Author Response to Referee #2 - Anonymous Reviewer

This manuscript introduces a new near-infrared hyperspectral (NIR HSI) scanning system for fast and continuous laboratory measurements of effective grain radius and infiltration ice content on polar firn cores. The system is based on previous work on seasonal snow and the authors first introduce their modifications to the system for firn core scanning. They then demonstrate that the results are consistent with traditional measurement of grain size and ice layer stratigraphy. They verify that cores should be cut into half rounds before scanning and that the results are largely insensitive to minor changes in objective lens focus. They then discuss the impact of the 2012 extreme melt season on firn structure as manifest in the 14 cores they study.

Overall, this is a well-written paper on an interesting analysis technique that has the potential to greatly improve the availability and resolution of structural data from firn cores, particularly if it can be adapted for use in the field. The paper seems quite technically complete. My only major concerns are with some of the discussion and interpretation of the 2012 melt signatures, but I also have a number of minor comments that I hope can help improve the clarity of the paper.

We would like to thank the reviewer for their thoughtful comments and constructive suggestions that have improved the quality of the paper. We address each of your comments below. Our responses to your comments are in blue, with any changes made to the paper written in *italics*.

Major Comments:

[1] How did you choose a threshold grain size of 1mm for classifying infiltration ice? Given you have a visual stratigraphy record for seven of the cores, I would have liked to see a more quantitative optimization of the grain size cutoff used to choose a threshold that maximizes the agreement between the NIR and visual ice layer stratigraphy.

We would like to thank the reviewer for this helpful suggestion. Initially, we chose a threshold radius of 1 mm somewhat subjectively, but we tuned the threshold until there was visually good agreement between visual and hyperspectral ice layer distributions, which we confirmed by showing in Figure A4 that this threshold radius reproduces ~99% of the visual ice layer stratigraphy. However, we agree that this methodology could be more robust, and we have added a subsection in the Methods section describing how we choose an optimal grain radius threshold for masking infiltration ice features, and we now use a threshold grain radius of 1.04 mm to mask infiltration ice in the paper.

"Pixels containing infiltration ice from refrozen meltwater are immediately apparent in the raw grain size retrievals as anomalously large radii compared to the surrounding firn grains. We developed an effective grain size threshold to classify infiltration ice features in the cores in order to both remove them from the maps to prevent them from biasing average grain sizes, and to create explicit maps of ice layer stratigraphy.

We first calculated the total percentage of infiltration identified visually in each core by summing the fractional extent of each ice layer in the core (expressed as a total height of ice) and dividing by the length of the full core (Eq. 2):

$$VI = 100 \times \frac{\sum (H_n \times W_n)}{L} \tag{2}$$

where VI is the percentage of infiltration ice identified through visual inspection, H_n *is the thickness of ice layer n,* W_n *is the width of ice layer n expressed as a fraction of the core width, and L is the total length of the core.*

We compared VI to the percentage of infiltration ice in the hyperspectral images. To quantify the hyperspectral infiltration ice, HI, we classified pixels as either infiltration ice or firn based on a threshold grain radius (Eq 3):

$$HI = 100 \times \frac{P_i}{P_t} \tag{3}$$

where HI is the percentage of infiltration ice in the hyperspectral images, P_i *is the number of pixels classified as infiltration ice, and* P_t *is the total number of pixels in the full core image.*

We leveraged our dataset of visual ice layer stratigraphy to determine the threshold grain radius characterizing infiltration ice. We iterated over a range of possible threshold grain radii ranging from 0.7 – 1.3 mm with a step size of 0.1 mm, and categorized any pixel with a retrieved radius greater than the threshold as infiltration ice and calculated HI for each core. We regressed HI versus VI for all cores and calculated the root mean square error (RMSE) during each iteration. Upon finding the threshold radius that minimized the RMSE of the regression (1 mm), we cycled over threshold radii between 0.95 mm and 1.05 mm, increasing the threshold by 0.01 mm for each iteration. Through this process, we minimized the RMSE between the hyperspectral infiltration ice content and the visual ice content and determined a threshold radius with a precision of 0.01 mm. An infiltration ice threshold radius of 1.04 mm minimized the RMSE (1.03%) (Figure 3).

