

Response to Editor

Manuscript Title: Temperature Dependence of Ice Crystal Size in Tibetan Ice Cores

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Dear Editor,

We sincerely thank you for your thorough, careful, and constructive review of our manuscript, and for the insightful suggestions and professional guidance you have provided. Your detailed feedback has been invaluable in strengthening the scientific rigor, logical clarity, and overall completeness of our work. We have carefully considered all of your comments and have made comprehensive revisions to the manuscript accordingly.

Key revisions include: unifying the terminology to "grain" throughout; supplementing quantitative results with mean $\pm$ SEM values for grain parameters; adding a new figure (Fig. A6) in the Appendix to present the distribution of the relative standard error (RSE) of mean grain area; clarifying the criteria for layer division and renaming the "firn-ice transition layer" as the "coarsening layer"; tempering overly absolute statements; moving the glacier comparison table to the main text; and correcting all figures, grammar, and wording issues as suggested.

Below, we address each comment and suggestion point by point. The comments are shown in black, [our responses are in blue](#), and the *revised text is in gray*.

We hope that the revised manuscript now meets the standards for publication in *The Cryosphere*.

Sincerely,

He Zhengqiang

Xu Baiqing

Revision

29 Jun 2026

Editor decision: Publish subject to minor revisions (review by editor)

by Kaitlin Keegan

Public justification (visible to the public if the article is accepted and published):

Dear Dr. He and Dr. Xu,

Thank you for your attention to most of the reviewers' comments. The revised manuscript provides clearer descriptions of the motivation and methods sections, but could be further strengthened by addressing the following comments:

(Line references with respect to line numbers in track-changes version of manuscript)

1) As identified by the referees, the Results and Discussion section would benefit from reporting specific values in sentences providing general results (e.g., 'The average grain area increases while the grain number decreases (L124)'), as well as a figure reference. Additionally, the results would be strengthened by reporting the error associated with the grain area and grain number, derived from the methods used to quantify those parameters.

Response

We added mean $\pm$ SEM grain values and figure citations in results. We also provided RSE error data (BJGR 7.16%, ANMQ 15.10%) in Methods to prove grain trends are not measurement noise.

2) The new organization of the Results and Discussion reads more clearly, but the methods used to determine each core zone discussed in each subsection remain unclear (see specific comments below).

Response

We clarified multi-criteria layer division rules (grain trend + density + temperature/impurity data) and renamed the transition layer to coarsening layer; detailed depth reasoning is shown in specific comments below.

3) The manuscript presents important observations from these two HMA sites and provides circumstantial evidence that temperature is an important driver of ice crystal size. To justify the strong language that temperature is the driver of ice crystal size, a more thorough discussion of other potential factors is needed. Otherwise, the tone of the conclusions should be tempered (e.g., 'the results suggest' instead of 'confirm').

Response

We replaced the definitive wording "confirm" with "suggest", and moved the cross-glacier comparison table to the main text for improved readability and to better demonstrate temperature control on grain size.

4) The manuscript Title and Introduction discuss 'ice crystal' size and number, but the Results and Discussion section report 'grain' size and number. Please add a short description of how those two terms are related in the Introduction or Methods section, or consider using one term throughout the manuscript.

Response

"ice crystal" and "grain" refer to the same thing in this study. We revised the title and unified the term "grain" throughout the manuscript, as this terminology is more widely adopted in *The Cryosphere*.

Specific Comments:

Section 3.1.2

Firn-ice transition layer (ANMQ: 35-45 m; BJGR: 35-45 m):

- Our general understanding of the firn column is that at a density of 0.830 g/cm³, the firn reaches a lock-in zone (LIZ) where some pores have closed, effectively locking off the open porosity below from the atmosphere. At depths with densities between 0.830 and 0.840 g/cm³ within the lock-in zone, the pores close off into bubbles, and the firn-ice transition depth occurs when the density reaches ~0.840 g/cm³ (Severinghaus and Battle, 2006). Looking at the density profiles in Figure A2b, it appears that the BJGR core reaches the LIZ at ~34-m depth, ANMQ reaches the LIZ at ~36-m depth, BJGR reaches the firn-ice transition (at ~0.84 g/cm³) at 35-m depth, and ANMQ reaches the firn-ice transition at ~35-m depth. Due to the melt layers, it might not be useful to use 0.830 g/cm³ as the indicator of the firn column zones, at least for the ANMQ core. Regardless, can you explain why the 35-45 m depth range was identified as the firn-ice transition layer for both cores?

