

We thank the reviewer for taking the time to consider the manuscript and the excellent ideas regarding Tables and Figures, which we find significantly improves the readability 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 #2

Referee comment on "NEEM to EastGRIP Traverse – spatial variability, seasonality, extreme events and trends in common ice core proxies over the past decades" by Helle Astrid Kjær et al., *Clim. Past Discuss.*, <https://doi.org/10.5194/cp-2021-99-RC2>, 2021

Review of manuscript cp-2021-99:

"NEEM to EastGRIP Traverse - spatial variability, seasonality, extreme events and trends in common ice core proxies over the past decades" by Helle Astrid Kjær et al.

This study presents new impurity data from six firn cores taken along a spatial transect in North Greenland and measured with a Continuous Flow Analysis system. The data are investigated in regard to their mean seasonal cycle, their temporal trends and their usability for indicating volcanic events and as a forest fire proxy. While the results could be of interest to the ice core and proxy community and hence to the *Climate of the Past* readers, I rate this paper to not sufficiently well communicate the novelty of the results and its overall presentation quality to be poor. In brief, I recommend the paper to be rejected.

We thank the reviewer for recognizing the importance of the records presented here to the community and are sorry that the reviewer finds the communication of the results not sufficient. We are hopeful that with the great comments and suggestions from both reviewers a second version of the manuscript will succeed to communicate the novel results from these 6 firn cores.

Major comments

Overall structure and writing. In my opinion, the text seems carelessly assembled and is poorly written. Many parts and sections lack a clear structure, most notably the abstract and the various results sections. Especially regarding the latter, there is no clear distinction between the presentation of the study's results and their discussion. While the journal offers the possibility of a combined results and discussion section, I find it unusual that the authors chose to start many sections with some kind of short literature review before they actually present their own new results.

We thank you for these comments and have removed large parts of the introduction from Section 4, 5 and 6 to the introduction. But we have chosen to keep the results and discussion part together, as we deliberately chose this format because the proxies inform on very different parts of the climate system.

Thus we find the reader could be from a variety of backgrounds perhaps interested in just one particular proxy. The way we have written section 4, 5 and 6 it would be easy for the reader to identify which part of the paper is of their main interest.

Additionally, results are very often stated or mentioned without any clear reference to a figure or table, which makes it difficult for the reader to retrace and verify a particular result.

We will double check that Tables and Figures are referenced the appropriate places.

Regarding the writing, the text suffers from frequent grammatical mistakes and "orphan sentences" which lack a subject or syntactically just peter out.

We will work on improving the English level throughout.

Figure quality. The figure quality is very poor overall. The resolution is too low, making the graphics grainy already at standard zoom, the labeling is faint and too small, and the line plots are thin and are using color scales that are very hard to distinguish and are even indistinguishable for color-blind people. I would strongly recommend the authors to study how to produce higher-quality graphics from the computer program in use, either by using scalable vector graphics or by using a sufficiently high dpi value for raster graphics. In addition, color scales which are legible for color-blind people and sufficiently distinct both for on-screen viewing as well as printing can be looked up on resources such as <https://colorbrewer2.org>. We will modify plots accordingly and ensure they are of sufficient quality.

Local deposition noise. Local deposition noise, and also the noise from intermittent precipitation, is an important issue but not treated appropriately in this study. It is either mentioned somewhat unmotivated, as is the case for example on P10 Line 29, or only briefly referred to at instances scattered throughout the text. In the recent years quite some literature was published on these topics, both for Greenland and Antarctica, which could be used to put the current data into context. While the available data might be a bit limited for this purpose, one could perform at least some statistical investigations, e.g., looking at the correlations between profiles at seasonal and annual resolution to see if there is any common signal among the cores along the traverse, depending on the impurity species. We note that correlations between the NH₄ records are discussed in the section about forest fires and presented in supplementary section S4, but we have chosen due to the length of this paper not to add the correlations between all records. However, we will add a Table of this to the supplementary and discuss it in section 4.

Trends (Section 5). In general, it is very difficult to follow from where you derive your results and conclusions about the various trends. Overall, the paper would benefit from showing additionally a plot with the annual mean time series for the individual impurities, maybe even showing only stacked annual mean time series from averaging across the firn cores in favor of a clear presentation. Then, clearly stating the results from linear regressions on the data, including slope uncertainty and p values, might help creating a concise picture on the overall trends. The temporal trends discussed for the acid/conductivity are not linear with time. We found that Figure 2 of the conductivity is enough to show the trend of a return from a 1970's high. In addition, we have in the supplementary already added a 5 year running average for each core of the conductivity (Figure S2)

showing clearly the decline from the 1970's. The acid as also mentioned in the text is subject to more annual variability and to measurement noise, but we will add in the supplementary a Figure similar to S2 of the acid.

