Response to the Comments of Reviewer3

We appreciate warmly for the reviewer's earnest work. The comment is constructive, and we will revise the manuscript accordingly. Detailed answers to all comments are provided below. An attachment is also uploaded named by *Response to RC3* to respond to your comments in the annotated copy point-by-point.

General comments:

Comment: The authors present an interesting account, albeit not new (many such studies have been done in the past), of the outcome of mechanical testing on sea ice. They make an instructive comparison between their data from sea ice they collected from the North, and the outcome of earlier studies by other investigators. One significant weakness I see in this paper is that it is based entirely on one block extracted at two sites, i.e., two blocks. Firstly, one block may or may not be representative of the site itself. Secondly, two sites are not likely representative of the Central Arctic as a whole. There is also a lot of scatter in their data, which adds limitations to the value of their conclusions. That, in my view, is ground for rejecting this paper. However, the exercise is worth bringing up, as long as the authors carefully elaborate on these limitations inside its own section (which could be entitled 'Limitations of this study'), in the conclusion and in the abstract. Overall, the English is good, but can be improved in many places. Much of the suggested improvements are the outcome of carelessness (more so than non-familiarity with English).

Response:

(1) Thanks so much for recognizing our work and pointing out the weaknesses of this paper that need to be improved.

(2) In section 4.1, the discussion on comparisons with previous studies, we will rephrase the original statement to correct our position. It is not convincing to draw such conclusions only using these two ice blocks, and there are many factors influencing the differences. Please see the detailed response below.

(3) As the reviewer suggested, we will add a new section (4.2 Limitations of the study) to admit the limitations in the study. Please see the detailed response below.

(4) In the section Conclusion, we will point out again the limitation of this study. Admittedly, the mechanical tests of sea ice described in this study were based entirely on two blocks extracted at two sites, which are not likely representative of

the Central Arctic as a whole.

(5) In the Abstract in new version, we will also stress that the data in this study is limited as they were derived from only two blocks extracted at two sites, and are not likely representative of the Central Arctic.

(6) The language will be checked carefully again.

Specific comments:

Comment: The rationale for this paper seems to be that past mechanical testing of sea ice was representative of colder ice, and not of today's warmer temperatures in the North. Is that what the authors mean in the introduction? If so, the authors may like to clarify this in their paper.

Response:

(1) Yes, what the reviewer said is exactly the rationale for this paper. We will move the viewpoint of this paper to the front of the Introduction. The past mechanical tests of sea ice were representative of colder ice, and not of today's sea ice with warmer temperatures in the Arctic. A question that arises consequently is whether or not the equations established on cold ice years ago are still appropriate for summer ice in the current Arctic.

(2) Based on the comments of you and the other reviewer, we will restructure the Introduction to make our rationale clearer and tell a better story.

First, we will talk briefly about the sea ice mechanical properties and the effect of reduced sea ice strength on the ships and offshore constructions.

Second, we will point out that the past mechanical tests of sea ice were representative of colder ice, and not of today's sea ice with warmer temperatures in the Arctic. The equations established on cold ice years ago may not be appropriate for summer ice in the current Arctic.

Next, we will give a review on the studies of sea ice uniaxial compressive strength, flexural strength, and strain modulus years ago, and show the restriction of previously reported equations.

Then, we will give a review on the recent researches of sea ice strength.

In the fifth paragraph, we will talk about that the sea ice mechanical properties in the summer Arctic may have also changed with global warming, and understanding the mechanical properties of sea ice in the summer Arctic is urgent.

Finally, we will show the main content and goal of this paper.

Comment: There is a large amount of work in the past English literature (in other languages also, no doubt) dedicated to the mechanical properties of sea ice. The authors provide three citations on line 33. They should point out those are only examples. For instance, simply state, "...was developed rapidly in the Arctic regions (g., Kovacs, 1997; Timco and Frederking, 1990; Timco and O'Brien, 1994), i.e., add "e.g."

