Replies to referees
Referee 1

Ref1: The authors present a very methodical, comprehensive examination of solid micro- inclusions in polar ice at a range of depths that shows the potential for such a systematic approach to answer many outstanding questions about the role of impurities in ice structure and evolution. The work represents the first investigation of solid micro- inclusions in fast moving polar ice, and uses the methods outlined by Eichler et al. (2017) to construct impurity maps of over 5000 micro-inclusions and allows a robust statistical analysis of the frequency of location of micro-inclusions within the ice microstructure at a level that has not been obtained to date, and helps shed light on several long-speculated processes.

Future implications are particularly tantalizing...e.g., the examination of the impacts of mineralogy, grain boundary sliding, and precipitation and recrystallization on ice properties from the microscale to the mesoscale, which has been suggested in past literature, but with no prior methodology for proving definitively, is a very interesting consequence of this work.

The methods, results and conclusions are well articulated and presented, I have only a few minor specific comments and a small amount of very minor, technical corrections.

Reply: We thank the referee for various comments and ideas to improve the manuscript. We adopted almost all of the suggestions and e.g., present a grain size comparison with the NEEM ice core (see details below). The individual comments are addressed below.

Specific comments:

Ref1: Figures: I found the figures particularly compelling and interesting, especially Figures 1 and 2 (but all of the figures showing the variability of the micro-inclusions both within and outside of grain boundaries is very interesting).
Reply: Thank you very much.

Ref1: Abstract, line 10:
"Analysing the area occupied by grain boundaries in the respective samples shows that micro-inclusions are slightly more often located at or close to grain boundaries in half of all samples. Throughout all samples we find strong indications of dynamic recrystallisation, such as grain islands, bulging grains and different types of subgrain boundaries."
I think understand this sentence, but it is slightly confusing to read it. (Took me a couple of times for it to make sense). I think just rewriting it as, "In half of all samples, micro- inclusions are more often located at or close to the grain boundaries by a slight margin (in the areas occupied by grain boundaries). Not sure that last bit is needed.
Reply: This sentence is indeed confusing. We happily adopted your suggestion and changed it.

Ref1: Pg 5, Figure 2 caption (and throughout): on the last line here, and in other areas throughout the text, you state that something is "rarely close" to the micro-inclusions. Is it possible to define what you mean by "close" and is it just the 300 micron buffer surrounding the grain boundaries that defines what "close" is?
Reply: The last line of the figure caption of Figure 2 only refers to the distance of micro-inclusions to subgrain boundaries. There is no universal definition of a Subgrain boundary in glaciology and we thus did not map them. The statement in the figure caption refers to careful visual inspections of the Subgrain boundaries in the derived impurity maps. In this case "close" means inclusions on the Subgrain boundary.
To clarify this we changed the caption to: "Micro-inclusions are rarely found on subgrain boundaries, which occur more often in larger grains." Mapping and analysing Subgrain boundaries in detail might be part of a future study.
For grain boundaries and inclusions "close" refers to the 300 micron buffer around the grain boundaries which we clarified throughout the text by changing "at grain boundaries" to "in the vicinity of grain boundaries".

Ref1: Pg 6, Line 114 what were the criteria for choosing samples, ie., what CFA values, grain sizes and orientation? For example, it seems like the Bolling Allerod period was targeted for sampling, and samples in the Younger Dryas and before and after the Holocene, but what other criteria were used to choose depths of