In case of insoluble dust fluxes, you do use annual mean time series, but for unknown reasons they are relegated to the supplement, and the trend results mentioned in the text are hard to verify by looking at Fig. S3. Maybe a logarithmic y axis scaling and adding the trend lines to the plot might help here. We have chosen to present the trends and p-values of the dust in Table 3 and added the annual dust loads in Figure S3. Figure S3 is already rather busy, so adding trend lines seems to only make matter worse.

Section 6. Overall, these sections are overly detailed, making it hard for the reader to grasp the main conclusions you want to convey here. One idea could be to put all of the results concerning the determined extreme and volcanic events, and the possible sources thereof, into a table, maybe also giving some indication for how certain you can be on relating a specific event in the records to a known eruption or other source. Then, the text could be significantly shortened to concisely present the main findings and conclusions from this table, which could make it much clearer for the reader how the new data can possibly advance our knowledge on the mentioned topics. We would like to thank the reviewer for this excellent suggestion. We have added a Table providing overview of the volcanic eruptions/forest fires observed in this study and other records where they are identified and added headers to the text to make it easier to grasp.

Minor comments

General. Frequently, the term "excess" is used to refer to specific data series, however, what this terminology means is nowhere explained. This is problematic since it is firstly not a common terminology for data series, and secondly it might be confused with the quantity of "deuterium excess" commonly measured on firn and ice cores. From what I understand, your usage of "excess" refers to either the deviations from the mean of the seasonal cycle data (Fig. 3), which more commonly would be referred to as "anomalies", or to the residuals after subtracting a five-year running mean from the data series (e.g., Fig. 4). I would suggest to adopt a more appropriate terminology or to clearly define your usage of the term "excess" in the Methods. We thank the reviewer for this comment. Our usage of excess throughout refers to what is left after removing the running 5 year mean, we use the word excess as what we have contains the seasonal cycle as well as extreme events and any measurement and site specific noise. Thus we find that neither the word residuals or anomalies are quite adequate for what we have left. We will define the term and use at first occurrence in the manuscript.

We have added the following "We remove the five year running average and in the excess investigate the seasonal cycles by formal month (Figure 3). Thus this seasonal cycle of excess concentration after removing the five-year mean contains also extreme events such as forest fires and volcanic horizons, which is however discussed in more detail in section 5-Temporal trends."

Title. I find the title too long and too general, merely listing key words rather than naming the key essence of the paper. In addition, the title should not have a full stop (I am referring to the pdf version here). Should be gradients if this title is used. As the cores represent a number of proxies, it is hard to describe the content of the paper without a long title. We have modified to "Canadian forest

fires, Icelandic volcanoes and increased local dust observed in six Greenland shallow ice cores”

Abstract. In my opinion, the abstract could be significantly shortened to convey only a brief introduction as well as the key messages and results of the study. There are several unnecessary filler sentences, e.g., “The temporal variability of the records is further assessed”, “By creating a composite based on excess ammonium compared to the five year running average...” etc.

We have rewritten the abstract:

“Greenland ice cores provide information about past climate. Few impurity records covering the past two decades exist from Greenland. Here we present results from six firn cores obtained during a 426 km long northern Greenland traverse made in 2015 between the NEEM and the EGRIP deep drilling stations situated on the Western and Eastern side of the Greenland ice sheet, respectively. The cores (9 to 14 m long) are analysed for chemical impurities and cover time spans of 17 to 50 years (± 3 yrs) depending on local snow accumulation that decreases from west to east.

The high temporal resolution allows for annual layers and seasons to be resolved. Insoluble dust, ammonium, and calcium concentrations in the 6 firn cores overlap, and also the seasonal cycles are similar in timing and magnitude across sites, while peroxide (H_2O_2) varies spatially because it is accumulation dependent and conductivity likely influenced by sea salts, also vary spatially.