Response: Thanks. We note that the reviewer has put forward some of these errors clearly in the annotated copy, we will correct them accordingly. We will also check throughout the manuscript to correct similar errors.

Comment: The authors should be careful in not confusing their two samples of ice with the two sites. I suggest they refer to the S1 'sample', not the S1 'site'. Alternatively, include a statement at the beginning of section 2, like "In what follows, we will assume the two samples are representative of both sites."

Response: We will replace "site" with "sample".

Comment: How was the modulus determined for the compressive tests? The initial tangential response of the stress-strain relationship?

Response: The modulus was not determined from the compressive tests, and it was only from the bending tests. We have explained it in L109 by stating "The first type was three-point bending test to measure sea ice flexural strength and strain modulus". To make it much clearer, we will also stress this point in Abstract, Introduction, and Conclusion in the new manuscript. The flexural strength and strain modulus were determined from bending tests, and the uniaxial compressive strength was determined from compressive tests.

Comment: The 3-point flexural test is valid only if the fracture occurs exactly at the point where it is loaded. Otherwise equation (1) is not valid. This is why a four-point test configuration is preferred, as the fracture plane can then occur anywhere between the two upper points.

Response:

(1) We have applied the 3-point bending method to perform many flexural tests of sea ice from Bohai Sea and the Antarctic Ocean (Xiu et al., 2022; Wang et al., 2022). Because of the limited amount of Arctic sea ice samples, we determined to still use the 3-point bending tests. We also realize the restriction of the 3-point bending tests that it is only valid when the failure occurs in the midspan. We are machining a 4-

point bending set-up, and will perform 4-point bending tests in future using sea ice in the polar regions and other icy waters.

(2) We will give a more detailed explanation on the 3-point bending test. It is noteworthy that Eqs. (1) and (2) are valid only when the failure occurs at the beam midspan.

(3) We will add a new figure (Fig. 4) to show the typical failure modes of bending tests, and the crack can be seen clearly. When ice broke, a single crack penetrating the ice section occurred below the central loading point.

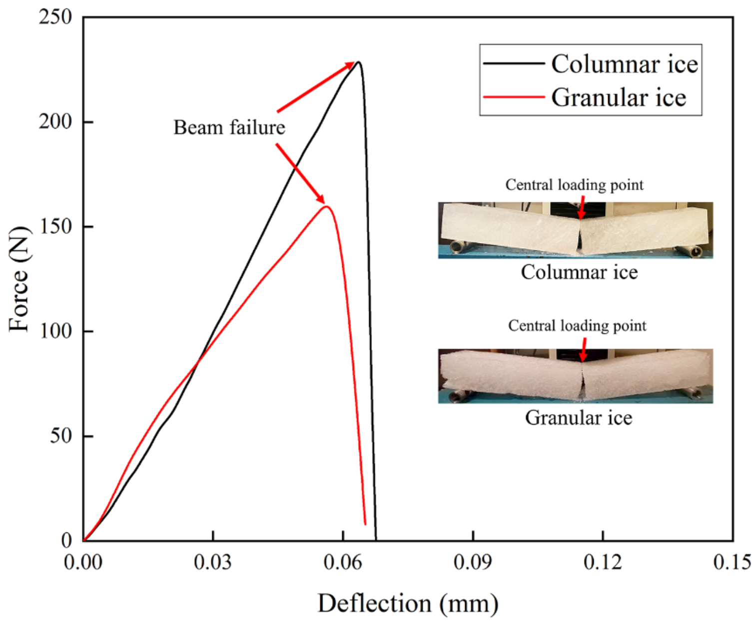

Figure 4: Typical curves of force versus deflection at the beam midspan with corresponding failure modes.

Xiu, Y., Li, Z., Wang, Q., Han, H., Zong, Z., Zu, Y., and Zhang, Y.: Experimental study on flexural strength and effective elastic modulus of granular ice in the Bohai Sea, China, Front. Energy Res., 10, 970051, https://doi.org/10.3389/fenrg.2022.970051, 2022.