Response

Our stratigraphic division is based on ice density and grain-size evolution. We define the firn layer as intervals with density below 0.830 g/cm³. However, melt-refrozen layers introduce substantial fluctuations in the density record, precluding a precisely defined boundary. Density profiles constrain this transition to within 34–36 m for both cores; we adopt 35 m as the boundary. This avoids overstating the vertical resolution (e.g., 34 m or 36 m would imply 1-m precision) and highlights the consistent layering pattern shared by the two cores.

Subsequent subdivisions are guided primarily by grain-area trends across size fractions, with impurity-layer distributions and borehole temperatures as auxiliary constraints. Both cores show rapid grain-area increases throughout the 35–45 m interval; the lower limit falls between 44 and 46 m, so we set 45 m as the base of this zone following the same rationale.

The upper boundary of the RRX layer is placed at 45 m for both cores, where grain areas cease to increase and instead fluctuate or decline, marking the onset of a dynamic balance between RRX-driven refinement and NGG-driven growth.

For the ANMQ core (45–140 m), grain area reaches a minimum at ~130 m. Between 130 and 140 m, grain area increases moderately with rising temperature, but shows a strong negative correlation with impurity-layer thickness, suggesting that thinning impurities may dominate the increase. At ~140 m, dense impurity layers disappear and grain area rebounds to pre-impurity-zone levels, where RRX refinement can no longer suppress growth. We thus define 140 m as the base of the RRX layer and the start of the SIBM layer.

For the BJGR core (45–73 m), grain area generally decreases down to 73 m. At 73 m, despite a thicker impurity layer than at 72 m, grain area reverses to an increasing trend, indicating that RRX- and impurity-induced refinement are no longer dominant. We therefore place the RRX/SIBM boundary at 73 m, with the minimum at 74 m attributed to the thickest impurity layers at that depth.

Finally, we agree that “firn-ice transition layer” inadequately describes the dominant process within this interval, and have renamed it the “coarsening layer”.

- You describe trends in average grain size and number in this section. Figure 4 caption states that ‘The number of grains in different size grades was statistically analyzed on a per meter basis.’ It would be helpful to state the changes in the average values of these parameters and also show the statistics that underlie the stated increases or decreases in those values. How do we know slight changes in value cannot be attributed to measurement error?

Response

We have added mean $\pm$ SEM values for grain parameters in Section 3.1.2. To avoid cluttering the figures, we did not include error bars in the main plots; instead, we added Fig. A6 in the Appendix to show the distribution of the relative standard error (RSE) of mean grain area for each thin section.

As shown in Fig. A6, the RSE values for the BJGR ice core are mainly below 10%, yielding a core-wide average RSE of 8.90%. For the ANMQ ice core, most RSE values in the upper 140 m are less than 20%, with an average

of 17.60% across this interval. The elevated RSE in the ANMQ core arises from two primary reasons: larger grain sizes reduce the number of complete grains captured per section and increase size dispersion. Below 140 m, this effect intensifies as oversized grains frequently extend beyond section boundaries, yielding an average RSE of 39.73%.

In the upper 45 m of both cores, mean grain area increases markedly (average RSE $\leq 15\%$; BJGR: 7.19%; ANMQ: 14.12%), along with increases in both the size and proportion of grains $>5 \text{ mm}^2$ and a reduction in total grain number. These trends far exceed measurement uncertainty.

Together, these observations suggest that grain growth in this interval proceeds via normal grain growth (NGG), with larger grains consuming smaller ones. The area and number of small grains show only minor fluctuations, which we attribute to continuous internal redistribution across size classes (e.g., grains $<0.2 \text{ mm}^2$ are consumed but replenished by shrinking grains from the $0.2\text{--}1 \text{ mm}^2$ pool, and so on). Importantly, whether these muted small-grain variations reflect intrinsic microstructural redistribution or minor measurement uncertainty does not affect our conclusion that NGG dominates grain evolution in these two layers.

