Response to Anonymous Referee #2

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

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Dear Reviewer,

We sincerely appreciate your constructive comments and suggestions on our manuscript. We have revised the manuscript accordingly. We have supplemented detailed descriptions of drilling, sample preparation, instrumentation, and laboratory conditions, and provided more comprehensive background information on the study sites. Furthermore, we have added key citations to reinforce our conclusions and expanded comparisons with other mountain glacier studies in High Mountain Asia and the Alps, which helps to better contextualize our findings and enhance the scientific contribution of this work.

All comments and suggestions are addressed point by point below. Reviewer comments are shown in black, our response is in blue, and the revised manuscript text is in gray.

Sincerely,

He Zhengqiang

General Comment:

The work in this paper focuses on the temperature dependence of ice-crystal size through the investigation of recovered mountain ice cores from Tibet. This type of work is important as there is a general paucity of physical properties research on smaller, mountain-glacier cores (most fabric or micro-structure analyses are carried on on large ice-sheet cores). As such, it is important that these types of studies are carried out to help strengthen and broaden ice physical properties across different regions (particularly those more acutely sensitive to modern climate change) and show if crystal properties can indeed retain a temperature signal.

In addition to multiple minor formatting, spelling, and grammatical errors, this manuscript most notably lacks specificity across several areas. There are noteworthy method description deficiencies and exclusions, as well as a lack of site and context details. In several places qualitative descriptions are used when specific quantitative measurements are justified and more appropriate. It also seems that many conclusions and/or assertions are not fully developed and require more explanation or references. There are also many places where explicit comparisons with other mountain glacier studies would strengthen the manuscript.

Specific comments:

Abstract

Comment (line 8):

“ice core” → “ice cores”.

Response:

We corrected this accordingly.

Introduction

Comment:

Very little context is given at the onset of the introduction. In general, this section would benefit from more "background" and previous research discussion, especially given that there is no dedicated background section that follows. There is a lot of important material to first introduce regarding deep ice-core work and the pioneering work on grain growth and temperature dependence from those in the 60s and 70s (such as Gow). Then a transition can be made to discussing a brief history of shallower mountain cores, and some important regional studies (and therefore the strong motivation for this work). Additionally, there needs to be a clear review of recovered cores from glaciers on the Tibetan plateau.

More clarification would be beneficial in the introduction as to complexity of mountain glaciers and what is known about ice crystal size and evolution. Also, it would help to be more specific as to what is included in the authors' use of "mid-latitude" in the context of mountain glaciers.

Response:

We revised the introduction according to your comments and added relevant references on microstructural studies of polar and mountain ice cores.

Pioneering work on ice microstructure was first carried out by Perutz & Seligman (1939) on the Great Aletsch Glacier.Since then, systematic studies have been conducted on mountain glacier surface ice and deep polar ice cores (Rigsby, 1951, 1960; Kamb, 1959; Gow, 1969; Gow et al., 1997; Faria et al., 2014a). These studies show that Ice crystal size can reflect glacial strain processes (Gow and Williamson, 1976; Alley et al., 1986a, b; Hellmann et al., 2020) and retain signals of climate change. Specifically, ice crystal size is smaller in ice layers dating to cold periods and larger in those from warm periods (Svensson et al., 2003; Durand et al., 2007; Fitzpatrick et al., 2014).

The term “mid-latitude glaciers” is commonly applied to glaciers in regions such as the European Alps, the Tibetan Plateau, and the Tianshan Mountains; however, its precise definition is not widely accepted. Therefore, we removed “mid-latitude” to facilitate comparison between our study and other mountain glacier ice cores.

Comment (line 32):

rather than just citing Yao et al., perhaps consider writing out some examples of heterogeneities (or at least include additional references).

Response:

We added relevant references regarding regional climatic and topographic differences (Sakai et al., 2017; Bolch et al., 2012; Nie et al., 2021).

Comment (line 33):

"and" is printed twice.