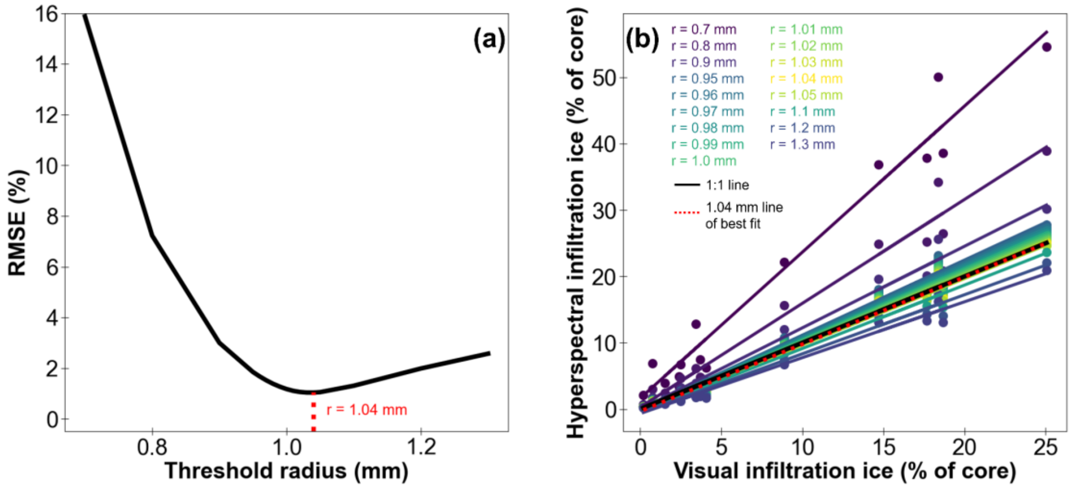


Figure 3. *The iteration process to determine the threshold grain radius used to classify infiltration ice. (a) A threshold radius of 1.04 mm minimized the RMSE of the regressed hyperspectral infiltration ice versus the visually-detected infiltration ice. (b) Regressions of hyperspectral infiltration ice versus visual infiltration ice for each threshold radius in the iteration are shaded based on the radius used to threshold out infiltration ice. Black line denotes the 1:1 line, and the regression using the 1.04 mm threshold is shown with the red dotted line. Each point represents the infiltration ice content for different cores.*

We also set a lower-bound radius threshold of 0.15 mm to remove anomalously small grain sizes retrieved along breaks in core segments by by reconciling grain radii maps from the NIR-HSI and visual stratigraphy and identifying regions where grain sizes either sharply decreased at breaks in the core segments.”

[2] GreenTRACS cores 10, 11, 12, 14, and 16 were collected at locations that did not have coincident OIB radar collection in Spring 2017. As a result, the lack of 2012 melt layer detections at these sites in the Culberg et al. (2021) dataset is simply because there was no data in those regions to analyze. This means that most of the discussion from lines 374-382 needs to be removed or rewritten since the absence of the ice layer in those regions does not actually say anything about the detection limits of the radar. On the other hand, Core 1 did in fact have 2017 radar coverage, but the 2012 melt layer was not detected. Culberg et al. (2021) speculated that this might be because there was so much infiltration ice throughout the entire firn column that the 2012 melt layer did not form a unique or distinct ice package with strong density contrasts relative to the surrounding firn. The data presented in this paper seems to me to confirm that speculation quite nicely, and that would be an appropriate comparison and discussion that could be included in the paper.

Thank you very much for this insightful comment. We believe that providing this more nuanced discussion of the relationship to the 2021 paper by Culberg et al. has significantly improved this section of the paper. We have revised this section to now read:

“Structural changes to the firn column from surface melting in the summer of 2012 were detected in radar soundings from ~9000 km of flight survey lines across all sectors of the Greenland Ice Sheet (Culberg et al., 2021). The lack of flight coverage or radiometric issues with the radar data prevented a melt layer detection at 5 core sites (Cores 10, 11, 12, 14, and 16) (Figure 5a). Given that surface melting occurred across 97% of the Greenland Ice Sheet during this extreme summer (Nghiem et al., 2012), evidence of meltwater percolation should be apparent within the shallow firn column across most of the ice sheet. Our stratigraphic maps provide evidence of a 2012 melt layer that is structurally-different from the surrounding firn column in Cores 10, 14, and 16. Each of these cores have elevated levels of infiltration ice within the 2012 melt layer compared to the surrounding sections of firn, and grain sizes in Core 10's melt layer are much larger than in the surrounding firn (Figure 8, Table A1). While we show evidence of a 2012 melt layer in regions that were not analyzed by Culberg et al. (2021), we also find a thick ice layer from the 2012 melt event in Core 1 that was not detected in the radar data. The detection algorithm of Culberg et al. (2021) was based on firn density contrasts that generate powerful radar reflectors. Culberg et al. (2021) speculated that the absence of the 2012 melt layer at lower elevations in the percolation zone was likely a result of increased background levels of infiltration ice in the firn column that prevented ice layers formed in 2012 from generating a sufficient density contrast. Evidence of the 2012 melt layer in these images while being undetected in the radar data appears to confirm this supposition.”

[3] At lines 394-396, you note that Core 11 shows infiltration ice features outside the temporal range expected for melt effects from 2012 and suggest that this indicates deep preferential infiltration and refreezing. However, it seems to me that these features in Core 11 are more likely to have been formed during the relatively high preceding melt years in 2010 or 2011. There is often significant regional variation in exactly which year in the early to mid-2000s had the highest melt volume for any given site, so it’s possible that 2010/2011 is a stronger signal at this location. Core 11 is clearly in a unique region with much higher local accumulation rates than its neighbors, so I would not be surprised if local melt also followed a different pattern. To me, that makes more sense than suggesting that the 2012 melt infiltrated more than 2 m without impacting the firn structure before suddenly leading to large/rapid grain growth at depth (e.g., suggesting somehow no wetting front ever formed, despite high melt volumes).
Again, we thank the reviewer for the insightful comment. We agree that differential melt patterns is a more likely cause for the lack of a 2012 melt signal and the evidence of firn wetting in deeper/older firn. We have added a short discussion on this point in a separate paragraph:

“Core 11 is the only core in which we find no evidence of previous firn wetting during 2012 (Figures 5b, 8); there are no statistical differences between grain sizes and the amount of infiltration ice in firn possibly affected by 2012 melt. Instead, there is a ~1 m thick section of enlarged firn grains and infiltration ice consistent with previously-wetted firn ~0.5 m below the analyzed region of interest that corresponds to firn deposited in 2009--2010. We suspect that the extreme melt season in 2010 created this structurally-different firn layer (Tedesco et al., 2011).