interest?
Reply: The sample choice was done in two major steps with the overall aim to reach a systematic (high-resolution) overview of one ice core (limited by the availability due to COVID-19).
1) Samples were chosen to give a good representation of the entire core down to the Glacial (depth-age relationship available until 1360 m only), i.e. roughly every 100 m. We were limited to available samples (many samples are still stored in the EGRIP camp and could not been retrieved due to COVID-19).
2) We focused on depths with high CFA insoluble particle concentration, which were also already analysed regarding their microstructure and fabric data. We chose areas of interest with comparably high insoluble particle content (if possible with a gradient in concentration) to increase the chance of being able to do reliable statistics. We furthermore wanted samples to represent different grain sizes (very small to large) and crystal orientations (random to girdle) throughout the core and (if possible) within the sample (e.g., medium sized grains with a layer of very fine grains). Showing and explaining the exact criteria and data for each sample would be too lengthy and we thus decided to show an overview plot (Fig. 1).
We extended the methods section in the following way: "Samples and specific regions of interest for microstructural impurity analysis were defined using CFA (Stoll et al., 2021a), grainsize and crystal orientation data (Fig. 1) with the aim to give an overview of the Holocene. Samples with high dust particle concentrations while simultaneously including different microstructural and fabric properties (e.g., small and large grains and different c-axes orientations) were chosen. We analysed ten samples in detail between depths of 138.92 and 1339.75 m (Fig. 1and Table 1). The nine shallower samples are from the Holocene and the deepest sample is from the last glacial termination,i.e. the Bølling Allerød (Mojtabavi et al., 2020)".

Ref1: Pg 8, Line 194, Is it worth discussing how it is determined if micro inclusions are plates or clathrate hydrates here? It is mentioned in the figure caption for Figure 4, but seems like there is some more details that could be added about that in the text.
Reply: We discussed this issue and decided not to go into more detail in the original manuscript, because of the different sizes of micro-inclusions and bubbles/hydrates. These additional features can clearly play a role regarding the deformation, but assumptions are difficult to make and would need a dedicated study/data set. However, we added a brief section to the main text mentioning and explaining these observations. An in-depth discussion goes beyond the scope of this manuscript, but is of interest for future studies (especially for deeper samples).
"Other features in the ice were visually identified as plate-like inclusions (caused by relaxation) (Nedelcu et al., 2009) and gas inclusions (air bubbles and clathrate hydrates) (Ohno et al., 2010; Weikusat et al.,2012) (Fig. 5C)."

Ref1: Pg 13, Line 240, Not sure if this is planned for the future work, or what exactly it would look like, but is it possible to plot grain size evolution of NEEM vs. EGRIP? That would be interesting to see. I understand there are likely limits that can be made in the intercomparison due to depth/age mismatches and differences in sample sizes and resolution, but the location of EGRIP over the ice stream vs. NEEM would be very interesting to see.
Reply: This is indeed an interesting comparison, we did it as far as possible and added it (see figure below). For a better comparison we also now use the 9 cm section means instead of the 55 cm means and thus change the first figure (see below). The general grain size evolution of both cores is similar down to the so far available depth. We added the comparison in the discussion in the following way:
"A comparison with the NEEM ice core shows a similar grain size evolution with depth (Fig. 7) even though the dynamic settings are different (ice divide vs. ice stream). EGRIP grain size is generally larger in the upper 550 m and steadily decreases below this depth. NEEM grain size increases until a depth of 740 m and is rather stable until 1350 m even though grain size variability is extreme such that is varies for several mm^2 between samples from similar depths. The cores are roughly 450 km apart, but show a similar depth-age relationship in the investigated depth range: the Glacial-Holocene transition is at 1375 m of depth at EGRIP (Mojtabavi et al., 2020) and at 1420 m at NEEM (Rasmussen et al., 2013). The ice stream thus seems to have an impact on grain growth via dynamic recrystallisation in the upper several hundreds of meters. However, within the depth regime below down to the dust-loaded Glacial ice the grain size evolution seems similar to NEEM and (so far) without observable effects by the ice stream.