"divergent" to what exactly? It may be unclear to readers exactly what is meant by this without additional citations or examples.

Response:

We corrected the typo and used “different” instead of “divergent” to avoid ambiguity.

Comment (line 35):

This would perhaps be the better place to reference the site map of figure 1 showing the locations.

Response:

We agree with your comment and revised the manuscript accordingly.

Comment (line 36):

It is unclear what "Microstructure Mapping system" means exactly. There either needs to be a more detailed explanation of this system, or at the very least, first-level references that clearly detail the system.

Response:

We add original method references here and added the details of Microstructure Mapping system in Samples and Methods

Comment (lines 37–40):

In general there are some necessary details missing here. Where in the firn? How was the firn defined in each core? It is also unclear how any of these samples were obtained. What sort of recovery system or drill was used etc? I know this is discussed more in section 2, but there should at least be some details here or note if recovery was done following methods and practices from a previous study.

Response:

We supplemented the Samples and Methods section with more detailed information regarding the glacial background, drilling procedures, and laboratory processing workflows.

This study is thus based on two ice cores recovered using an electromechanical drill from the accumulation zones of mountain glaciers on the Tibetan Plateau: Animaqing (ANMQ) and Bugyai Kangri (BJGR)(Fig. 1a). Using a Microstructure Mapping system following established protocols (Kipfstuhl, 2006; Fegyveresi, 2015), we successfully obtained continuous longitudinal microstructure images spanning from the firn to the base of both ice cores.

Samples and Methods

Comment:

Additional details are needed on the drilling itself. What drill was used, how was that drilling carried out and over what time frame, how was recovery handled, etc.

Response:

We supplemented the full drilling information as follows:

In November 2020, a full-depth ice core (ANMQ: 169.45 m length, 9.4 cm diameter) was drilled from the summit accumulation zone of the Weigeledangxiong Glacier, Mount Animaqing, eastern Kunlun Mountains (99.45° E, 34.81° N, 5750 m a.s.l.). This glacier has a total length of ~10 km and an area of 12.53 km², making it one of only three glaciers exceeding 10 km² in the region (Wu et al., 2020). In November 2022, another full-depth ice core (BJGR: 77.6 m length, 8.2 cm diameter) was drilled from the summit accumulation zone on the southern slope of Mount Bugyai Kangri, eastern Tanggula Mountains (94.7094° E, 31.8118° N, 6180 m a.s.l.). This glacier stretches 10.6 km with an area of 22.27 km². Climate in both regions is dominated by the Asian monsoon. The annual precipitation and average temperature near the ELA (BJGR: 5300–5400 m a.s.l., ANMQ: 4900–5190 m a.s.l.) are 600–700 mm and −6 ℃ for the BJGR region, and 700–900 mm and −9.4 ℃ for the ANMQ region (Liu et al., 2016; Jiang et al., 2018). Over recent decades, these two regions have experienced a significant warming trend, with precipitation showing a fluctuating increase and concentrated in summer. Both glaciers have been retreating in recent decades.

Ice core drilling was initiated from excavated snow pits at depths of 1.3 m (ANMQ) and 1.5 m (BJGR), using an electromechanical drill. The recovered ice cores were sealed in clean polyethylene bags, placed in insulated hard core barrels, transported by refrigerated truck, and stored in the −20 ℃ ice core laboratory at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITPCAS).

Comment (line 52):

There are no details given for this passing remark of "borehole temperatures were measured." There are many studies that measure borehole temperatures...with several varied techniques and instrumentation. This needs to be clearly articulated for this study. What sensors were used (thermistors? platinum rtds?), what was the measurement technique? Were measurements punctuated with long waiting intervals to allow the air temperatures in the boreholes to re-equilibrate? etc. Also given the sites and their sensitivity to regional climate, carefully detailing the field and recovery timing of the drilling and borehole measurements is critical.

Response:

We supplemented the details of instrumentation and measurement procedures.