The complete absence of any melt signal from 2012 in Core 11 is likely driven by its unique climate setting. There is a high accumulation region near Core 11 that nearly doubles the average accumulation rate at this site compared to neighboring cores (Lewis et al., 2019). In 2012, the accumulation rate at Core 11 (0.61 mm. w.e. yr^{-1}*) was almost 3x that at Core 12 (0.25 mm. w.e. yr*$^{-1}$*) and also exceeded the accumulation rate at its southern neighbor, Core 10 (0.53 mm. w.e. yr*$^{-1}$*) (Lewis, 2021). Given that Core 11 was collected in a distinctly different accumulation regime, we suspect that local melting at this location is also different from other cores, which could explain the absence of a 2012 melt layer here. The high accumulation rate in 2012 could have prevented snowpack metamorphism accelerated by positive albedo feedbacks that would have driven surface melt at this location (e.g., Tedesco et al., 2011).”*

Minor Comments:

How good is the vertical positioning in the reconstructed core-length images, compared to the spatial resolution in the vertical?

Good question. The vertical resolution of the grain size maps is 0.4 mm, while the vertical positioning of features in the maps is accurate to within 2–3 cm. We have added text discussing the uncertainties in feature depth in the Methods section as well as a short section of text in the discussion section. Please see these textual additions to your comments below.

Maybe consider adding a table with all the imaging settings in one place for the reader who is interested in reproducing your setup.

We appreciate this suggestion; however, we believe that an addition of a table with this information is unnecessary. We note the frame rate and integration time in Section 2.2, and these settings are the only ones that the user needs to specify in the Spectranon software.

Is the “grain radius” shown in all the figures the effective grain size (r_e)? Perhaps add that label explicitly on the colorbars.

Thank you for helping to improve the clarity of the figures. Reviewer 1 also raised this point. We have changed “Grain radius” to *“Effective grain radius”* in each figure in the revised paper.

Line 29-31: these two sentences could use a better transition. That is, show the reader how sentence #1 implies or leads to the statements in sentence #2.

Thanks for this suggestion. Taking into accounts from both you and Reviewer 1, the end of this paragraph now reads:

“The interconnected interstitial spaces between firn grains, i.e., open porosity, allows for gas, vapor, and liquid movement within the column; however, the total open porosity of the firn column is dependent on local climate conditions (e.g., Gregory et al., 2014) and can be progressively reduced by filling with meltwater (e.g., Harper et al., 2012). Therefore, an understanding of firn structure and properties, and their spatiotemporal evolution, is critical to determine how ice sheets respond to changes in climate.”

Line 32: should be “pore close-off” rather than “pore-close off” as currently written.
Thanks for catching this. We have fixed this typo.

Line 34: I am not sure if listing past accumulation rates as something that can easily be obtained from density profiles is quite accurate, since core dating is also required, which is a much more complicated/laborious process. But based on the references, maybe you meant that density profiles enable accumulation estimates from ice-penetrating radar measurements? In that case, I would suggest being precise about that application in the writing.
Thanks for raising this point and the suggestion to improve clarity. We have revised this portion of the sentence to say that density can be used to *“ascertain past accumulation rates from ice-penetrating radar measurements (e.g., Miege et al., 2013; Hawley et al., 2014; Lewis et al., 2019)”.*

Line 38: perhaps "not that only important metric to characterize firn structure" would be more correct than “not a perfect proxy for firn structure”? Density certainly is part of the structure, not just a proxy, but it does not tell us all the information we need for sure.
This is a fair point. We have revised the text here to read: *“...indicating that density is not the only metric that should be used to characterize firn structure”.*