Wang, Q., Li, Z., Lu, P., Xu, Y., and Li, Z.: Flexural and compressive strength of the landfast sea ice in the Prydz Bay, East Antarctic, The Cryosphere, 16, 1941–1961, https://doi.org/10.5194/tc-16-1941-2022, 2022.

Comment: A short description of how the beam failed and what the maximum load was should be provided for both the flexural and compressive tests. It is easy to produce numbers, but the reader would benefit from some idea of how these numbers were obtained. A representative photograph of each would be desirable.

Response:

(1) For bending tests, as the response to the previous comment, we will add a new figure (Fig. 5) to show the force-deflection curves and failure modes. Additionally, we will also add a statement to describe the figure. The force increased linearly until peak with increasing deflection and dropped abruptly at ice failure. When ice broke, a single crack penetrating the ice section occurred below the central loading point.

(2) For uniaxial compressive strength tests, we will add a new figure to show the time curves and failure modes. Figure 7 shows the typical curves of sea ice under uniaxial compressive strength tests. Sea ice compressed under different strain rates exhibited different behaviors. At a low strain rate (Fig. 7a), both load and displacement increased with time after compression, and then the load decreased gradually after reaching a peak value. The sample after compression maintained integrity in appearance, and only local cracks were seen in both ends. With an increase in the strain rate (Fig. 7b), sea ice behaved in a brittle manner. Ice lost its strength suddenly once the load reached the peak. Ice samples broke into parts with cracks penetrating through the section. For vertically-loaded columnar ice, the cracks developed along the long axes of the columnar grains, and ice was broken due to buckling of slender columns. While for horizontally-loaded columnar ice and granular ice, the samples were broken with inclined cracks, because force was applied on the brain boundary, and sliding along the grain boundary was triggered (Ji et al., 2020).

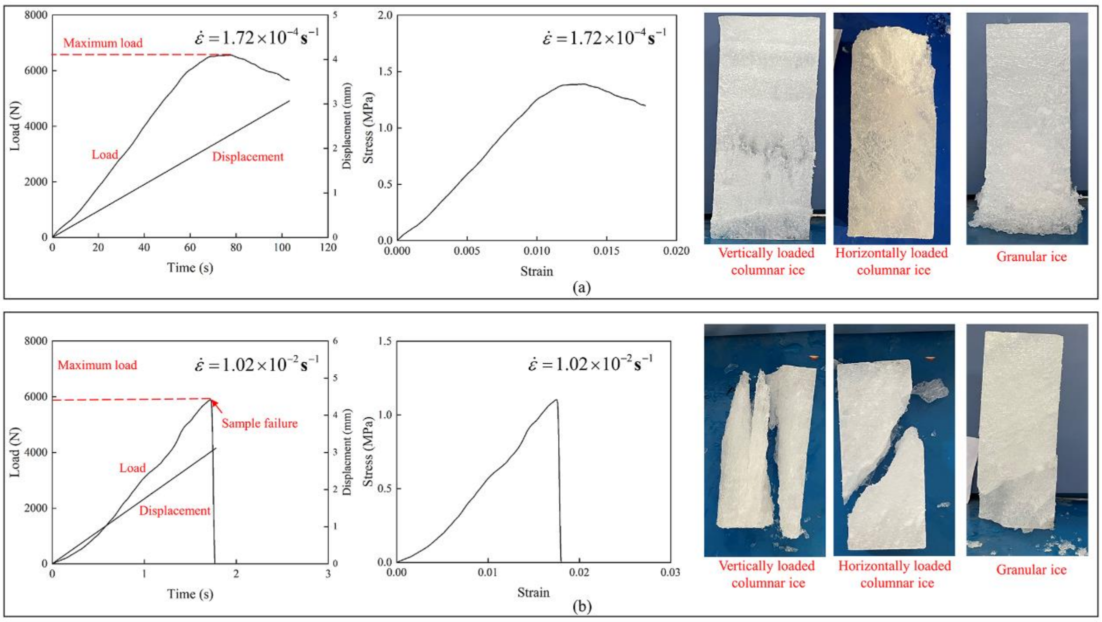

Figure 7: Typical time curves, stress-strain curves, and failure modes of uniaxial compressive strength tests for (a) ductile and (b) brittle failure.