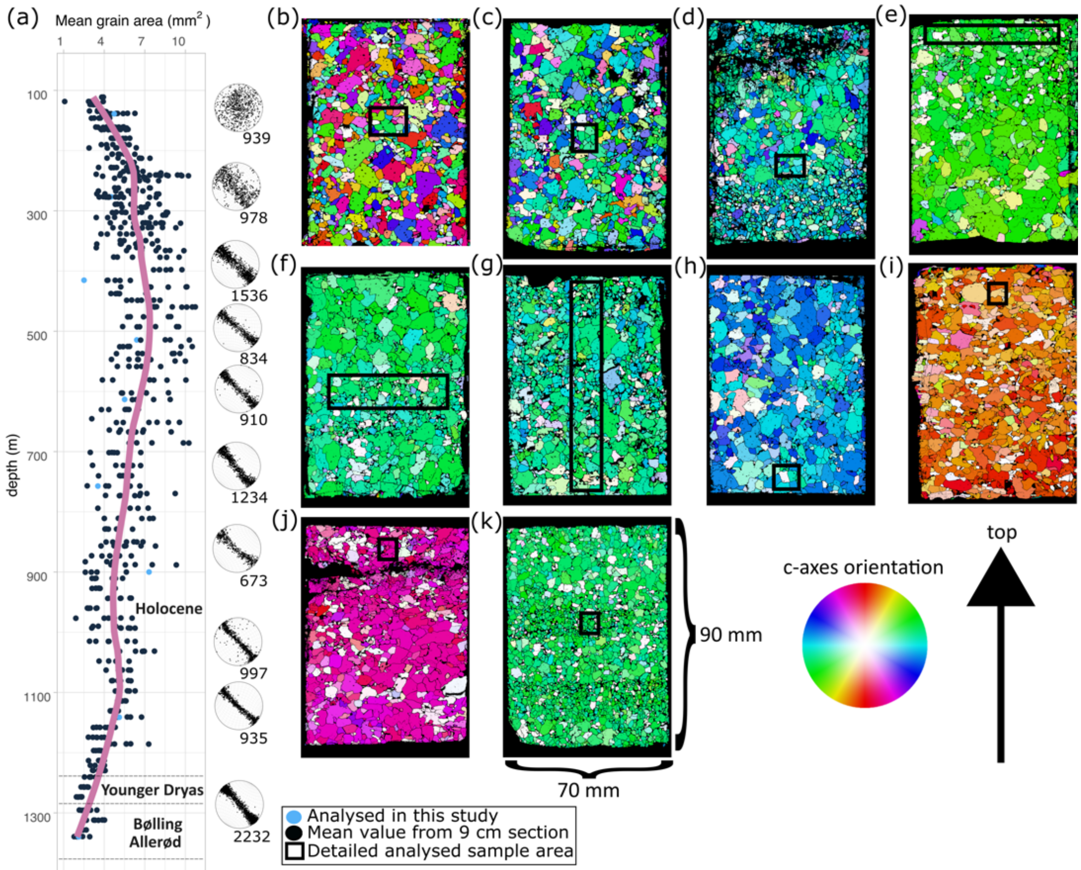

Figure 1 Grain size, CPO and fabric data from the upper 1340 m of the EGRIP ice core. a) 9 cm section mean grain sizes derived via FA G50. The violet line is a locally weighted regression with a smoothing parameter of 0.3. C-axis orientations of each section projected into a horizontal plane rotated towards their most likely position (Westhoff et al., 2020), the true orientation was lost during drilling. The number is c-axes per section. b)-l) Fabric data from the analysed thin sections. The colour code (legend) indicates the c-axes orientation, vertical c-axes appear white. Fabric image surfaces are not the same as in impurity maps due to sample processing and the focusing into the sample. Black areas are background corrections.

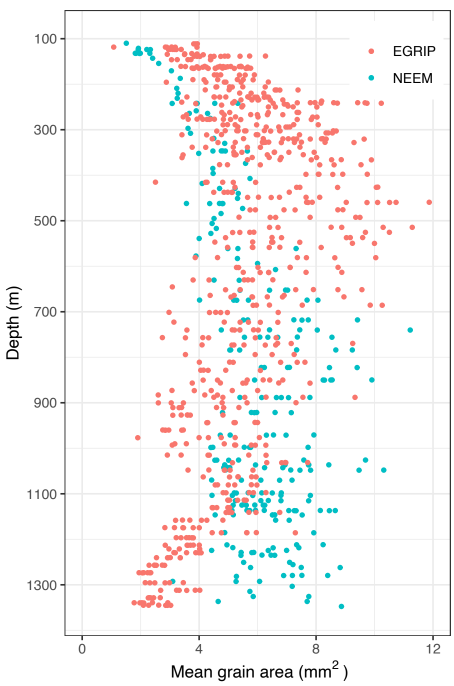

Figure 2 Grain size evolution at EGRIP and NEEM down to 1340 m. NEEM data from Montagnat et al. (2014).

