

RC1:

General comments

The paper provides a dataset of effective thermal conductivity of snow on sea ice from tomographic images as well as from SnowMicroPen measurements. Data from the tomographic images are used to study the anisotropy of the thermal conductivity and assess existing parameterizations based on density. A new fitted regression is suggested. Data from the SMP measurements are used to study how thermal conductivity evolves with time and how it varies for 4 situations: snow lying on first year ice, on second year ice, on leads and snow on ridges. Associated variability in snow height and snow density are also presented and used to provide possible explanations for thermal conductivity variations.

The presented study will be largely beneficial for the snow and ice community as it provides a key dataset for the energy balance of sea ice. The dataset, involving in situ microCT, is unique. An impressive amount of field work and data analysis was provided and should be acknowledged. The idea to use SMP measurements to access more data and investigate spatial and temporal variations is new and seems well-suited.

However, the paper does not meet scientific standards in terms of data description and analysis. Some data lack thorough description or seem to be interpreted only half-way. Some statements are unclear or lack quantitative support. Additional work will be required to rigorously address the topic and provide a comprehensive presentation. I strongly encourage the authors to improve the paper as the topic can make for an important publication.

Thank you for this valuable feedback on the manuscript. I have implemented all your suggestions and I believe this has drastically improved the flow of the paper and its thoroughness. Your suggestions to conduct more statistical tests, improve the figures and make my explanations have suggested have been extremely beneficial throughout this review process.

The major issues regard

- FEM computations of effective thermal conductivity

It is unclear how the effective thermal conductivity was computed from the 3D images (see specific comment below) and which value of thermal conductivity is plotted in the different figures. Especially, in Figure 2, I believe it is the z-component of the thermal conductivity that is plotted, unlike what is mentioned. This point impacts the interpretation of the figure.

Thank you for this comment, We agree that the description of the FEM method is too short and some abbreviations could lead to confusion. We have made the following changes:

On line 108 we have included an explanation of the effective thermal conductivity ($k_{eff,z}$) alongside the definition. K_{eff} is always the vertical component of the thermal conductivity tensor (z-direction). We shortened $K_{eff,z}$ to K_{eff} throughout this manuscript.

Additionally, to avoid confusion K_{eff}^X has now been changed to K_{eff}^P where the P represents different parameterisations.

I have included an explanation of FEM in the section μ -CT to explain how the full 3-D tensors of effective thermal conductivity were calculated. In addition I have explained how we take the vertical temperature gradient (z-direction) and discard any lateral heat flow. Later I refer to the x, y, and z components when talking about calculations of thermal anisotropy.

We have added a figure to better explain the methods.