Ji, S., Chen, X., and Wang, A.: Influence of the loading direction on the uniaxial compressive strength of sea ice based on field measurements, Ann. Glaciol., 61, 86–96, https://doi.org/10.1017/aog.2020.14, 2020.

Comment: Examples of stress-strain response should be provided in this manuscript, to accompany the description. Also, to better explain was is meant by ‘ductile’ vs ‘brittle’ behavior. Also, what the ‘transition’ strain rate is. The text is insufficient to clearly show that.

Response:

(1) As the response to the previous comment, we will add a new figure (Fig. 7) to show examples of ductile and brittle stress-strain curves. At a low strain rate (Fig. 7a), stress increased linearly with strain until peak followed by a gentle decrease without abrupt change, indicating ductile behavior. With an increase in the strain rate (Fig. 7b), sea ice behaved in a brittle manner. Stress increased linearly with strain, and then dropped abruptly.

(2) We will also add a new figure (Fig. 8) to show the sea ice uniaxial compressive strength varying with strain rate, in which the ductile, brittle, and transition strain rate regimes are able to be seen clearer. According to failure modes and stress-strain curves of samples compressed at different strain rates, the uniaxial compressive strength of sea ice can be divided into three regimes. Taking the horizontally loaded columnar ice for example, the strength at the same strain rate was averaged, and Fig. 8 shows the sea ice uniaxial compressive strength varying with strain rate. At the strain rates where ice breaks in a ductile manner (termed “ductile strain-rate regime”), the uniaxial compressive strength increased with increasing strain rate. At a brittle strain-rate regime, the uniaxial compressive strength exhibited strain-rate weakening. There is a strain rate above which sea ice transits from ductile to brittle behaviors, and when sea ice transitions from ductile to brittle failure, it reaches maximum uniaxial compressive strength (Schulson, 2001; Wang et al., 2022). Indeed, the transition strain rate is affected by sea ice porosity and grain size (Schulson, 2001). Therefore, in the strain rate-uniaxial compressive strength plot, there is a transition strain rate regime. For horizontally loaded columnar ice, it was 1.2×10^{-3} to 4.0×10^{-3} s^{-1}.

