the right to the left (if I well interpreted) while it would be easier if they were shown in the opposite direction. I can understand that ice core records go backwards in time but in this case I find it confusing. We will reverse the direction

Also, I would replace the term "Excess" in Figure 3 with "anomaly" or, at least, would explain it well also in the caption. We use the word excess when referring to the data after removing the 5 year running average- we will clarify this in the first sentence of section 4-seasonal cycles and in the caption of the Figure showing the seasonality and stick with the word excess as this "excess" contains both the seasonal cycle, but also extreme events such as volcanic eruptions and forest fires.

We will as be suggested reverse the seasonality to go from left to right.

A higher definition would be helpful for Figure 3. We will improve the resolution

Line 30 page 10. It is not clear if the Authors refer to reproducibility here, how it is calculated and how “site specific noise” was evaluated. The issue of “noise” is recurring through the text, rightly so, and it deserves a more detailed discussion. We will evaluate this and other sections to be more concise about the phrase “noise”. Further we will add the suggested whiskers plot and a table of correlation values between the records to better argue our claims.

■ Temporal trends

Line 14 page 11. Again, the reference to “noise” should be made clearer. Do the Authors refer to the whole core or just to the most recent part? Even though median and topical quantiles are reported in Table 2, the calculation of trends and related significance would be important, in my opinion. The possible existence of trend cannot be read immediately from the Table. We will add a figure in the supplementary similar to S2 of the acid. Further we will rephrase the specific sentence; “Unfortunately, the interannual variability in the acidity record is large making it difficult to assess the temporal trend (Table 2). This is mainly a result of the measurement technique being subject to flow sensitivity (Kjær et al., 2016), but also influenced by individual peaks associated with volcanic events (discussed in section 6.1).”

■ Extreme events

I would add a mention in the section (for instance after Line 3 page 15) to the fact that other markers different from the ones analysed here can be more specific for detection and assessment of impact of volcanic eruptions (for instance, non-sea salt sulphate) as well for annual layer counting. The Authors could refer to some topical papers in the field, such as Sigl et al. (2016, CP) and Severi et al. (2012, CP). We will add as suggested “Also we note that other markers are more specific to volcanic eruptions than the ones used in this study, e.g. non sea salt sulphate or S isotopes.”

Line 32 page 18 – lines 1-2 page 19. Since the Authors state (lines 9-11 page 5) that only hydrogen peroxide (with a supportive contribution of calcium) was used for dating, cannot understand now if the dating of A2 and A4 cores was tuned by using ammonium record, in the end, in order to achieve a definitive ice core chronology. It could be reasonable but it deserves a brief discussion since the time scale is basic to go on with further data interpretation. We are sorry that the text was not clear.

Indeed, only hydrogen peroxide and to some extent ca was used for the dating. However, annual layer counting is as I suspect the reviewer well knows, to some extent a subjective method, where some years can be hard to distinguish. Thus all records were annual layer counted by multiple individuals who in a few cases chose different annual peaks, allowing for some dating uncertainty as shown in Table 1. However, in the end one timescale focusing on H₂O₂ and calcium for the dating was chosen. Thus for most of these records as also indicated in table 1, the age is subject to some uncertainty. When investigating the peaks in ammonium, we found it surprising that the peaks between 1990-2000, looked similar in spacing but shifted. Thus here we merely test if shifting the records, the allowed ± 1 yr makes the correlation to the Canadian fire index better. This shift is only invoked in this section and thus is not used in any other part of the records shown, and did not improve the correlation to the fire index either.

We have rephrased this section

"The dating for especially the eastern cores are uncertain. This allows the records to be shifted and thus as a test we shifted A2 and A4 to be one year younger, to better match the peak in 1998 and thus improve the combined proxy, however changing the dating in such way does not improve the ammonium composite ability to work as a proxy for Canadian forest fires (R-0.48, $p10^{-4}$, 1987-2015). "

And in the section about chronology added the information;

"Several of the other proxies analysed also show strong seasonal cycles, however as one of the aims of the study is to investigate the seasonal cycle between sites, we stick with a dating based on mainly H₂O₂, as it is the one proxy most direct related to the solar cycle. In addition, we note that acid horizons are commonly used to match ages between cores. However, we have chosen not to do so, as another aim for is to investigate if the acid layers in recent time do deposit between all sites investigated. The total age of each core and the uncertainty was defined as $\pm \frac{1}{2}$ a year for each uncertain year and can be found in Table 1."

Supplementary Material

Figure S1. As mentioned above, please add the detail of the metal coin to the figure, since I have gathered that it is relevant to prevent the by-side effect to "backward sucking" and cannot be appreciated from the figure. Besides, a slightly higher definition for the figure would be welcome. **The figure will be modified as suggested**

Technical corrections

Abstract

Ok Line 23 page 1. I would replace "contribute" with "ascribe"

okLine 29 page 1. English check suggested: "peak ammonium" and "peak volcanic layers" should be corrected.

Introduction

OkLine 8 page 2. English correction: "ammonium peak concentration" should probably be "ammonium concentration maxima" or similar.

Ok Line 12 page 2. Add full stop and the end of the sentence (similar missing punctuation issues all through the text).

Ok Line 15 page 2. English change suggested: maybe "has facilitated" could be replaced by something more apt, such as "allowed obtaining".

Methods

OK Lines 26-27 page 2. Please check the format of NEEM and EastGRIP site coordinates.

Ok Lines 5 and 6 page 2. Check punctuation: remove an "and" and insert semicolon.

Figure 1 page 3. The labels of the red circles indicating the drill sites overlap one with the other and cannot be read easily. **A new map have been prepared**

Ok Table 1 caption, line 7 page 3. The reference is written in a different format from the rest of the text.