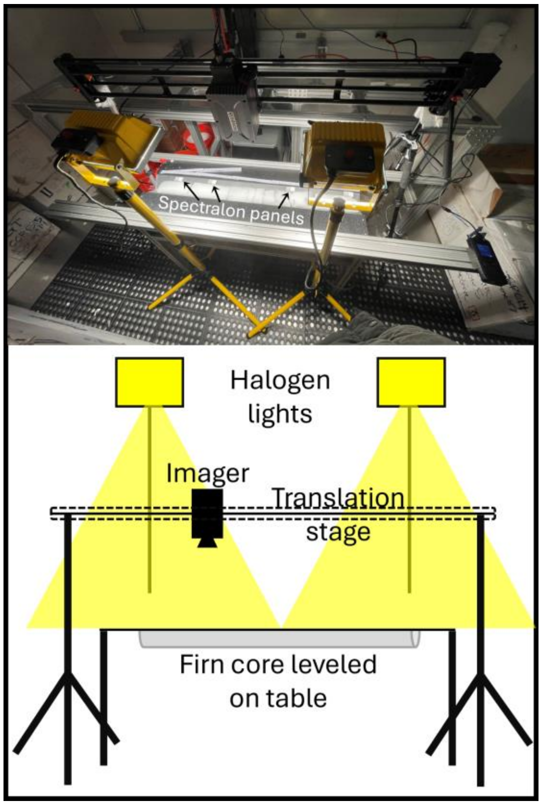
Lines 43-45: grain size is largely irrelevant for radar measurements since the grain scale is orders of magnitude smaller than the wavelength (mm grain sizes vs decimeter to meter wavelengths). It may be relevant for some high-frequency microwave applications (scatterometers, radiometers, SAR, or radar altimeters) operating at center frequencies greater than 10 GHz. I would drop reference to radar and perhaps add a caveat on the frequency range of interest to the statement of on microwave sensitivity.
Thank you for this comment. We have removed reference to radar and now focus only on microwave/optical remote sensing measurements. The two sentences here are now: *“Additionally, analysis of microwave and optical remotely-sensed measurements to determine ice sheet mass balance requires consideration of firn grain size. The firn's grain size controls the penetration depth of high-frequency (>10 GHz) microwaves in firn and governs scattering and emissivity (Rott et al., 1993; Brucker et al., 2010).”*

Line 89: “maps to millimeter – centimeter scale” is a bit ambiguous. Do this mean that pixel sizes in the image are of this order, or that mm-cm scale grains can be resolved?
Thanks for catching the ambiguity here, and apologies for the confusion. In a previous draft of the manuscript we discussed more background about spectral methods to determine snow grain scale. Airborne spectrometers can map effective grain size across landscapes, but their spatial resolution is on the meter scale. For example, a single grain size is estimated for a ~100 m^2 pixel based on the “bulk” spectral reflectance. Contact spectrometers are effective at producing localized grain size estimates (e.g., on a snowpit wall), and their resolution is ~ 1-5 cm. The NIR-HSI can further increase the resolution to the mm scale. For clarification the end of this revised paragraph now reads:

“The millimeter – centimeter pixel resolution of near-infrared hyperspectral imagers (NIR-HSI) produces grain size maps at a high spatial and spectral resolution. Studies utilizing a NIR-HSI have been proven to efficiently and accurately produce high-resolution maps of grain size of laboratory snow samples (Donahue et al., 2021), along the vertical profile of a snowpit wall (Donahue et al., 2022), and at the snow surface when mounted to a drone (Skiles et al., 2023). In addition to providing grain size data, regions of low reflectance in the high-resolution images can allow for ice layers to be easily detected (Donahue et al., 2021).”

Lines 100-104: these sentences would be more appropriate for the conclusion than the introduction. Here you just want to present a concise outline of the structure of the paper, not get into discussing the results.
We appreciate the suggestion from both reviewers to outline the structure of the paper rather than provide conclusions here. The revised paragraph now reads:
"This study was motivated by the need for high-resolution datasets of firn grain size and ice layer stratigraphy for a variety of firn research applications. We aimed to test the performance of a NIR-HSI system in retrieving accurate and continuous grain size profiles and ice layer distributions from 14 firn cores in a cold laboratory. To evaluate the efficacy of the NIR-HSI grain size retrievals, we (1) tested the sensitivity of retrieved effective grain sizes to the orientation of firn cores and the objective lens focus of the NIR-HSI; (2) compared the effective grain size retrievals with "traditional" grain size measurements colocated in 7 cores; amd (3) correlated visual ice layer distributions with ice layer stratigraphy generated by the NIR-HSI. We demonstrate that scanning firn cores with a NIR-HSI is a robust technique for developing detailed grain size and ice layer profiles, and demonstrate an application of the high-resolution dataset to quantify structural changes to the firn column following the extreme 2012 summer melt event.”

Figure 2: consider adding a label for the Spectralon panels.
We have now added labels on the photograph pointing to the spectralon panels.



Lines 180-181: define “continuum normalized absorption feature” and “continuum reflectance” for the reader.

We have slightly reworded this section to provide clarity with those less-familiar with the technique. These lines are now written as:

“The scaled band area, A_b, is the area between the measured reflectance, R_m, and the continuum reflectance, R_c, integrated over the ice absorption feature centered at 1030 nm and scaled by the continuum reflectance:

$$A_b = \int_{962\ nm}^{1092\ nm} \frac{R_c - R_m}{R_c}$$

R_c represents the reflectance spectrum in the absence of ice absorption and is defined as the slope between the shoulders of the ice absorption feature.”

Line 186: did you run any sensitivity tests with higher impurity concentrations? 0 ppb seems quite unlikely for Greenland cores, and I assume there might be some chemical information available from the GreenTRACS cores to inform a better average value.

You are correct that 0 ppb is not realistic for natural settings, but this is an acceptable simplification for grain size forward modeling because impurities lower reflectance primarily in the visible wavelengths. This impact does not extend out into the portion of the NIR spectrum used to retrieve grain size (wavelengths spanning the ice absorption feature centered at 1030 nm). A useful visualization of this can be found in Figure 2a,b from Bohn et al., 2021.