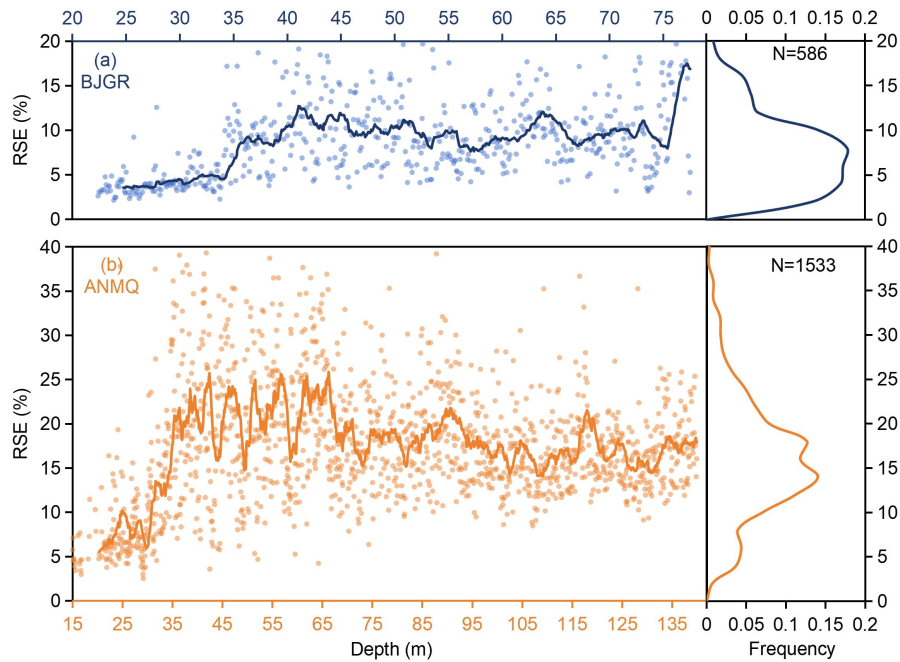


Figure A6. Depth profiles of relative standard error (RSE, %) of average grain area for each thin-section, together with the frequency distribution of RSE values (right marginal panels).

3.1.2 Coarsening layer (ANMQ: 35–45 m; BJGR: 35–45 m)

In this layer, pores become isolated from the free atmosphere, with $\sim 10\%$ of the original air volume eventually trapped as enclosed bubbles and gradually compressed into ellipsoidal shapes (Schaller et al., 2017). The firn transforms into ice, and the average grain area of both ice cores increases rapidly with fluctuations (ANMQ: $11.19 \pm 2.65\text{--}18.00 \pm 5.52 \text{ mm}^2$; BJGR: $3.90 \pm 0.43\text{--}8.06 \pm 1.16 \text{ mm}^2$). The grain size becomes heterogeneous, and grain boundaries begin to curve. Based on these observations, we define the 35–45 m interval as the coarsening layer.

Notably, the firn layer and coarsening layer exhibit consistent evolutionary trends (these two layers are often classified as a single unit in polar ice core studies). The average grain area increases (ANMQ: $1.96 \pm 0.11\text{--}18.00 \pm 5.52 \text{ mm}^2$; BJGR: $1.32 \pm 0.04\text{--}8.06 \pm 1.16 \text{ mm}^2$) while the total grain number decreases (ANMQ: $47.64\text{--}11.58 / \text{cm}^2$; BJGR: $46.30\text{--}23.65 / \text{cm}^2$). The average grain area and proportion of grains $> 5 \text{ mm}^2$ increase (ANMQ: $9.20 \pm 0.65\text{--}39.63 \pm 6.82 \text{ mm}^2$, $11.5\%\text{--}25.4\%$; BJGR: $6.81 \pm 0.18\text{--}17.77 \pm 1.66 \text{ mm}^2$, $9.1\%\text{--}19.8\%$, Fig. 4, and A3a). This indicates that grain growth primarily results from larger grains consuming smaller ones. The average grain area and proportion of small grains ($\leq 1 \text{ mm}^2$) remain relatively stable (Fig. 4), as they are continuously replenished by larger grains shrinking into this size class. Additionally, typical "foam" textures formed by Normal Grain Growth (NGG) are observable in microstructure images (Fig. 3d) (Svensson et al., 2005;

Kipfstuhl et al., 2009).

These observations indicate that grain size in these two layers is significantly influenced by NGG, which is primarily regulated by temperature (Gow, 1969). Generally, higher temperatures tend to promote the formation of larger ice crystals (Cuffey & Paterson, 2010). Consistent with this relationship, the ANMQ ice core, with a temperature range of -0.22 to -4.09 °C (warmer than the BJGR core at -1.54 to -7.04 °C; Fig. 1b), exhibits a larger grain area compared to that of the BJGR core.