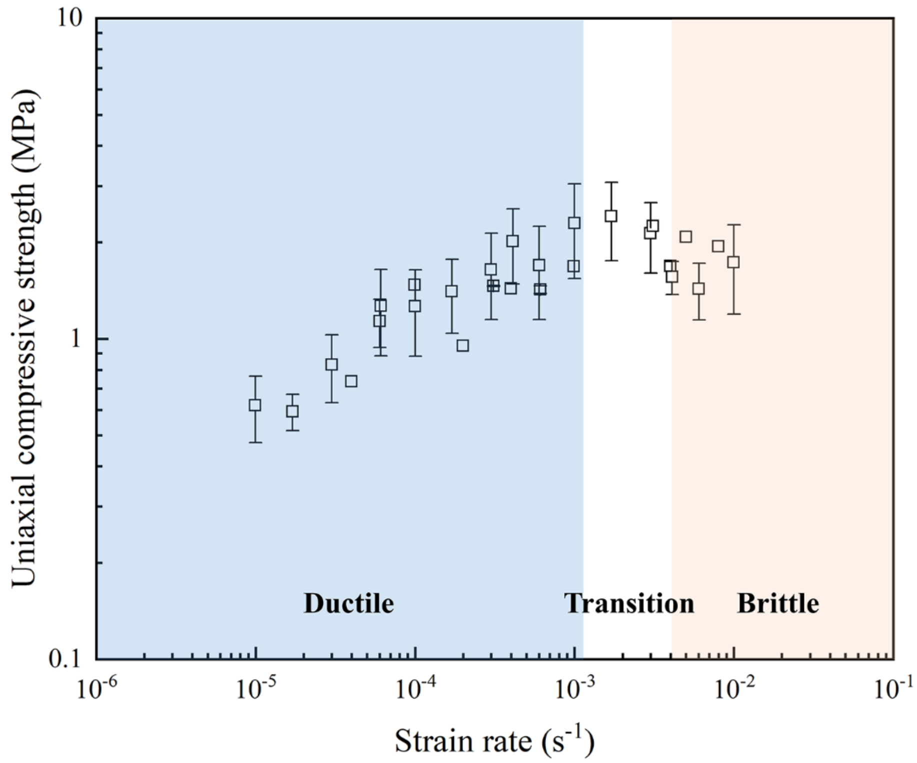

Figure 8: The uniaxial compressive strength varying with strain rate for horizontally loaded columnar ice.

Comment: In section 4.1.1, the discussion on the uniaxial strength, the reader is led to believe that the outcome of this study should be considered 'correct', and thus others that do not match that outcome would need to be adjusted. For instance, with this sentence: "While for vertically loaded columnar ice, both estimations by Timco and Frederking (1990) and Wang et al. (2022) overestimated the measured strength." Is that the intention? The reason I ask is that, the analysis in this manuscript is only on two ice blocks, which is very weak basis. The authors should rephrase their text to clarify.

Response: Thanks for your suggestion. It is not convincing to draw such conclusions only using these two ice blocks.

(1) There are many factors influencing the comparisons. For vertically loaded columnar ice, both calculations by Timco and Frederking (1990) and Wang et al. (2022) were higher than our measured strength. The difference may be attributed to several factors. The first factor is the tests in Wang et al. (2022) were conducted using fast ice which grain size is larger than that of ours. The force is applied on the column cross section, and thus the columnar ice with larger grain size has higher vertically loaded uniaxial compressive strength. Besides, the ductile to brittle transition strain rate reported in Timco and Frederking (1990) was 2.0×10^{-4} s^{-1}. The 3 points

deviating the most from the diagonal line in Fig. 10a were under the strain rate of 1.0×10^{-4} s^{-1}. Therefore, the calculated strength was almost the maximum value.

(2) As the reviewer suggested before, we will add a section (4.2 Limitations of the study) to elaborate on the limitations in this study. The rationale of this paper is that the past mechanical tests of sea ice were representative of colder ice, and not of today's sea ice with warmer temperatures in the Arctic. So, mechanical tests were conducted using ice blocks in the summer Arctic, and the measured data were compared to those calculated using previously reported equations, as did in sect 4.1. We have to admit the limitations exist in this paper are that, firstly, one block may not be representative of the site itself, and secondly, two sites are not likely representative of the Central Arctic as a whole. In addition, sea ice mechanical tests are inherently scattered. Deviation was shown between measured and calculated strength, but it cannot confirm that the equations established on cold ice years ago are not appropriate for summer ice in the current Arctic due to a limit amount of our measured data.

(3) As it is not convincing to draw such conclusions only using these two ice blocks, we determine to delete the statement on the comparisons between measured strength and calculated strength using previously reported equations in section Conclusion.

Comment: Similarly to the point above about section 4.1.1, but this one about section 4.1.2 regarding flexural strength. Consider the authors' statement at line 344: "The overestimation of Timco and O'Brien (1994) than [sic] our measured strength confirmed that flexural strength more accurately depended upon the porosity, especially for warm sea ice". Later on also (e.g., line 372: "Karulina et al. (2019) underestimated our measured data"). This seems to indicate that the two ice blocks used in this study, and their analysis thereof, are sufficient to define a firm basis against which all other studies should be compared. This is surprising, given that Timco and O'Brien include tests over all temperature ranges, including those next to melting. The authors should correct the text to clarify their position: do they really think their data (on two ice blocks) are sufficient to draw such conclusions?