The borehole temperatures were measured with a 152 m - long cable (Cable No. 16BX-XBQ-1A) equipped with 15 platinum RTD sensors at 1 m intervals, with a measurement accuracy of ±0.02 ℃. At each depth, sensors were stabilized for at least 30 minutes to ensure thermal equilibrium between borehole air and the surrounding ice. Temperatures below 150 m were not measured in the ANMQ core. Based on the positive linear temperature trend from 130 m (−6.56 ℃) to 152 m (−6.23 ℃) ($R^2 = 0.93$), the basal temperature at 170 m depth is estimated to be approximately −5.94 ℃.

Comment (lines 55–60):

The sampling collection and interval is somewhat unclear. It's noted the samples are "longitudinal", and fig 2a shows a cut plan, however there's no mention of where and how those cuts were made and how the raw samples were prepped before creating the thin sections (were they traditional thin sections?). I would suggest also adding considerably more detail regarding the sample preparation. Clearly articulate the microtoming process (if indeed the "slicer" is a microtome), and then how the samples were mounted (if they were was it using glass plates and silicone or glue?) before imaging. As mentioned before, "Microstucture Mapping" should be clarified somewhat beyond just the citations. What sort of camera stage was used? etc. Also, it would be helpful to see an explanation and description of the lab where these measurements were carried out.

Response:

We supplemented the details of preparation and Microstructure Mapping description.

We prepared vertical ice slices following standard microtoming procedures (Fig. 2a). First, continuous ice slabs were cut longitudinally along the ice core using a band saw. These slabs were then cut into smaller pieces 6–10 cm in length, ~4.5 cm in width, and ~7 mm in thickness. For the BJGR ice core, sampling started at 22.30 m and continued downward to the base, yielding a total of 560 slices (covering 71% of the total length). For the ANMQ ice core, sampling started at 14.94 m and continued downward to the base, yielding 1890 slices (covering 91% of the total length). The upper firn section of both ice cores was not sampled, as they were too porous and unconsolidated to prepare intact thin sections.The slices were then frozen onto microtome glass plates using a

~1% ethanol solution, and were microtomed to produce a flat surface with a Leica SM2000R microtome. Finally, the slices were placed in a lidded foam box and sublimated at −20 ℃ for approximately 15 hours until their surfaces were smooth and grain boundaries were clearly visible.

We used a Microstructure Mapping system to acquire microstructural images, following protocols described in previous studies (Fig. 2b; Kipfstuhl, 2006; Fegyveresi, 2015; Eichler et al., 2017).

The system comprises an imaging module (a Canon EOS 5D Mark IV camera with an 180 mm macro lens), an illumination module (a vertical coaxial light source and controller), and a manual X-axis translation stage. Photographic parameters, autofocus, and image capture were controlled using Canon Camera Connect software.

Each ice slice was placed on a black sponge background and illuminated under vertical coaxial light. Under this lighting, air bubbles and grain boundaries appear dark, while subgrain boundaries appear gray.

Each panoramic slice image, with a resolution of ~8 μm per pixel, was automatically and seamlessly stitched from 5 consecutive photographs using the Photomerge function in Adobe Photoshop (Fig. 2c).

Comment (line 65):

is the "Extraction" just a built in function of the MorphoLibJ plugin or is there more involved with that extraction process. Also, how are these data extracted...into a standard data file (e.g. CSV), or is additionaly manipulation/refinement needed before they are used for statistical analyses?

Response:

We revised the sentences concerning the data extraction and processing workflow for clarity.

The irregular edges of each panoramic slice image were cropped, and interfering features (e.g., scratches and cracks) were manually removed. Binary segmentation was performed using the U-Net neural network (Ronneberger et al., 2015), and grain boundary maps were generated using ImageJ software with the MorphoLibJ plugin (Fig. 2a–2c; Legland et al., 2016). After scale calibration, grain and bubble areas, positions, and shapes were automatically extracted into a .CSV file using the Particle Analysis function in ImageJ. These results were then combined with depth data for statistical analysis. Grains with an area smaller than 0.01 mm² and bubbles with an area smaller than 0.006 mm² were excluded from the analysis.