Section 3.1.3:

- How is the depth range of the RRX layer determined? What defines the 45-140 m and 45-73 m RRX layer for the ANMQ and BJGR cores, respectively?

Response

This has been explained in our response to Section 3.1.2 above.

- **L141-145:** It would be helpful to reference the temperature profiles in Figure 1b here, and state specific values of grain size and temperature for each core and depth here. As is, this statement is too vague for the definitive conclusion stated.

Response

We have supplemented detailed descriptions of ice temperatures and grain areas throughout the manuscript.

These observations indicate that this layer is primarily influenced by RRX. Under stress conditions, subgrain boundaries form inside grains and gradually develop into grain boundaries, splitting large grains into smaller ones (Kipfstuhl et al., 2009; Weikusat et al., 2009; 2017). This stress-induced grain refinement restricts the growth of large grains (Duval and Castelnau, 1995). Grain size in the RRX layer thus represents a dynamic balance between stress-driven refinement and temperature-driven growth, consistent with previous polar ice core studies (Alley et al., 1986a, b; Faria et al., 2014a, b; Weikusat et al., 2017). Notably, even under greater vertical stress, the average grain area in the deeper, warmer section of the ANMQ (-4.09 to -6.37 °C) remains larger than that in the shallower, colder section of the BJGR (-7.04 to -8.17 °C). For instance, at ANMQ 100 m (-6.63 °C), the grain area is 11.68 ± 2.24 mm², whereas at BJGR 70 m (-8.15 °C)—despite lower stress—it is only 3.73 ± 0.30 mm². This contrast suggests that higher temperatures enhance grain growth, yielding a larger equilibrium grain size, and temperature exerts a more dominant control on grain size than stress in this comparison (Gow, 1969; Cuffey and Paterson, 2010; Montagnat et al., 2014).

Section 3.1.4:

- How is the depth range of the SIBM layer determined?

Response

This has been explained in our response to Section 3.1.2 above.

Table A1:

- The manuscript is not excessively long and would be improved by including specific parameter values when describing how they change throughout the manuscript. Accordingly, I think it would be valuable to put Table A1 into the main manuscript so that the reader can easily check the differences in temperature and grain area described in Section 3.2.

- It would be helpful to add citations for the cores listed in the table so that readers can find the primary source for the data reported.

Response

We agree that placing Table 1 in the main text will significantly improve the readability, as readers can directly compare the temperature and grain size across different mountain glaciers without flipping to the appendix.”

We added corresponding citations for each dataset within the table.

Table 1. Ice temperature and grain size at ~35 m depth in different mountain glaciers

Ice Core	Location	Elevation (m a.s.l.)	Length (m)	Firn Thickness (m)	Temperature (°C)	Grain Area (mm ²) (Diameter (mm))	Reference
Tsanfleuron	Western Alps	2800	39.86	36	~0	> 78 (> 10)	Tison & Hubbard, 2000
Urumqi Glacier No. 1	Middle Tianshan Mountains	4050	90.24	3	-1	20–35	Zhang et al., 1993
ANMQ	Eastern Tibetan Plateau	5750	169.45	35	-2	5–10	This study
BJGR	Eastern Tibetan Plateau	6180	77.6	35	-6.2	3–5	This study
KCC(Colle Gnifetti)	Western Alps	4484	72	36	-13	2–4	Kerch, 2016
Guliya	Western Tibetan Plateau	6200	308.6	1	-14.8	> 50 (> 8)	Li et al., 2017

Technical comments:

L8: 'remain' should be 'remains'

Response

We have revised the manuscript accordingly

L114: From Figure A2b, it appears that the ANMQ core reaches 0.830 g/cm³ about 1-1.5 m deeper than the BJGR core.

Response

We have explained this in our response to Section 3.1.2 above.

L116: This description of the grain size range is confusing. Do you mean grains 1 to 5 mm² make up 50% of the grains? As written, it suggests that grains 0-1 mm² make up 50% of the total, grains 1-5 mm² make up another 50%, and grains larger than 5 mm² make up another 10% (equaling more than 100%). Please clarify.

Response

We have revised the manuscript accordingly

For both ice cores, grains > 1 mm² and those ≤ 1 mm² each account for ~50% of the total. Within the >1 mm² fraction, grains > 5 mm² account for ~10% of all grains (Fig. 4).

L164: should be '... melt-refrozen ice is rarely...'