Overall, we determine a rather constant dust flux over the period, but in the recent years (1998-2015) we identify an increase in large dust particles that we ascribe to an activation of local Greenland sources. We observe an expected increase in acidity and conductivity in the mid 1970’s as a result of anthropogenic emissions followed by a decrease due to mitigation. Several volcanic horizons identified in the conductivity and acidity records can be associated with eruptions in Icelandic and in the Barents Sea region. From a composite ammonium record we obtain a robust forest fire proxy associated primarily with Canadian forest fires ($R=0.51$). We find that ammonium peaks in the individual cores appear more scattered between cores than the volcanic layers, suggesting that the forest fire signal is more dispersed in the atmosphere than the acid from volcanic eruptions.

“

P2L17. Maybe here a word about possible complications with CFA measurements is appropriate, such as the intrinsic diffusion-like smoothing of the CFA system.

Modified “... despite its intrinsic dispersion of the signal and small sample loss around core breaks and is favored for the effective sample decontamination and high sampling resolution (Breton et al., 2012; Erhardt et al., 2022).”

P2L19-23. I find the here-stated motivation for the paper a bit vague, e.g., “constraining proxies analysed by means of CFA” could be understood in a technical sense from a measurement quality point of view, which is I guess not what you have in mind. Could you elaborate more precisely on the main aims of the study? We have reiterated the text “We evaluate the impurity concentrations as determined by means of CFA in six shallow Northern Greenland firn cores across Northern Greenland sites. The cores are dated individually to allow comparisons of temporal and spatial trends in both mean concentrations and seasonal cycles. Further we investigate extreme events, such as the deposition from forest fires and volcanic eruptions, and their representation between the 6 sites. The sites chosen cover the lower accumulation area in the central North

Greenland and has only limited prior analysis of this kind (Du et al., 2019a; Vallelonga et al., 2014; Fischer et al., 1998; Gfeller et al., 2014; Schüpbach et al., 2018; Kjær et al., 2021a). ”

P4L6. I guess by “acid” you refer to the H⁺ measurements here, which is, however, unclear at this point, since you use one or the other term throughout the text, and it is also a bit misleading, since in normal language acid could mean any kind of acid (I guess you refer to the Brønsted–Lowry acid definition here?). Please choose one terminology, introduce it here and then use it consistently throughout the text. *Thanks for pointing this out. We will call it acidity when referring to the acid measure in the firm 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.*

The same goes for the other species, which you alternatingly refer to either by their chemical composition (e.g., NH₄⁺) or by the common name (i.e., ammonium). The text would be much easier to follow if you stuck to one option throughout. *We will change from the spelled out version to the chemical version as suggested (NH₄⁺, Ca²⁺ and H₂O₂).*

P5L1-11. This method description is hard to follow and seems incomplete. What I understand you do in essence is seasonal layer counting to derive an age-depth relationship for your cores, for which you use the peroxide mainly, and additionally calcium, if the former has not good enough quality. *Indeed, that is the case. We have rewritten the text to clarify.*

What remains a bit unclear is how you derive the age scale in Fig. 2; I guess you use the age-depth relationship from the peroxide peaks to interpolate your depth series into a time series using the constant accumulation assumption stated in the second paragraph.

However, this is not entirely clear since you mention the equal accumulation assumption and formal month definition only in relation to “investigating the seasonality” (Fig. 3). *We have rewritten the chronology section to make the methodology related to the making of age scale more transparent.*

In addition, from the caption of Table 2 it seems that you block-average your depth series data into monthly means following the formal month definition; is that correct? If so, it should be mentioned here. *The section have been rewritten.*

P5L6-9. But could you maybe give an educated guess for how far off you might be with the constant accumulation assumption from the actual seasonal accumulation variations? *It is hard to make such an educated guess, as that would require knowledge about daily or seasonal accumulation. This kind of data is available from EastGRIP and NEEM from weather stations, but only for a short time period of a few years. For the remainder of the sites no such weather station data exists. Thus we have chosen not to go into this discussion. Re-analysis data from central Greenland get the annual mean accumulation wrong by factors of ~30%, and thus I would expect the seasonal data to be potentially worse. Thus this approach as also mentioned in the text seems not viable.*

That noted, for NEEM Gfeller et al. (2015) states; *“Model evaluations of summer–winter accumulation ratio show consistently more accumulation during summer than during winter (Steen-Larsen et al., 2011). Accumulation data from the*

Greenland Climate Network (GC-Net) Automated Weather Stations (Steffen et al., 1996) at NEEM and Humboldt (closest automated weather station to NEEM) show significant gaps due to power failure but, nevertheless, they point to a more equal summer to winter ratio than in the model."