Results/Discussion

Comment (line 69):

A relevant citation here is warranted (perhaps Gow 1969?)

Response:

Yes, we added the reference.

Gow, A. J. (1969). On the rates of growth of grains and crystals in South Polar firn. Journal of Glaciology, 8(53), 241-252.

Comment (line 76):

Might be better to note "surface down" to 35 if that is indeed the density-derived firn/ice transition...or specify if the upper surface is not included in the "firn". With this all said, where did the density measurements come from? Was a field method used to determine density (i.e volumetric snow measurements or a borehole instrument), or was density measured later in a laboratory setting?

Response:

We replaced the title with "3.1.1 Firn layer (ANMQ: 0–35 m; BJGR: 0–35 m)" and added details of the density measurement method in the Samples and Methods section.

The density of each ice core tube was calculated from its measured length, diameter, and mass in the laboratory.

The density of each ice slice was deduced using the formula: Density = (1 − porosity) × 0.917 g/cm³ (Kerch, 2016)

Comment (line 79):

consider avoiding qualitative descriptors like "small" when explicit sizes are defined.

Response:

We deleted redundant qualitative descriptions.

Comment (lines 85–89):

This section seemed a bit out of place here. Consider rewording or moving up.

Response:

We reworded the first sentence to improve the flow and coherence of this section.

Notably, the firn layer and growth layer exhibit consistent evolutionary trends (these two layers are often classified as a single unit in polar ice core studies).

Comment (lines 100–104):

If indeed higher temperatures are enhancing grain growth, this is where additional discussion and citations would strengthen the paper.

Response:

We revised the manuscript, and cited supporting references to validate the relationship between temperature, stress, and equilibrium grain size in the RRX layer.

Specifically, we have revised the relevant description as follows:

However, the average grain area in deeper, warmer section of ANMQ remains larger than that in the shallower, colder section of BJGR, even though ANMQ experiences higher vertical stress. This confirms that higher temperatures enhance grain growth, resulting in a larger equilibrium grain area (Gow, 1969; Cuffey and Paterson, 2010; Montagnat et al., 2014). Grain size in the RRX layer thus represents a balance between stress-driven refinement and temperature-driven growth, consistent with polar ice core studies (Alley et al., 1986a, b; Faria et al., 2014a, b; Weikusat et al., 2017).

Comment (lines 113–115):

When basal temperatures are noted here...is this in reference to borehole measurements, or direct temperature measurements of the ice upon recovery. Borehole temperatures are reported in Fig 1b, but it is unclear if that is where the "basal temperatures" noted here are from. To reiterate a comment noted above, there are no borehole temperature or direct temperature methods reported in the study. Is the "temperature transition" at 150 in reference to borehole temperatures?

Response:

We supplemented the ice temperature data and measurement details in the Samples and Methods section, and revised the relevant paragraph as follows:

These observations are consistent with rapid grain boundary migration dominated by Strain-Induced Boundary Migration (SIBM), which tends to occur when ice temperatures are above -10 ℃ (Duval and Castelnau, 1995; Faria et al., 2014b). The basal temperatures of both ice cores satisfy this criterion（BJGR: -8.31~ -8.17 ℃, ANMQ >-6.38 ℃）. Notably, in the ANMQ ice core, ice temperature reaches its minimum of −6.84 ℃ at 126 m depth, where grain area is also minimized at ~5 mm². Below 126 m, the temperature trend reverses from decreasing with depth to increasing, and grain size increases accordingly. Below 150 m (>-6.27 ℃), grains grow rapidly, accompanied by abnormally large grains (> 400 mm²) and a 5 m thick basal bubble- free ice layer.These observations indicate that basal temperature also influences ice crystal size in this SIBM layer.