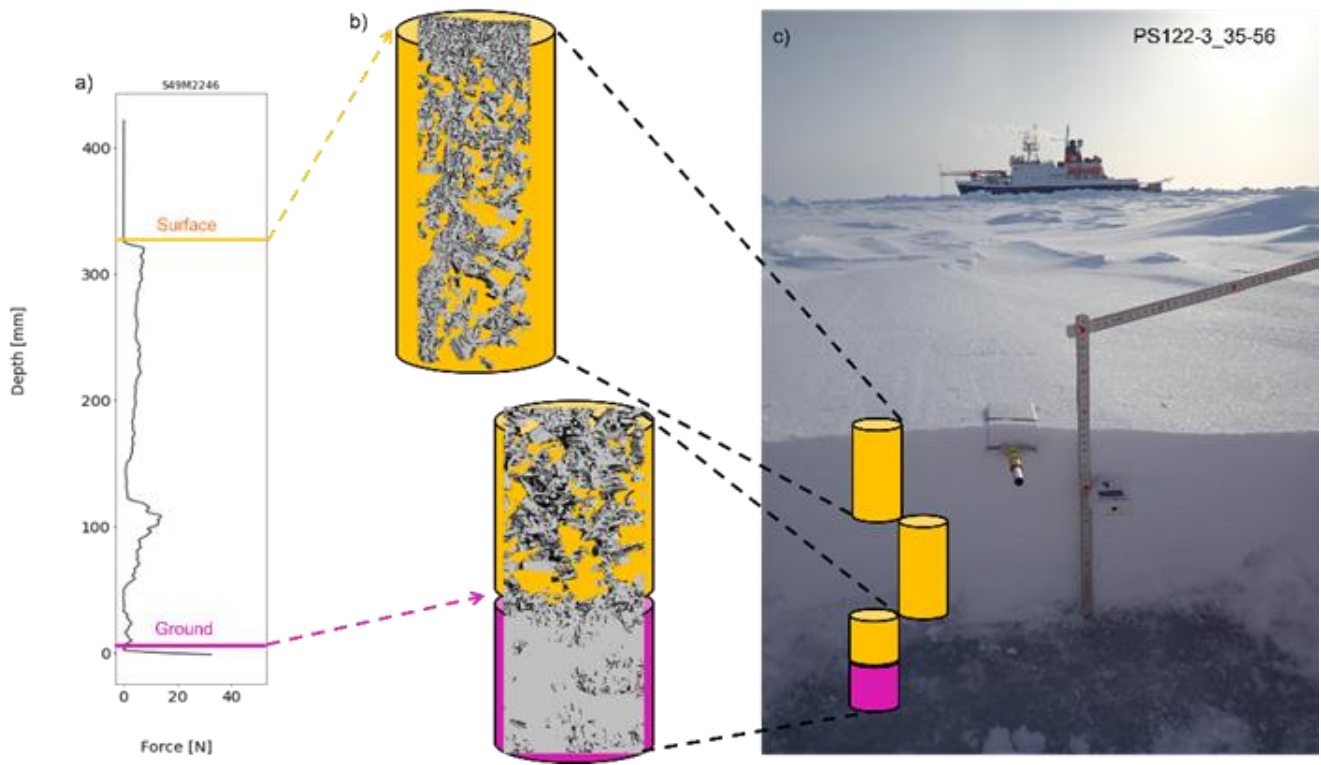


Figure 1. a) A snow micro penetrometer (SMP) force signal showing stratigraphy of the snowpack during Event PS122-3_35-56. b) Three-dimensional reconstructions of two μ -CT samples showing a typical surface (top) and snow-sea ice interface (bottom) sample. c) The overview photo of the snowpit during Event PS122-3_35-56.

Little information is provided on the relationship between thermal conductivity and microstructure. It is restricted to density although the authors have data of correlation length and geometrical anisotropy but they are not presented.

To provide more information on the relationship between these parameters we have taken the following steps: A_K , A_g and correlation length values are published alongside the Pangaea dataset. We use the correlation lengths to obtain geometrical anisotropy, see Equation 1 and a figure has been added to Appendix 1 which shows the relationship between A_K and A_g . We would also like to highlight the relationship between A_K and thermal conductivity shown in Figure 3.

The new dataset needs to be compared to existing datasets for snow on sea ice. The comparisons done with the Yen, Sturm and Calonne parameterizations are relevant, but in a first step it is indispensable to compare with the available data of thermal conductivity of snow on sea ice.

We have included an improved literature review in the introduction about the current thermal conductivity measurements in the Arctic. This has helped when re-writing parts of the discussion. Sturm paper is the only

existing dataset measuring thermal conductivity directly using the needle probe. We have investigated this method and compared the derived parameterization from Sturm. We reference the methods used by Merkouryadi and Hunke and discuss the values used for thermal conductivity in the modelling community further in the introduction.

We agree that the community will benefit from future studies comparing different instruments and independent datasets from the MOSAiC expedition which each measure the thermal conductivity of snow in the Arctic.

- parameterizations of thermal conductivity

The equations of the tested parameterizations, their domain of validity (density range) and information about how they were obtained (measurements, simulations) are lacking.

We have included a table with this information and expanded the section 4.1 Assessing existing parameterizations to two sub sections: Snow (density 50 – 550 kg m⁻³) and Interfacial and icy layers (density > 550 kg m⁻³) to improve the analysis of each range. In this study we have tested the complete range of snow and ice. These threshold labels are included in Figure 3 as vertical red lines which are further explained in the caption.

Up to 550 kg/m³ was used for snow as we found some hard wind-packed depth hoar layers with this density value. Above 830 kg/m³ was classed as ice. The values in between we have assumed originate from icy layers in the snowpack and dense layers at the snow-ice interface. We were fortunate to have the complete range in the mosaic measurements. Thresholds were used to separate the statistical tests, of which a new table has been added.

The evaluation of the parameterizations lacks scientific rigor and is only qualitative (e.g. performances described only by “work well” (line 232)). The comparisons should be supported by statistical scores. Performance scores for low/high density and low/high anisotropy should be provided if discussed. The authors recommend using Equation (3) for snow on sea ice but arguments are elusive. The authors should review their statistical measure they use. R² values are insufficient for the conclusion they make.

I have added additional statistical analysis for snow density ranges (50-550 kg/m³) and firn & ice density ranges (> 550 kg/m³) under the sub-section “Assessing existing parameterizations”. This includes an additional table giving the mean absolute error for individual cases.