> Bohn, N., Painter, T. H., Thompson, D. R., Carmon, N., Susiluoto, J., Turmon, M. J., ... & Guanter, L. (2021). Optimal estimation of snow and ice surface parameters from imaging spectroscopy measurements. *Remote Sensing of Environment*, *264*, 112613. https://doi.org/10.1016/j.rse.2021.112613

We have added this statement of justification to the manuscript text:
"While an impurity concentration of 0 ppb is not realistic for natural settings, it is an acceptable simplification for this forward modeling because light absorbing particles lower reflectance primarily in the visible wavelengths and this impact does not extend into the portion of the NIR spectrum used to retrieve grain size (Bohn et al., 2021)"

Lines 197-198: how do you handle core gaps and gaps from image cropping when reconstructing the full-length core images?
Good question. After cropping ~1 cm off the top and bottom of each image, we stacked them to create an image of the full core and then assigned a depth for each row of pixels by creating a depth array that was the same size as the number of rows and started at the top depth of the core and ending at the bottom depth. The effect of this treatment is that the core image was a few cm shorter than the real core but was then slightly stretched when we assigned the depth array. This certainly could introduce ~2-3 cm uncertainty in the depths of features in the hyperspectral images. However, we also note that determining the visual depths/lengths of cores can have similar uncertainties, since it is often difficult to see where ice layers begin/end and the edges of core segments can be jagged or deteriorated and it is hard to accurately assign a precise start/end depth for each core segment on the light table. For this reason, it is often difficult to get features from the cores to exactly align (as you note in Figure 5).

While this treatment of stacking/stretching core images does not impact depth uncertainty at levels greater than from visual inspection, we do believe that you raise an important point that should be mentioned in the text here. We have added the following text to the end of the paragraph:

"Once stacked the full image of the core was ≤10 cm shorter than the real core, an artifact of the edge cropping of individual images. We assigned a depth array equal to the number of rows of pixels in the image with the start and end depth equal to the visually-identified top and bottom depths of the core. In effect, by equating the depths this slightly stretched the core image, and the depth uncertainty of features in maps created from the images ~2–5 cm. We note that this is approximately the same as the uncertainty in the depths of visually-identified features, since it is often difficult to measure exactly where ice layers begin/end, and the top and bottom of core segments are often jagged or deteriorated, which makes it challenging to accurately set the

length of each core segment. These uncertainties can result in slight depth discrepancies between visually-identified and hyperspectrally-retrieved firn core stratigraphy."

Section 3.1: is there any relationship between ratio of traditional to effective grain size and the degree of past firn wetting? Squinting at Figure 4, it seems like there might be a larger difference in grain size in wetted regions of the cores, but it's hard to tell. This would be interesting to check in case rapid grain growth in saturated firn produces a different dominant grain geometry than the slower growth in dry firn.

Thank you for this nice suggestion. We have added regions of wetted firn identified through visual inspection on the light table (see McDowell et al. (2023) describing this). We then calculate the traditional/effective ratio for each full core, wetted firn sections, and dry firn sections. The ratios of traditional/effective grain size is actually *smaller* than in wetted firn than in dry firn, suggesting that these wetted grains are rounder than dry firn grains. As Figure 4 from Brun (1989) shows, grains quickly lose their dendritic characteristics and become round as the liquid water content increases. Therefore, wet firn metamorphism will transform these grains into a shape that more-closely resembles an effective sphere.

Brun, E. (1989). Investigation on wet-snow metamorphism in respect of liquid-water content. Annals of glaciology, 13, 22-26.

McDowell, I. E., Keegan, K. M., Wever, N., Osterberg, E. C., Hawley, R. L., & Marshall, H. P. (2023). Firn Core Evidence of Two-Way Feedback Mechanisms Between Meltwater Infiltration and Firn Microstructure From the Western Percolation Zone of the Greenland Ice Sheet. *Journal of Geophysical Research: Earth Surface*, *128*(2), e2022JF006752.