Ref1: Technical corrections:
Pg 2, line 26, "depend" should be "depends"
Reply: Changed it to "depend".

Ref1: Pg 3, line 62, I think you should add the word "microstructure" to describe localization, to differentiate it from the broader, cm to m scale localization...since that is a key point of this work, that you can actually identify the microstructural context of the solid impurities within the matrix vs. a CFA approach where you lose that information. In my opinion, it's good to point that out just to make clear.
Reply: Good point, we added "microstructural" to clarify the scale.

Ref1: Pg 3, Line 83, "question" should be "questions"
Reply: Changed.

Ref1: Pg 6, Line 108, "was obtained" should be "were obtained"
Reply: Changed.

Ref1: Pg 6, Line 113, "interests" should be "interest"
Reply: Changed.

Ref1: Pg 8, Line 189, Does 1 refer to Table 1 in "see 1 column nmi"
Reply: Yes we changed it to Table 1, column n_{mi}.

Ref1: Pg 10, Figure 4 caption, 2nd line, "micro-inclusion" should be "micro-inclusions." Also, I mentioned this in the specific comments, but in this caption it is mentioned that there are plate-like inclusions and clathrate hydrates, but there is no mention in the text about the difference and how it the two types are determined. Guessing it's just a visual determination?
Reply: Changed. The inclusions were determined visually and a brief explanation is provided in the methods section (see point above).

Ref1: Pg 10, Line 201, I think that this should be "an upper-limit assumption"
Reply: Changed.

Ref1: Pg 11, Table 1, Does "Size" refer to sample size? Or a region of interest?
Reply: Changed, we refer to the sample size here.

Ref1: Pg 16, line 299, "inclusion" should be "inclusions"
Reply: Changed.

Ref1: Pg 16, Line 325, Does "1" refer to Table 1?
Reply: Yes, thanks for noticing. We added "Table".

Ref1: Pg 17, Line 330, think that both instances of "effected" should be "affected" unless you mean that the reduced grain growth is causing the grain evolution.
Reply: You are right, changed to "affected".

Ref1: Pg 17, Line 339, This sentence is confusing as it's written: "Our results (Fig. 3) indicate that solid micro-inclusions are not a main driver of e.g., grain size change via localised deformation along grain boundaries." Is it that micro-inclusions are not a main driver of grain boundary sliding (and the grain size change is an example of what grain boundary sliding would be that is not present)? or a main driver of grain size change? I think there is something missing after "of" or that the sentence should be rewritten to make clearer.
Reply: We referred to grain size change, to clarify this we changed the sentence to:" Our results (Fig. 3) indicate that solid micro-inclusions do not have a major impact on the grain size evolution by e.g., enhancing the gradients of internal strain energies due to localised deformation along grain boundaries".

Ref1: Pg 18, Line 366: I don't understand what the phrase "thus exist at grain boundaries" means. I think it is referring to amorphous water veins existing at the grain boundaries, but then the phrase in the parentheses is confusing.
I think this sentence is saying, "amorphous water veins, which can be either liquid-like, e.g., Mader, 1992, or solid-like, thus exist at grain boundaries"
Reply: Yes that is correct, we changed it.

Ref1: Pg 18, Line 367, "changed temperature" should probably be "changes in temperature" as a more common phrase.
Reply: Very true, we changed it.

Ref1: Pg 18, Line 368, "Comparably" should be "Comparable"
Reply: Changed.

Ref1: Pg 18, Line 382, missing parenthesis after Fig. 1.
Reply: Changed.

Ref1: Pg 19, Line 414, "indicates" should be "indicate"
Reply: Changed.

Ref1: Pg 20, Line 438, "in" should be "with"
Reply: Changed.