Suggesting our equal accumulation scenario is fair. We have added the following line to highlight that "Accumulation from the GC network at NEEM suggests that a fairly equal summer to winter ratio (Gfeller et al., 2014), while at EASTGRIP unpublished data suggest July to October to hold about 2/3rds of the accumulation."

P5L13. "profiles": If I understand your methods correctly, Fig. 2 actually shows monthly mean time series for the individual impurity species and cores. This should be explicitly mentioned/repeated here to ease understanding and to avoid confusion with the original depth series. *No the data presented in Figure 2 is in full resolution on a timescale (better than monthly)*

P7L5. Do you mean the interannual variability here? Where do I see that the variability is large, and what do you mean with the "concentration variability between sites is masked"? *The section has been rewritten. We have further added a whiskers plot to better illustrate the data*

"The interannual variability in the individual records is large for all proxies. Spatial concentration changes (Table 2, Figure whiskers) between sites in insoluble dust, Ca_2^+ , NH_4^+ , H^+ , and conductivity is not easy to distinguish from the variability within the data caused by the annual variability and site specific noise despite the firn cores spanning a distance of 426 km and accumulation (Table 1) being double or more in the northwest (T2015-A1, T2015-A2, T2015-A3) compared to the central north and northeast (T2015-A4, T2015-A5, T2015-A6) (Kjær et al., 2021b)."

P7L19-20. How do you derive that conclusion, based on the values in Table 2? Did you perform any statistical test to check whether the null hypothesis of identical mean and/or distribution cannot be rejected? *Yes, the conclusion was derived based on the values in Table 2 solely. We will add a table of correlation values between records in supplementary and in main text when relevant.*

P8L2-4. Speaking of spatial variability here is misleading, since variability is more commonly understood to mean random variations. I could imagine what you instead observe here is a spatial gradient in concentration due to a gradient in accumulation. *We have rewritten the sentence to clarify "We observe a clear dependence on accumulation in H_2O_2 (Table 2)"*

P8L13. Rather use "average seasonality", "average seasonal cycle" or "climatology" for describing these results. *Thank you for these suggestions that have been implemented*

P10L3-4. "The variability is high and unevenly distributed" – again, where can I see this? Can you quantify it, i.e., it is high relative to what? What means unevenly distributed?

Sentence have been rewritten.

"The variability is high between the individual years (whiskers plot) and the annual maximum is wide and not very sinusoidal as evidenced in the 15-85% quartiles (Figure 3, b). This is a result of an additional source in summer and early autumn namely the Canadian forest fires, and the uneven seasonal shape is

evidenced more so in the cores closest to the Canadian forest fire source area (T2015-A1 and T2015-A2).”

The 15-85% quartiles can be seen in Figure 3 and Table 2 and we will add also a whiskers plot to illustrate it

P10L14. It is unclear to which species you refer to here. What means “high deviations in adjacent months”? Isn’t that in general the case for a seasonal cycle? We have rewritten the section “The average Ca^{2+} seasonal cycles (Figure 3,d) in the traverse cores show a late winter/early spring maxima (Ca^{2+} Jan-March, insoluble dust Feb-May) as also observed by others (Kang et al., 2015; Kuramoto et al., 2011; Amino et al., 2020). Minimum concentrations are found in the summer months July and August. The Ca^{2+} seasonal cycle is smooth compared to that of the insoluble dust, where we observe high insoluble dust loads also in the adjacent months as evidenced by the 85% quantile (Table 2 and Figure 3, c). In the cores T2015-A4, T2015-A5 (EastGRIP site) and T2015-A6 (central divide) it looks like insoluble dust is deposited twice a year (early spring and late autumn/early winter).”

Technical comments (by far not exhaustive)

OK Throughout text. The core names are inconsistently labelled either T2015-A1 or 2015TA1, and so on. Please use one consistent nomenclature.

Ok P1L24. Change “70’s” to “1970s” (more similar instances throughout the text).

Rephrased P1L25-26. The sentence “After detrending using...” is difficult to understand and should be rephrased.

Omitted P2L3. “intricate”: I would avoid such an evaluative adjective in a scientific text.

Ok P2L11. Should be changed to “at the deposition site”.

Ok P2L5 and L12. Please note the hyphenation needed in phrases such as “large-scale atmospheric circulation patterns” or “high-resolution climatic signals”. This is a frequent mistake needing correction throughout the text.