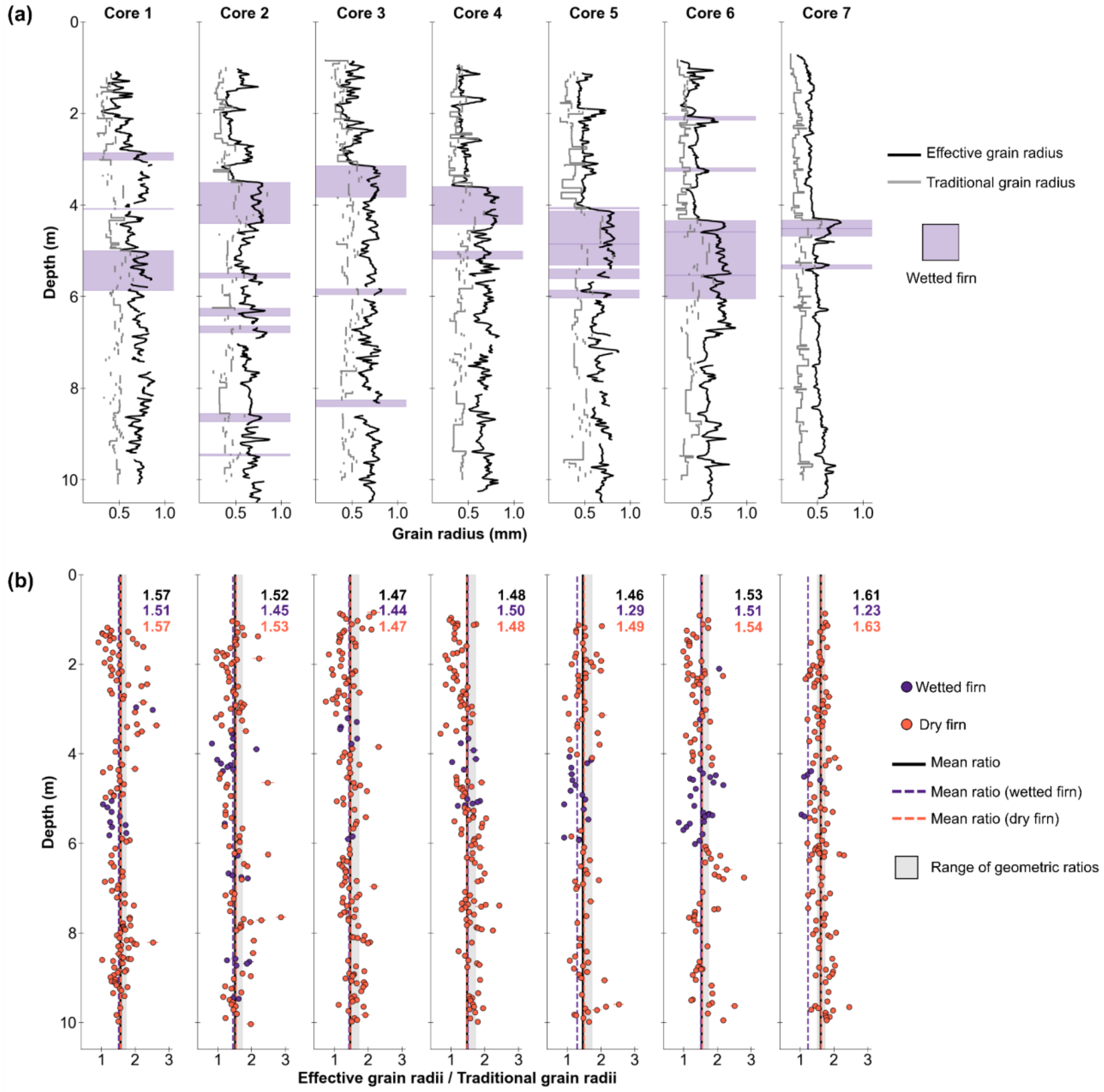


Figure 6. *Effective vs. traditional grain sizes. (a) Grain size profiles from digital grain diameter measurements from McDowell et al. (2023) (grey) and from the NIR-HSI (black). Regions of refrozen firn indicating previous wetting from McDowell et al. (2023) are shown in light purple. (b) Ratios of effective grain sizes to traditional grain sizes. Dry firn grain ratios are shown in orange, while firn grains from previously-wetted regions are in purple. The dashed orange and purple lines represent the mean ratios of dry firn grains and wet firn grains respectively. The mean ratio from the full core is shown as a black line. Each ratio for the individual cores are written and colored corresponding to their classification. The light gray shading denotes the range of Effective/Traditional ratios expected given a hypothetical firn grain geometry of a truncated octahedra.*

Figure 3: consider adding the 2017 CReSIS OIB flight lines in light grey as an underlay in panel (a) so that it is clearer whether gaps in the ice slab and 2012 melt layer detections are due to lack of detections or lack of radar data.

(b)The legend is a bit confusing here, since you use a black box outline to show the 2012 melt layer region, but the legend labels a white box with black outline as being infiltration ice. I assume the legend is trying to indicate that white colors in the grain size colormap are infiltration ice? Maybe it would be better to add white the top of the colorbar, label it as grain size > X, and then just note in the caption that regions of the core where the grain size exceed X are interpreted as infiltration ice.

Thanks for these good suggestions. We have added OIB flightlines analyzed by Culberg et al. (2021) in panel (a) and we have revised the legend per your suggestions. The revised figure is below.

