Response to the Comments of Reviewer4

We appreciate warmly for the reviewer's earnest work. The comment is constructive, and we will revise the manuscript accordingly. Detailed answer to the comments is provided below. An attachment is also uploaded named by *Response to RC4* to respond to your comments in the annotated copy point-by-point.

The authors present an interesting study addressing changes in the mechanical properties of Arctic sea ice associated with the increasing temperatures in this region. Although such investigations are relevant for various applications the present study has several weak points:

- **Comment:** The structure of the manuscript, single paragraphs yet also some sentences need to be improved. In the current version, the manuscript is not always easy to follow as the flow is repeatedly interrupted.

  Response:

  (1) We will restructure the Introduction to give 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.

  (2) We note that the reviewer has pointed out many misleading statements and paragraphs with unclear structure of the manuscript in the annotated copy, we will correct them accordingly.

(3) We will also check through the manuscript again to make it clearer and more fluent.

- **Comment:** The different sections/parts of the manuscript are not always connected, i.e., the red thread is missing. This is particularly evident for the Results and the Discussion section.

  Response:

  (1) For the sentences that the reviewer has pointed out in the annotated copy, we will delete them or move them to the sections where they should belong.

  (2) We will also check through the manuscript to correct if there are other misplaced statements.

- **Comment:** The sample size is critically small. Two samples are not sufficient to conclude that the presented empirical relationship is superior to other well-established (empirical) models/relationships obtained for larger data sets.

  Response: As the reviewer said, the significant weakness in this paper is that it is based entirely on two blocks extracted at two sites. The limited sample size is not sufficient to support the conclusion. Based on the comments of you and the other reviewer, the manuscript will be revised as below:

  (1) A new section titled by Limitations of the study will be added to explain the limitations in the study. 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.

  (2) In section 4.1, the discussion on comparisons with previous studies, we will rephrase the 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.

  (3) The limitation of this study will also be stressed in the section Conclusion. 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.

  (4) In the Abstract, we will also state 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.

  (5) In the Conclusion, we will delete the sentences about the comparisons between

presented empirical relationship and other well-established models.

- **Comment:** References underpinning certain statements are missing in some parts of the manuscript.
  Response:
  (1) For the statements that the reviewer specifically pointed out, we will add the references.
  (2) We will also check through the manuscript to correct similar mistakes.

- **Comment:** The authors repeatedly fail to communicate results and the associated interpretations/findings in a quantitative way.
  Response:
  (1) We note that the reviewer has pointed out several qualitative statements in the manuscript, especially in the discussion. The reason is that we did not give a quantitative description on the comparisons between calculated strength using well established equations and measured data. So, in the revised manuscript, we will add two tables to give the mean errors and root mean square errors of the calculations compared to measure data for uniaxial compressive strength, flexural strength, and strain modulus. The corresponding statements will then be modified.
  (2) For the other qualitative descriptions that the reviewer has pointed out, we will correct them following the reviewer's comments.

- **Comment:** In general, the English is sufficient, yet the usage of the English language should be improved to make the manuscript more accessible.
  Response: The reviewers have put forward many detailed suggestions to improve the language, we will correct the manuscript accordingly.

In the current version, the manuscript is not acceptable for publication in The Cryosphere but requires major revisions addressing the weak points/limitations listed above. Some general suggestions:

- **Comment:** The authors should establish a better story to adequately present this study and restructure the manuscript accordingly.
  Response:
  (1) Telling an attractive story is important in the Introduction of a paper. So, we will

revise the part of Introduction first. As the response to previous comment, the thread running through the story 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. With global warming, sea ice physical properties in the summer Arctic has changed, probably bring changes to sea ice mechanical properties in the summer Arctic. Consequently, understanding the mechanical properties of sea ice in the summer Arctic is urgent.

(2) As stated above, a major reorganization will be made in the Introduction.

In the first paragraph, we will talk about the sea ice mechanical properties and the effect of reduced sea ice strength on the ice engineering.

In the second paragraph, 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.

In the third paragraph, we will give a review on the earlier studies and well established equations of sea ice uniaxial compressive strength, flexural strength, and strain modulus years.

In the fourth paragraph, we will give a review on the recent researches of sea ice mechanical properties.

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.

In the last paragraph, we will show the main content and goal of this paper.

(3) We also note that the reviewer has pointed out many other statements and paragraphs in the paper that need to be restructured, we will correct them accordingly.

- **Comment:** A more thorough appreciation of existing literature is required.

  Response: In the revised Introduction, we will make a more detailed review on the earlier and recent studies of sea ice mechanical properties.

  For earlier studies, Moslet (2007), Timco and Frederking (1990), Timco and O'Brien (1994) will be reviewed because equations of sea ice mechanical properties were proposed in these studies. The restriction that exists in the well-established equation of Timco and O'Brien (1994) will then be pointed out by reviewing Timco and Weeks (2010) and Wang et al. (2020). Estimating the sea ice strain modulus is even more complicated, so the engineering standards of ISO19906 (2010; 2019)

will be reviewed.