We apologize for a typo in the depth of the ice temperature transition. This depth has been corrected from 150 m to 126 m in the revised manuscript.

Comment (line 117):

The authors might consider rewording/rearranging the section 3.2 title.

Response:

We reworded the title to: “Temperature, melt-refreezing, and impurity effects on ice crystal size”.

Comment (line 133):

consider expanding on the statement "when comparing to other mountain glacier ice cores" - what cores and from what regions? etc.

Response:

We revised this section and added the comparisons with Urumqi Glacier No.1 and Tsanfleuron Glacier, supplemented detailed information for these glaciers, and presented the data in Table 1.

We compared the two ice cores with four additional ice cores from mountain glaciers in the eastern Tibetan Plateau, Tianshan Mountains, and European Alps (Table 1; Zhang et al., 1993; Tison & Hubbard, 2000; Kerch, 2016; Li et al., 2017). At a depth of ~35 m, we observed the following ice temperature ranking: Tsanfleuron > Urumqi Glacier No.1 > ANMQ > BJGR > KCC > Guliya. This ranking is broadly consistent with the grain area ranking at the same depth: Urumqi Glacier No.1 > ANMQ > BJGR > KCC. These comparisons further confirm that temperature is the dominant factor controlling grain growth in these mountain glaciers.Note that the grain areas of the Tsanfleuron and Guliya ice cores were measured using the linear intercept method (Pickering, 1976), which tends to overestimate the average grain area.

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 (℃)	Grain Area(mm^2) / Diameter (mm)
Tsanfleuron	Western Alps	2800	39.86	36	~0	> 78 / > 10
Urumqi Glacier No.1	Middle Tianshan Mountains	4050	90.24	3	-1	7–12 / 1.5–2
ANMQ	Eastern Tibetan Plateau	5750	169.45	35	-2	5–10
BJGR	Eastern Tibetan Plateau	6180	77.6	35	-6.2	3–5
KCC (Colle Gnifetti)	Western Alps	4484	72	36	-13	2–4
Guliya	Western Tibetan Plateau	6200	308.6	1	-14.8	> 50 / > 8

Comment (line 139):

"cloudy bands" is not necessarily a standard and formally recognized term in the ice core sciences. It would help to define what is meant here. Is it assumed that these are faint tephra layers? dust layers? other impurities? or perhaps just a density contrast of some kind? It would also help to maybe add a sentence or two giving examples of other cores with similar cloudy bands and the conclusions those authors drew regarding formation origin.

Response:

We revised the term “cloudy bands” to “impurity layers”. We cited study of the Monte Perdido Glacier in the Pyrenees, which documented a similar inverse relationship between impurity content and grain size (González-Santacruz et al., 2023)

Comment (lines 146–159):

In general, this section lacks detail and more discussion (and a deeper dive into existing and/or supporting literature)

Response:

In this study, we observed a significant negative correlation between grain area and the total thickness of impurity layers within one meter. This aligns with previous glacier and polar ice core studies, in which impurities have been widely found to restrict grain growth, typically by inhibiting grain boundary migration and pinning grain boundary. In our samples, grain boundary pinning features are visible in the micrographs, but the exact nature of the pinning particles cannot be fully resolved owing to resolution limits. Notably, some studies have suggested that impurities will change ice properties by influencing grain internal strain (Eichler et al., 2017, 2019; Stollet al., 2021). However, the deep discussion of these mechanisms is beyond the scope of the present work and may be addressed in future research.

Comment (lines 160–164):

In this section it is implied that impurity layers are analogous to those seen in Greenland cores that time with long glacial (or perhaps shorter stadial) periods....but it isn't really clear the time interval context as written here in this study.

Response:

We added dating data for the two ice cores over the depth interval of 45–51 m (BJGR: 1975–1985; ANMQ: 1957–1969), indicating that grain area may retain the signal of seasonal climate variations.However, no robust age constraints are available for the dense zone of impurity layers at the bottom of the two ice cores, whose time span is inferred to be on the millennial scale.