Response:

(1) We will rephrase related statement in this section 4.1.1 to correct our position. A number factors could explain the comparisons. The measured strength in this study was lower compared to the calculations by Timco and O'Brien (1994), which was because flexural strength more accurately depended upon the porosity, especially

for warm sea ice. Calculating the flexural strength using brine volume fraction for warm ice would produce overestimations (Timco and Weeks, 2010). Our measurements were higher than the calculated strength by Karulina et al. (2019). The difference may be attributed to that their experiments were performed by full-scale beam tests. More potential weakness contained in the large beam and stress concentrations at the root of the beam caused lower flexural strength.

(2) In the newly added section 4.2 Limitations of the study, we will also make a discussion on the comparisons between previous and our studies.

Deviation was shown between measured and calculated strength, but it cannot confirm that the equations established on cold ice years ago are not appropriate for summer ice in the current Arctic due to a limit amount of our measured data. Unlike sea ice uniaxial compressive strength that has already been related to porosity, although it is recognized that calculating the flexural strength of warm, decaying ice based on brine volume fraction would produce overestimation (Timco and Weeks, 2010), no equation has been suggested to related sea ice flexural strength to porosity. Figure 5 shows a statistical significant declining trend of flexural strength with increasing porosity. The bending tests of sea ice in the Antarctic during melt season performed in Wang et al. (2022) also showed that sea ice flexural strength were statistical dependent on porosity rather than brine volume fraction. It is difficult to extract large numbers of ice blocks in one voyage in the polar regions. Therefore, more efforts are still required in future to accumulate the data of sea ice strength, especially in current warm Arctic, to understand the mechanical properties of Arctic sea ice under global warming.

(3) In the section Conclusion, we will also rephrase the original statement on the sea ice flexural strength, and the focus will be paid more on this study.

The flexural strength of sea ice in the summer Arctic was dependent on sea ice porosity, and showed declining trends with increasing porosity. The sea ice flexural strength was independent on brine volume fraction. The previously reported equations for sea ice flexural strength using brine volume fraction was not appropriate for calculating the strength of Arctic sea ice in this study. Therefore, an equation was established to relate sea ice flexural strength to porosity (Eq. 4), which compensates for the lack of applicability to warm ice using previous models based on brine volume.

Comment: Abstract: Please ensure it is reviewed and made compatible with the final version of this manuscript.
Response: We will check this part carefully.

Technical corrections and suggestions

Comment: L27: Do not use "ice-infested". That term was used in the past, but since then, it has become politically incorrect (ice is not an infestation) and utterly anthropocentric. Consider instead "...in icy waters" or "in frozen waters", ...
Response: Thanks for your correction. We will replace it with "icy waters".

Comment: L27: "...which causes excessive and uneconomic outcomes applying the design codes". Not clear or clumsy. Do you mean the design codes may no longer be adequate?
Response: Based on the other reviewer's comment, we will rephrase it as "and thus applying design codes based on sea ice mechanical properties derived from measurements conducted decades ago might cause excessive and uneconomic construction measures".

Comment: L30: commonly used (with a hyphen).
Response: Corrected accordingly.

Comment: L32: "...oil exploration was extensive in the Arctic regions".
Response: Corrected accordingly.

Comment: L34: Delete 'although'.
Response: Corrected accordingly.

Comment: 'is flourishing', not 'are flourishing'.
Response: Corrected accordingly.

Comment: L36: Replace 'sea ice mechanics is' with 'the mechanical properties of ice are'.
Response: Corrected accordingly.

Comment: L44: Replace ‘cause a less content of brine gas’ with ‘increase the amount of gas relative to the brine content’

Response: Corrected accordingly.