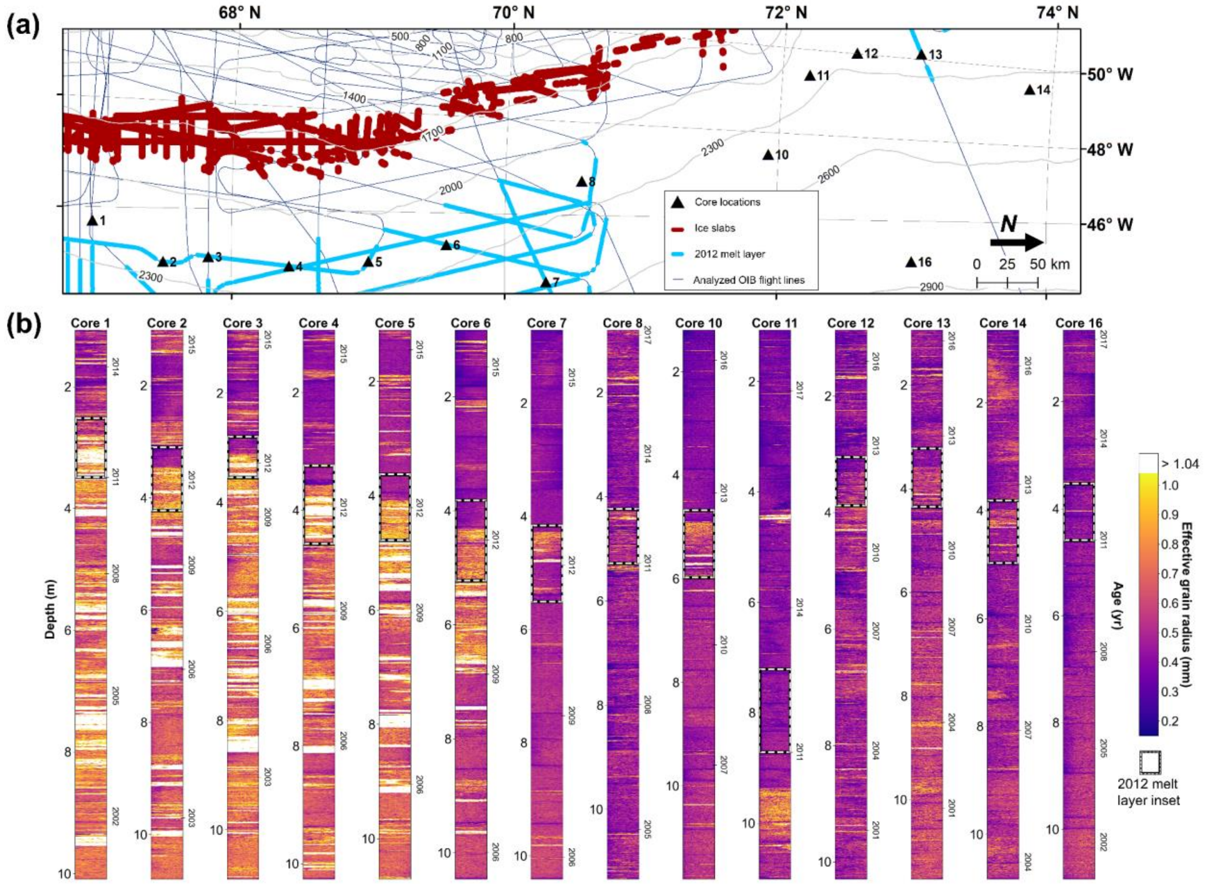


__Figure 5.__ Firn core stratigraphy maps. (a) Inset map from Figure 1 with firn core locations labeled in black, impermeable ice slab extents in red (MacFerrin et al., 2019), and the 2012 melt layer detections in blue (Culberg et al., 2021). Operation IceBridge (OIB) flightlines analyzed by Culberg et al. (2021) are displayed as thin blue lines. (b) Firn core stratigraphy shaded by effective grain radius (r_e). Pixels with an effective grain radius >1.04 mm are classified as infiltration ice and masked. The black and white dashed extent indicators denote firn deposited between January 2011 and January 2013, which should have been affected by the extreme melt event of 2012, that are shown in Figure 8.

Figure 5: there are some interesting spatial offsets here – for example, Core 10 where the NIR stratigraphy seems to be consistently translated downwards by a centimeter or two compared to the visual stratigraphy. What is the uncertainty in vertical positioning for each of the stratigraphic measurement methods and how might that affect your comparison here?
Thanks for raising this point. It is important to mention the slight offsets arising from depth uncertainty of these features in the text here. We have added the following text to this section to address this. It references our discussion of uncertainty that we have added in the Methods section.
"There are slight vertical offsets between infiltration ice identified in hyperspectral images and on the light table. These slight discrepancies arise from small (cm) uncertainty in the depths of these features introduced during both the cropping of hyperspectral images and logging core stratigraphy on a light table as described in Section 2.4.1."

Section 3.3: I would consider moving this section earlier in the results. The best organizational flow would be to first present evidence that your methods are robust (sensitivity tests on core curvature and focusing), then quantitatively verify your results (comparison to traditional grains size and visual stratigraphy), and finish with interpreting those results (2012 melt layer stuff).
Thanks for the helpful organizational suggestion. We agree that is a logical flow to the manuscript. The revised order of the sections is:
3.1. Sensitivity tests
3.2. High resolution maps of grain size
3.3. Traditional and effective grain size comparisons
3.4. 2012 melt layer analysis

Line 336: typesetting issue with the ~
Fixed - thanks for catching this Latex error.

Figure 7: what are the distinct lenses/stripes of low grain radius – for example, in Core 11? Are these physical features, or an effect of core breaks and image splicing?
This is an artifact from lighting variations at the end core segments that were not fully removed by image cropping. Cropping the images required balancing some lighting artifacts to not crop a significant portion of the core. We made a note of this in the figure caption (see below). We also now write on line 197 of the previous version of the manuscript:
"Some bands of anomalously small retrieved grain sizes appear in the maps that have not been removed from cropping, since we attempted to strike a delicate balance between removing lighting artifacts and not cutting a significant portion of the firn core from the images."