Response

We have revised the manuscript accordingly

L180: Without more detailed analyses demonstrating that other factors do not substantially influence grain size, it is more appropriate to say 'These comparisons further suggest that temperature...'

Response

We have replaced "confirm" with "suggest" in the manuscript.

L189: It would be helpful to perform the same statistical analysis as was done for the correlation in the AMNQ core and report the r and p values here too.

Response

We calculated the Pearson correlation between impurity layer thickness and grain area for the 66–75 m depth interval of the BJGR core, yielding an insignificant correlation ($r=-0.07$, $p=0.86$). Compared with the 120–140 m

section of the ANMQ core, this interval contains far fewer impurity layers with lower cumulative thickness and weaker contamination. Such faint impurity signals only exert moderate controls on grain area evolution, so we did not label the corresponding r and p values in the figure.

L198: should be either ‘...ice cores, but the exact nature...’ or ‘...ice cores. The exact nature...’

Response

We have revised the manuscript accordingly

L213-214: Were the 1975-1985 and/or 1957-1969 time periods climatically different for this region? That information would help to support this discussion. In the second sentence, I think you mean to say ‘short-term climate variations’ instead of ‘seasonal’ (which would suggest sub-annual variations).

Response

Interannual climate variations within the 1957–1969 and 1975–1985 decades are indistinct, and we have not identified a direct correlation between meteorological station observations and grain area records for this interval. Following your suggestion, we have revised the relevant text to use “short-term climate variations” rather than “seasonal climate variations”.

Within the 45–51 m depth segment of the BJGR ice core, grain area variations show an anti-phase oscillations against $\delta^{18}\text{O}$ signals. We interpret these grain area maxima and minima as seasonal signals corresponding to summer and winter temperature contrasts. Green dating markers have been added to Figure 6a to visualize this seasonal cycle. As illustrated in the figure, grain area reaches its peak in summer while $\delta^{18}\text{O}$ falls to its minimum. Summer $\delta^{18}\text{O}$ values are distinctly lower than those in dry winters due to the amount effect (Yang, 2024, unpublished doctoral dissertation). This suggests that grain area may temporarily retain the signal of short-term climate variations.

According to the dating results, the age ranges corresponding to this depth interval are 1975–1985 for BJGR and 1957–1969 for ANMQ, respectively. Although no prominent decadal-scale climatic shifts occurred during these periods, the anti-phase correlation between grain area and $\delta^{18}\text{O}$ suggests that grain size may temporarily retain signals of short-term climate variations.