The description of the proposed parameterization with anisotropy is incomplete and its purpose is unclear. First, the complete set of equations should be provided including the term $k(L)$ from Löwe et al. 2013 as well as the values for the involved parameters Ω , β , k_0 . There are two components k_z and k_x described in Equation (2) of Löwe et al. 2013 and it is not mentioned which one is used. With this complete description, it is still unclear how this parameterization with anisotropy can be applied to other density datasets to derive the thermal conductivity. The benefit for the paper and the general profit are unclear.

Added details into an appendix and re-worded to explain that, instead of using the linear empirical adaptation from Loewe (2013), we used a similar empirical adjustment (Equations ~11 and 12) as suggested in Sundu (2023) for the elasticity tensor to cover the entire range of densities. More details are given in Appendix 2.

The introduction

lacks a comprehensive description of the state of the art. Some relevant studies are provided in the introduction but it needs reorganization and completion, so the picture of the state of the art and the current limitations become clear. The reader should know which measurements were done on the thermal conductivity for snow on sea ice, which tools were used, and what range of values was found. To give an example, Sturm et al. 2002 “Thermal conductivity and heat transfer through the snow on the ice of the Beaufort Sea” appears but there is no description. This comment also refers to the parameterizations and the modeling – how is currently model snow on sea ice heat transfer? In the current state, the introduction mixes studies for ice, snow and snow on ice, which is confusing.

Thank you for this suggestion, we have adapted the introduction to include more literature review of the current measurements of thermal conductivity of snow on Arctic sea ice and the approaches used in the modeling community.

Specific comments

27: It could be helpful to include one sentence of the main characteristics of snow on sea ice. This way the reader can follow when the importance of the different heat transport processes are discussed.

Added a sentence on the highly variable snow cover, explaining that variability stems in the meter-scale.

28 “3/ vapour diffusion between the snow grains” → do you refer to phase change?

Yes thank you for this comment. I have added phase change

34 “X-ray micro-computed tomography (microCT) has enabled snow research to advance by measuring the exact ice skeleton without damaging it (Riche and Schneebeli, 2010)” → this reference is not the paper introducing CT on snow.

Added reference to: Coleou, C., Lesaffre, B., Brzoska, J.B., Ludwig, W. and Boller, E., 2001. Three-dimensional snow images by X-ray microtomography. *Annals of glaciology*, 32, pp.75-81.

39: “Density is currently used to parametrize thermal conductivity because it is a simple, low cost and quick measurement in the field” → no; first of all, it is because of the first order dependency between thermal conductivity and density.

Changed the sentence to explain how density is used to parametrise thermal conductivity because of the first-order dependency between thermal conductivity and density. Additionally, it is a simple, low cost and quick measurement in the field

51 “Spatial heterogeneity of the snow on sea ice requires a very high number of measurements, which can not only be realized by microCT.” → replace with “The study of spatial heterogeneity of the snow on sea ice requires a very high number of measurements, which can not only be realized by microCT.” Also, choose your wording between heterogeneity or variability, throughout the paper.

Thank you for this suggestion. I changed this throughout the manuscript and now use heterogeneity to explain landscapes and variability over a temporal scale.

62: “We up-scaled individual microCT” and throughout the paper → it is unclear what up-scaling refers to.

Added a sentence on how we related individual point measurements to a larger area by increasing the sample size

91: the cylindrical drill was operated by hand or was an electric drill used?

Added electric

151: The interest of computing thermal resistance R, compared to solely thermal conductivity, should be mentioned here.

If snow is considered as an interface between the atmosphere and the ice in models, it requires a thermal resistance rather than a conductivity. We have included a more detailed explanation in the text and added an extract from Bigdeli et al. (2020) which provides a very useful analogy.

Figure 2: It is unclear why snow samples with vertical anisotropy show higher values of $k_{\text{eff}}^{\text{FEM}}$ and inversely for horizontal anisotropy. Is $k_{\text{eff}}^{\text{FEM}}$ the average of $k_{\text{eff}}(x)$, $k_{\text{eff}}(y)$ and $k_{\text{eff}}(z)$, with $k_{\text{eff}}(x)$ the effective thermal conductivity computed under a heat flux in the x-direction and so on for y and z? This needs to be clearly defined in Section 2.2.1.

The more the structure is orientated in the direction of the temperature gradient the better the conduction even when the density remains the same. We take the z component of k_{eff} throughout this study. K_{eff}^X has now been changed to K_{eff}^P where the P represents different parameterisations. We have included this in 2.2.1, thank you for the suggestion.

Figure 2: a zoom for the 0 – 300 density range would be helpful to read the data.