The histograms in panel b are pretty hard to read with this aspect ratio. It is nice to have them aligned with the cores, so I do not have an immediate easy fix, but consider playing around with some different layouts that might allow for some stretching of the x-axis so that the differences between histogram peaks within each plot are more legible.

We agree that the histograms were difficult to see. We have changed these to violin pots and we hope this increases the legibility of the figure.

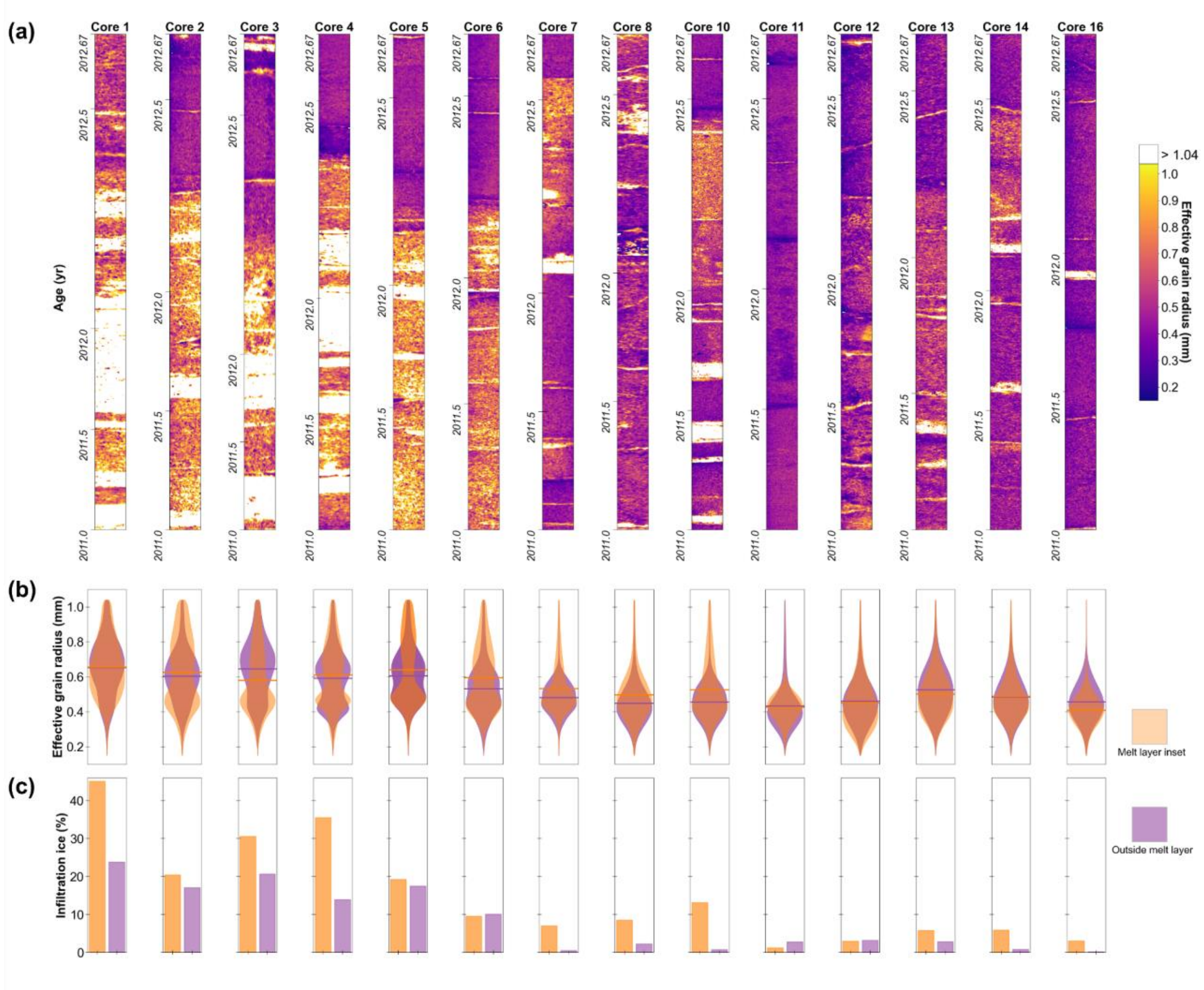


Figure 8. *Firn structure within/outside of the 2012 melt layer. (a) Grain size and ice layer maps of firn spanning the 2012 melt layer from 1 September 2012 to 1 January 2011. Pixels with a retrieved effective grain radius >1.04 mm are classified as infiltration ice and masked. The thin bands of smaller effective grain size retrievals are artifacts caused by lighting effects at the ends of firn core segments that have not completely been removed by image cropping. (b) Violin plots showing grain size differences from firn within the melt layer (orange) and outside of the melt layer (purple). Horizontal lines represent the means of the grain size distributions. (c) Bar charts quantifying the amount of infiltration ice found within the 2012 melt layer (orange) and outside of the melt layer (purple). Table A1 contains values of the mean +/- standard deviation grain sizes and total infiltration ice content in firn within and outside of the 2012 melt layer.*

Line 432: should be “SMS” not “SMK”?

Thanks for catching this! We have fixed this typo.