Comment: L45-46: Proposed rephrase: ‘Sea ice modulus has received relatively little attention’.

Response: Corrected accordingly.

Comment: L53: Suggested rephrase: ‘A question that arises consequently is whether or not the equations...’

Response: Corrected accordingly.

Comment: L56: Replace ‘provided’ with ‘showed’.

Response: Corrected accordingly.

Comment: L57: ‘...in response to global warming...’

Response: Corrected accordingly.

Comment: L58: Replace ‘...decreased than decades ago...‘ with ‘...decreased more than they did a few decades ago’.

Response: Corrected accordingly.

Comment: L63: ‘...which could help better understand the response of Arctic sea ice...’

Response: Corrected accordingly.

Comment: L65: Replace ‘the domestic laboratory’ with ‘our cold room facilities in China’.

Response: Corrected accordingly.

Comment: L66: ‘we present the results of flexural strength,...’. You should use the present tense, not the past, for what is described in this paper. Another example on L68 – equations ARE given, not were given. Please correct throughout your manuscript. Why the past? It is currently in the paper!

Response: Thanks for your correction. We will check the tense throughout our manuscript carefully.

Comment: L70: design construction, ... in support of offshore activities in the Arctic during the summer.

Response: Corrected accordingly.

Comment: Section 2.1: At the beginning of this section, state the amount of time the voyage required (two months? From when to when?)

Response: During the Chinese National Arctic Research Expedition in 2021, the icebreaker RV *Xuelong* explored the Arctic sea ice zone from 29 Jul. to 3 Sep. We will add the information.

Comment: L75: Unclear whether the ice blocks were from the level ice, which you mention one line before, or pack ice. These are two different zones. Please clarify.

Response: The ice blocks were from the level ice. It will be replaced with "stopped in the level ice zone".

Comment: L77: 'That ice at both sites WAS covered...'

Response: Corrected accordingly.

Comment: L82: '... IT WAS DETERMINED THAT the ice in the Central Arctic Ocean...'

Response: Corrected accordingly.

Comment: L83: Clarify this: 'experienced 40 day melt'. What do you mean?

Response: The Arctic sea ice melt data issued by NASA's Goddard Earth Science Laboratories shows that the melt onset of sea ice in the Central Arctic Ocean in 2021 was in late June. So it was determined that the ice blocks we sampled had experienced at least 1-month melt at the time of sampling. We will rephrase the statement as above.

Comment: L84: '......showed no cracks in the ice. However, the top had undergone some damage due to the interaction with the ship hull during its retrieval.'

Response: Corrected accordingly.

Comment: L85: Replace 'archived carefully using plastic bags' with 'put inside plastic bags'.

Response: Corrected accordingly.

Comment: L86: '...were stored in a cold room at -20oC'. No need to mention solar radiation (it's in a cold room).

Response: Corrected accordingly.

Comment: L86-87: Remove 'at home', move '2 month expedition' to the beginning of section 2.1.

Response: Corrected accordingly. As the previous response, we will also give a more detailed time information.

Comment: L94: '... observing THEM under...' – '...of ice blocks FROM S1 and S2 sites...'

Response: Corrected accordingly.

Comment: L97: '...because the thin sections INADVERTENTLY melted after preparation during a defrosting event in the cold room...'

Response: Corrected accordingly.

Comment: L98: 'Based on the horizontal sections, it is inferred that the top 35cm of ice on that sample was made of granular ice."

Response: Corrected accordingly.

Comment: L100: 'The columnar ice crystals were seen to grow and extend downward from the granular ice,...'

Response: Corrected accordingly.

Comment: At this point, I am going to stop, as this was getting too labor-intensive. I am including a copy of the annotated manuscript. I would encourage the authors to give those annotations due consideration.

Response: Thank you so much for detailed and constructive comments, which help a lot to improve our manuscript. I have responded all comments in the attachment named by *Response to RC3*.