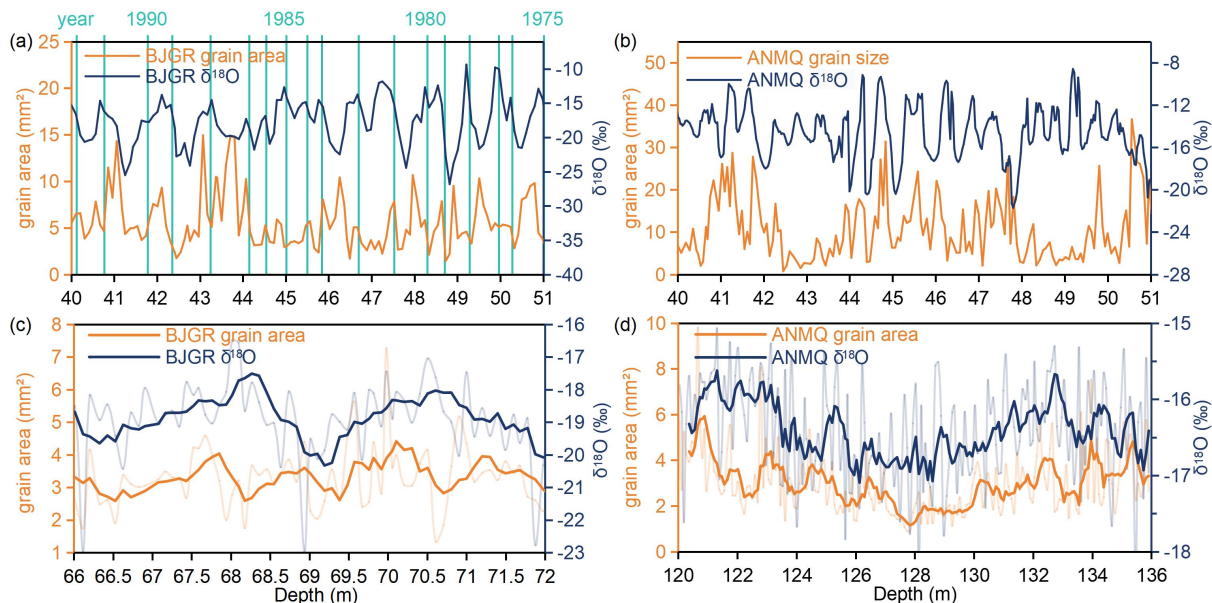


Figure 6. Comparison of average grain area and $\delta^{18}\text{O}$ values. (a) BJGR, 40–51 m interval (for 45–51 m: $r = -0.286$, $p < 0.01$). (b) ANMQ, 40–51 m interval. In the 40–51 m interval, both records exhibit inverse fluctuations, which are attributed to the “amount effect” (i.e., lower $\delta^{18}\text{O}$ values in summer and higher values in winter; Yang, 2024, Unpublished doctoral dissertation). (c) and (d) show similar fluctuations within the dense zones of impurity layers (for ANMQ, 45–51 m: $r = 0.205$, $p < 0.01$); The thin lines represent original data, the bold lines represent the 5 point smooth.

Figure 3 caption: It looks like panels (b) and (c) are derived from the original image shown in panel (a). If so, please make it clear that they are all versions of the same image/sample. Please include information about which sample(s) are shown in panels (d-f).

Response

We have revised the manuscript accordingly

Figure 3. Microstructural images and processed maps for ice core samples: (a) Raw micrograph from sample ANMQ T49B15; (b) Corresponding grain boundary map generated from panel (a); (c) Corresponding pore and bubble map generated from panel (a); (d)–(f) Independent microstructural images from three distinct sections of the BJGR ice core: (d) Straight grain boundaries and triple junctions within the firn layer (BJGR T38B3); (e) Abundant subgrain boundaries in the RRX layer (BJGR T93B5); (f) Coexisting subgrain boundaries and highly curved grain boundaries in the SIBM layer (BJGR T121B8).

Appendix Specific Comments:

Figure A1 Caption: I think you 'Example' instead of 'Exemplary' here

Response

We have revised the manuscript accordingly

L281: What does 'The section below 45 m of the ANMQ core is compressed onto a reduced scale.' mean? Please clarify.

Response

We have removed this sentence from the the figure caption. The original sentence was intended to note that the horizontal axis for depths below 45 m in the ANMQ core is plotted at a compressed scale. This scaling treatment makes the grain-area variations of the ANMQ ice core (45–170 m) visually aligned within the same horizontal range as those of the BJGR ice core (45–80 m) in the figure.

Figure A4: What do the bands of varying darkness of gray represent? I see the legend matching the color to a range of values. What are those units? Do the represent the concentration of one type of impurity or multiple? Please include information about what correlation the r and p values are describing in the top panel (a).

Response

We have added detailed explanations to the caption of Figure A4 (now FigureA5). The gray bands with different shades correspond to the total impurity layer thickness per meter of ice core, which intuitively illustrates the vertical variation of impurity layer thickness at different depths, with centimeters (cm) as the unit. Meanwhile, we clarified that the r and p values in panel (a) are the Pearson correlation coefficient and significance level ($p < 0.01$) between impurity layer thickness and grain area for the 120–140 m section of the ANMQ ice core.

Figure A5 Vertical variations in total impurity layer thickness and mean grain area along depth. (a) ANMQ ice core: A significant negative correlation exists between impurity layer thickness and grain area within the 120–140 m depth interval ($r = -0.715$, $p < 0.01$). (b) BJGR ice core: ($r = -0.07$, $p = 0.86$ for the 66–75 m depth interval). Gray shaded regions denote the total impurity layer thickness (in cm) for each metre depth interval.

Figure A5: It would be most logical to have this figure first in the appendix, as the images in Figure A1 and data shown in the figures afterwards are a product of the setup you show in Figure A5.

Response

We have rearranged the figure order and relabeled this figure as Figure A1.

References:

Severinghaus, J.P., & Battle, M.O. (2006). Fractionation of gases in polar ice during bubble close-off: New constraints from firn air Ne, Kr, and Xe observations. *Earth and Planetary Science Letters*, 244(1-2), 474-500. <https://doi.org/10.1016/j.epsl.2006.01.032>