Line 6 page 4. In my opinion, "acid" is too vague and not corresponding to what is measured. It should be replaced by another expression, such as "acidic content", "free acidity" or just "H+" or any other apt wording. This remark holds for the whole paper (e.g. already a few lines later, line 8, again "acid").

We have changed accordingly and call it acidity when referring to the acid measure in the firn cores using the dye technique, as also done in Kjær et al. 2015 and Winstrup 2019 and acid when referring to volcanic eruptions as that can be many types of acid.

Ok Line 10 page 4. I guess the Authors refer to 8 pieces, each 55 cm long, please correct the expression in brackets.

OK-only found this one place Line 17 page 4. Please correct ammonium formula using superscript. Check carefully these format issues all through the text.

Ok Line 20 page 4. I would replace "in sufficient resolution" with "with sufficient resolution".

OK Line 22 page 4. I would write "it is produced" adding a verb. Otherwise, please rephrase.

Ok-rephrased Line 27 page 4. "Sufficiently high enough" contains a repetition, I find.

Ok Line 3 page 5. Please use the same shortened name for the same core (e.g. 2015T-A6 or T2015-A6).

Lines 6-11 page 5. There is probably an issue with tense of verbs; please choose past tense (as mostly used in the rest of the text) or present.

Corrected to 15 and 85 both places. Table 2 caption page 7. It is quite peculiar that you use 15th and 85th percentile here while you use 16th and 84th percentile in Figure 3; I don't think it changes the result, of course, am just curious to know.

■ Spatial variability

OK Figure 2 caption page 6. As remarked earlier, I would replace the expression "acid", here and through all the text.

Ok Table 2 (page 6 and 7). Please, check the format of the analysed parameters (namely superscripts and symbol for "micro").

OK Table 2 caption (page 6 and 7). I would add some details for the unit of measurement for dust in the Table or in the caption. Is it "#" referring to the total number of particles or to one particular size range?

OK Line 10 page 6. They are not "estimates", actually; I would use the word "measurements".

Rephrased Line 11 page 7. "Lower estimate": what do the Authors mean with it? The minimum value? A small percentile?

OK Line 15 page 7. Please, add the right symbol ($\pm$).

Line 20 page 7. "Counts mL⁻¹" is an unit of measurement for a signal, not for a concentration, which I find it more correct, to estimate a noise (signal is highly variable among different instruments, also in the case of dust measurements, I believe).

Unfortunately we do not understand this reviewer comment, could the reviewer please re-iterate the concern. The dust is measured in counts of particles (1-10 μm) per mL?

■ Seasonal cycles

Ok Line 5 page 10 (also line 18 page 18). Please add brackets for publishing year for Gfeller et al. (2014).

OK Line 8 page 10. As above.

■ Temporal trends

Is present McIlhattan, E. A., Pettersen, C., Wood, N. B., and L'Ecuyer, T. S.: Satellite observations of snowfall regimes over the Greenland Ice Sheet, The Cryosphere, 14, 4379–4404, <https://doi.org/10.5194/tc-14-4379-2020>, 2020
Line 19 page 11. The reference does not appear in the Reference list.

Ok Line 21 page 11. Please, correct of format of "micro", also later in the section

Ok Line 29 page 11. "assuming all spheres were perfectly round": would rephrase f.i. "assuming all particles are perfectly round".

Rephrased Lines 4-5 page 12. Please, rewrite the sentence starting with "Thus"; it appears to be broken.

"The largest particles ($>10.5 \mu\text{m}$) are omitted from further analysis as they are subject to poor statistics and the smallest sizes ($<1.25 \mu\text{m}$) as well as they are noisy"

Rephrased Line 6 page 12. I would complete the sentence this way: "...parting the data set this way..."

"We find that by parting the dust data this way we have 12-28% of the total dust in the small range..."

OK Table 3 page 13. check format (width of the first column, superscript in header of the second column, ...)

■ Extreme events

OK Line 3 page 16 and line 5 page 17. Check format (superscript in km^3).

OK -found only this and one other incidence Line 17 and line 31 page 16. Please, do not use the shortened expression "1986 Nov" and similar in the text

Rephrased Line 5 page 17. After "...eruption signal" the sentence is not clear, please rewrite.

Ok Line 23 page 18. Naming the sites located west of the ice divide would help the reader who is not extremely familiar with Greenland morphology.

Ok Lines 28-29 page 18. Please check the format of p value.

We will redraw the lines Figure 6 page 19. Dotted lines for the fire records are not well visible.

Ok Line 5 page 19. ">97.5% of full records": I assume the Authors refer to the 97.5th of each full record but it would be useful if they report it explicitly.

OK Line 18 page 20. No capital letter is needed for "levoglucosan"

OK Line 19 page 20. I believe "high concentration values" or "concentration peaks" are missing in the sentence. Same at line 10 for dehydroabietic acid and **line 14** for fire tracers.

OK Line 13 page 20. NEEM is with capital letters.

We will add this information. Line 21 page 20. I am sure this correlation coefficient (is it R or R², by the way?) is highly significant but the Authors could report the associated significance and the number of data as well.

Conclusions

OK Line 7 page 21. Please correct the symbols of "micro".

OK Lines 9-10 page 21. Please, correct the format of publication year for Nagatsuka et al. and Amino et al. Again, the sentence starting with "Thus" appears to be broken, please rephrase.

Data availability

OK Please check punctuation and core names.

References

Yes published Lines 24-26 page 24. This paper should be published now and not on TCD anymore; please, update.

Supplementary Material

OK Line 3 page 3. Please correct format for hydrogen peroxide (subscripts)