Investigations of sea ice mechanical properties have been sparse in the last few years, and Bonath et al. (2019), Skatulla et al. (2022), Karulina et al. (2019) as well as Strub-Klein and Høyland (2012) will be reviewed.

Bonath et al. (2019) conducted uniaxial compressive and tensile strength tests using ice from first-year ridges, and found sea ice porosity and brine volume were the main parameters influencing the compressive and tensile strength of ice from first-year ridges.

The uniaxial compressive strength and elastic modulus of winter first-year ice were in the Antarctic were measured in Skatulla et al. (2022). The elastic modulus and uniaxial compressive strength of Antarctic winter young sea ice were lower than reported in the literature for columnar Arctic winter sea ice, which was attributed to the predominantly granular ice textures of the sampled Antarctic ice.

Karulina et al. (2019) performed a series of full–scale flexural tests on ice beams, and the results reported more accurate relationships of the flexural strength and the effective elastic modulus versus the brine volume specifically for the ice at Svalbard archipelago by comparing with the previously suggested relationships.

Strub-Klein and Høyland (2012) sampled ice in matrices of different sizes and spacings for physical property measurements and uniaxial compressive strength tests to examine the spatial and temporal distributions of sea ice strength. Their results indicated that the the variability in uniaxial compressive strength correlated with the variability in sample salinity and with the mean brine fraction.

Bonath, V., Edeskär, T., Lintzén, N., Fransson, L., Cwirzen, A.: Properties of ice from first-year ridges in the Barents Sea and Fram Strait, Cold Reg. Sci. Technol., 168, 102890, https://doi.org/10.1016/j.coldregions.2019.102890, 2019.

ISO19906: Petroleum and Natural Gas Industries–Arctic Offshore Structures, ISO, Geneva, Switzerland, https://www.iso.org/standard/33690.html (last access: 17 October 2022), 2010.

ISO19906: Petroleum and Natural Gas Industries – Arctic Offshore Structures, ISO, Geneva, Switzerland, https://www.iso.org/ standard/65477.html (last access: 17 October 2022), 2019.

Karulina, M., Marchenko, A., Karulin, E., Sodhi, D., Sakharov, A., and Chistyakov, P.: Full-scale flexural strength of sea ice and freshwater ice in Spitsbergen Fjords and North-West Barents Sea, Appl. Ocean Res., 90, 101853,

https://doi.org/10.1016/j.apor.2019.101853, 2019.

Moslet, P. O.: Field testing of uniaxial compression strength of columnar sea ice, Cold Reg. Sci. Technol., 48, 1–14, https://doi.org/10.1016/j.coldregions.2006.08.025, 2007.

Skatulla, S., Audh, R. R., Cook, A., Hepworth, E., Johnson, S., Lupascu, D. C., MacHutchon, K., Marquart, R., Mielke, T., Omatuku, E., Paul, F., Rampai, T., Schröder, J., Schwarz, C., and Vichi, M.: Physical and mechanical properties of winter first-year ice in the Antarctic marginal ice zone along the Good Hope Line, The Cryosphere, 16, 2899–2925, https://doi.org/10.5194/tc-16-2899-2022, 2022.

Strub-Klein, L. and Høyland, K. V.: Spatial and temporal distributions of level ice properties: Experiments and thermomechanical analysis, Cold Reg. Sci. Technol., 71, 11–22, https://doi.org/10.1016/j.coldregions.2011.10.001, 2012.

Timco, G. W. and Frederking, R. M. W.: Compressive strength of sea ice sheets, Cold Reg. Sci. Technol., 17, 227–240, https://doi.org/10.1016/S0165-232X(05)80003-5, 1990.

Timco, G. W. and O'Brien, S.: Flexural strength equation for sea ice, Cold Reg. Sci. Technol., 22, 285–298, https://doi.org/10.1016/0165-232X(94)90006-X, 1994.

Timco, G. W. and Weeks, W. F.: A review of the engineering properties of sea ice, Cold Reg. Sci. Technol., 60, 107–129, https://doi.org/10.1016/j.coldregions.2009.10.003, 2010.

Wang, Q., Lu, P., Leppäranta, M., Cheng, B., Zhang, G., and Li, Z.: Physical properties of summer sea ice in the Pacific sector of the Arctic during 2008–2018, J. Geophys. Res.-Oceans, 125, e2020JC016371, https://doi.org/10.1029/2020JC016371, 2020.

- **Comment:** Provide enhanced formulations in the text by taking into account formulations in existing studies.

  Response: The reviewers have listed many misleading statements of this manuscript in detail, we will correct all of them accordingly. In addition, we will also check through the manuscript again carefully.

- **Comment:** Address the limitations/shortcomings of the study (in comparison to existing literature).

  Response: As the response to previous comment, based on the comments of you and the other reviewer, the manuscript will be revised as below:

(1) A new section will be added titled by Limitations of the study to admit the limitations in the study. 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.

(2) The limitation of this study will also be stressed in the section Conclusion. 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.

(3) In the Abstract, we will also state 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.

(4) In section 4.1, the discussion on comparisons with previous studies, we will rephrase the 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.

Additionally, I provide detailed comments and suggestions in the annotated copy of the manuscript attached here.

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 RC4*.