Added a zoomed area to the figure

107 : « The thermal conductivity of the micro-CT sub-samples ... were compared ... as seen in Fig2.. » Figure 2 should be placed in Section 3.1 where it is actually described.

Moved the figure to be in section 2.2.1.

159 SWE is not defined

Thank you for noticing this. I have added the definition for SWE in section “Density Profiles”

161 « Due to a reduction of density... » → rewrite the sentence

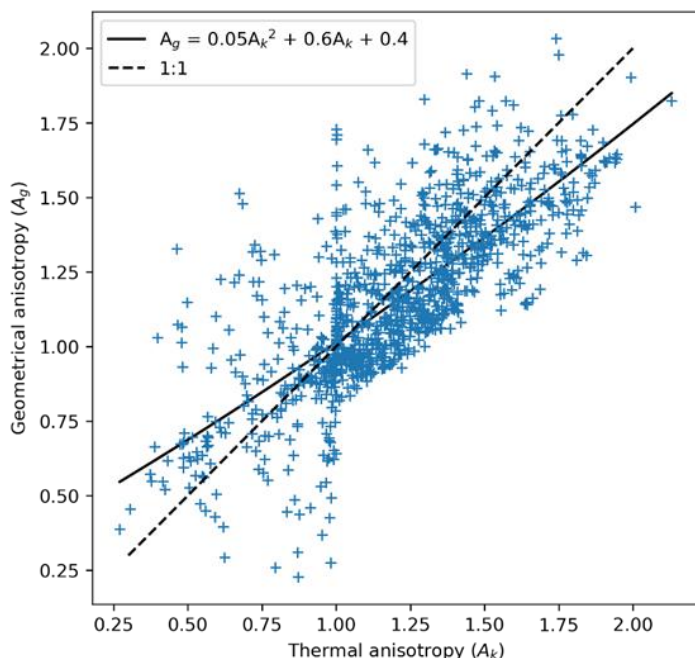
This section of the manuscript has been adapted as we did not have enough data points to make this conclusion about the density reduction. We therefore do not cover this in the discussion as heavily.

175 : It would be informative to describe which type of snow has low A_k values and high values (depth hoar?), if possible. To my knowledge, there has been little report of A_k values as low as 0.25 in the past, so it would be interesting to know what kind of snow it is.

We were able to measure icy layers due to the electric drill, I have added: “Extreme values of anisotropy in the lower range show icy layers and high values are depth hoar samples.”

In addition, the range of values of the geometrical anisotropy should be provided here, so the link between both anisotropy ratios can be done.

Both A_k and A_g will be published alongside the dataset in Pangaea. I have added the below figure into the appendix



Legend of Figure 3 : description of the bar plots of color yellow and green is missing the line colours

Figure adapted

Section 3.1. Overall, the link between the thermal conductivity and snow microstructure could be better addressed. An idea could be to provide a CT image of a typical stratigraphy of snow on sea ice together with vertical profiles of density, correlation length, A_g , thermal conductivity, and A_k .

Added a figure of the snow collection protocol with a microCT figure and parameter extraction from the SMP.

185: remove parenthesis

Parenthesis removed

Legend Figure 4. Check the structure of the sentence.

This figure caption has been re-written according to the new labels in the plot.

187: “Without including anisotropy in the parameterization, $k_{Mac(l)}$ eff is the best representation of k_{eff} , as it has the highest r^2 value compared to this dataset”. Only commenting on the performance of the regression that was fitted to the dataset is weak in terms of finding – it was not necessary to compare with other (independent)

parameterizations to come to this conclusion. To allow for fair comparisons, the validity range for the regression of Yen and Sturm, which have an upper density limit, should be provided.

Further statistical tests have been conducted in the section “Assessing existing parameterizations”.

Section 3.3: provide a general description of Figure 5 before giving detailed comments.

Thank you for this suggestion. I have changed this to “Fig. \ref{fig:BarChart_Keff} shows the snow heights, snow density (measured using the SMP and the \cite{king2020local} parameterization) thermal conductivity and thermal resistance for each ice type and for ridge areas. This can be seen in the grey box plots in the background of Fig. \ref{fig:BarChart_Keff}.”

188: “We use this parametrization and introduce the SMP to upscale our measurements of k_{eff} , of which we do not have corresponding A_k or A_g measurements”. Is the second part of the sentence necessary? I don’t understand the link with A_k and A_g here.

The meaning of this sentence is that if we did have A_g or A_k we wouldn’t use this parameterisation we would be able to use $Mac(II)$. I have added “Anisotropy is critical for reducing uncertainty in thermal conductivity, this is mentioned again in the discussion, and future work is suggested.” I then discuss this further in the discussion.