P2L18. “sample decontamination”: To my understanding this means cleaning from toxic components or from radioactive radiation. Is this what you actually mean here? Decontamination here is the removal of the outside ice as it can contain impurities that infer with the analysis. I believe the word decontamination is sufficiently wide and suitable in this context also. Further the word is used in other articles about CFA eg, Kaufmann et al. (2008) and Bigler et al. (2011), Morganti et al. (2007) with more

OK P2L25. “Neem” should be “NEEM”; “May to June” of which year do you mean? You also should explain the various site acronyms at some point in the manuscript (preferably at their first respective instance).

P2L26,27. Please format the site coordinates correctly. Besides, I would welcome giving the coordinates in decimal degrees, since that is easier to handle in a numerical context.

“Six shallow firn cores were collected during the NEEM to EastGRIP (N2E) traverse in May to June (Karlsson et al., 2020). The traverse went from the NEEM (The North

Greenland Eemian Ice Drilling) deep ice core drill site (77.5°N, 51.0°W, 2481 m a.s.l.) to the EastGRIP (The East Greenland Ice-core Project) deep ice core drill site (75.64°N, 36°W, 2712 m a.s.l.)."

OK P2L31. A comma is missing between "Greenland" and "and then shipped".

OK P3L2. Please rephrase to "prior to the CFA measurements".

OK Fig. 1 caption. Please mention the information relevant to the study first, i.e., first the firn cores, then afterwards the information on the surface elevation data set.

Rephrased Table 1 caption. The column of core depths is not mentioned in the caption. Additionally, you write that the core labels go till "2015T-A5", but there is another core ("2015T-A6") listed in the table.

Rephrased P4L4. "in 2017": this could be mistaken to mean that you only measured the impurity content for the year 2017; I guess instead you mean the CFA measurements took place in 2017; please rephrase.

Ok P4L5. Add a comma before "by adding".

Ok P4L8. Please change to "were converted into units of concentration".

Rephrased P4L9-10.

- Do you mean "A baseline was established"?
- You should explain what "milliq water" means; not every reader might be familiar with the laboratory terminologies.
- What is "eight 55 cm pieces stacked" supposed to mean?
- "Although" is not the correct wording here; I guess you mean something around "In general the baseline was established by... However, for the top 1.65 metres, where the core was fragile [...], the baseline was established...". Please clarify.

Rephrased P4L13/15. The firn cannot "suck anything". Melt water can flow or percolate into the firn driven by capillary forces; please use the correct physical terminology.

Rephrased P4L15. I don't understand how excess water can be limited to an amount of 0.5-1 cm; what does this unit mean here? Please bear in mind that not every reader might have worked with a CFA system him- or herself.

P4L18. "response time": Again, a reader not familiar with the CFA technique will have problems understanding this; what do you mean by response time and how does this affect the effective depth resolution?

The term is commonly used e.g. Emanuelsson et al. (2015), Maselli et al. (2013), but we have rewritten the text to make it easier for the unfamiliar reader "while for the conductivity and dust with shorter step-change response times (time it takes to go from a level of 5% to 95% of a concentration) a depth resolution of 8 mm was achieved"

Ok P4L20. Please change to "at a sufficient resolution".

Rephrased P4L21. Do you mean "which are used to constrain...?"

Ok P4L22-22. Please change to “as it is produced by a photochemically-derived”.

OK P4L27. Please change to “this exchange can cause smoothing”.

OK P5L3. Please change “invoked” to “used”. **P5L9-11.** Why not? If you mention this explicitly here then you should give a reason for not doing it.

We believe we do give a reason namely that it is known that “even high-resolution weather re-analysis performs poorly on the central ice sheet”. We however mention it because splitting the accumulation into seasons is sometimes done in other studies (eg Gfeller), mainly when direct evidence of precipitation from weather stations have been obtained for several years. As this is not the case for all of our sites we refrain from splitting the year into a fancier precipitation scenario

Figure 3. It is rather counterintuitive to display the formal months in the reversed temporal order summer – spring – winter – autumn. *We will reverse the order*

OK P20 L27. “dissolves” is the wrong wording, please use “resolves” instead.

P20L29. As mentioned earlier, you mix up spatial variability (random variations) with spatial gradients or spatial variations. Please be careful to use the appropriate wording throughout the text. *We have gone through the text and rewritten accordingly*

Rephrased P21L4. Please change to “We thus highlight” and to “of using the same methods”.

OK P21L6. Please change to “in the acid and conductivity profiles”.

Ok P21L7. Please change to “an increase over time, especially for the large ...”.

Rephrased P21L9-11. Please change the reference to the standard format; the final sentence is grammatically wrong.