190 to 194: This paragraph could be placed in Section 3.3, as it is about using SMP and harmonic means to explore spatial and temporal variability and not about comparing parameterizations.

Moved this paragraph, thank you for the suggestion

Figure 5: The legend needs to be reviewed (repetitions, incorrect wording). The meaning of the grey box and of the grey stars are missing.

I have removed the repeating legends and included the grey box and grey star meaning in the figure caption “These profiles are grouped by underlying ice type, topographic feature (seen in the grey bar charts in the background of the figure, with grey stars indicating the outliers), and month (seen in the coloured bar charts, of which the outliers are not shown”

197: As a general comment, the paper is lacking descriptions of figures or tables. For example, it is too not sufficient to write “Table 1 gives the median and standard deviation of each.” without any supporting comment. A short sentence as “On average more snow is found on Ridges with $HS = 335$ mm and less on Leads with 84 mm” is very helpful for the reader.

Thank you for this suggestion, I have implemented it in the manuscript

Section 3.3 (related to the previous comment). The writing of this section should be improved. The description of the figures should include more quantitative descriptions. No value is provided in the entire section. For example, line 196 – 199: snow height trends are described using “increase” / “decrease” / “highly variable” / “high spatial heterogeneity” without providing supporting values.

Added supporting values of ranges and re-worded the text

199 “Leads and ridges show consistently high spatial heterogeneity” → Is it shown on Figure 5?

Changed to “The range of snow depth on ridges (0 to > 1000 mm) shows consistently high spatial heterogeneity throughout the winter season; therefore, temporal changes are less discernible than in FYI and SYI areas.”

Figure 6. Provide a comprehensive description of the figure. Increase the figure resolution as the text (n=, M =) is difficult to read on a printed copy of the paper. Some sentences of the legend are actually figure analysis and should be placed in the text.

Changes made to the figure

208 “keff has a slightly lower median on FYI and SYI, compared to leads and ridges with a higher keff”. The first comment should rather be that values of harmonical mean of keff for each site are very close to each other. The grouping FYI-SYI and leads-ridges is not clear.

Changed this paragraph to $\overline{k_{\text{eff}}^{\text{Mac}(l)}}$ has a standard deviation between 0.04 and 0.06 $\text{W K}^{-1} \text{m}^{-1}$ for all ice types the difference between the median $\overline{k_{\text{eff}}^{\text{Mac}(l)}}$ of these ice types is 0.04 $\text{W K}^{-1} \text{m}^{-1}$, meaning the values are very close and are not significantly different. This data can be found in Table [\ref{tab:overview}](#).

The temporal increase in density and k_{eff} is rather until between February and March depending on the site (Fig 5).

Changes made in section 3.3, due to insufficient data to draw conclusions about the density decrease we have decided to reduce the emphasis on this in our discussion.

217 “When using these parametrizations to investigate the heterogeneity of the snow cover, the microCT was not an ideal method for obtaining a representative sampling of the snow cover due to the time required for one measurement” → suggestion: To investigate the spatial variability of the snow cover, the microCT is not an ideal method due to the time required for one measurement

Thank you for the suggestion

229 “A snow sub-sample with a density of 400 kg m^{-3} can have a thermal conductivity value ranging from 0.2 $\text{W K}^{-1} \text{m}^{-1}$ to 0.6 $\text{W K}^{-1} \text{m}^{-1}$ if the snow is isotropic or anisotropic, respectively.” → This should read as “if the snow is isotropic or anisotropic in the vertical direction, respectively”. Anisotropy in the horizontal direction leads to even lower values, if the interpretation of this figure is correct.

Added “in the vertical direction” as we only assess thermal conductivity in the z-direction. I have made adjustments to the manuscript to clarify this.

Section 4.2: It could be interesting to discuss the possible impacts of the ice type and the topography on snow and so on the thermal conductivity. What was the initial motivation to study snow on different ice types, did you expect differences? (this could be included in the introduction).

The initial motivation is that this is the first time we have data to be able to do this. Thermistor strings and point measurements have not allowed this in past studies. Added “This is the first time we have been able to group a dataset of thermal conductivity measurements by underlying ice type (FYI, SYI and leads) and topographic feature (ridges) for one winter period. This has allowed us to analyse different features of importance for heat transfer.”

Line 259 – 266: this paragraph is not about spatial variability as it is about comparing measured values with values used in models, so it appears out of subject here.

Re-phrased this paragraph as the spread of values in figure 3 is due to spatial heterogeneity of the slow and I have now explained that one value in the models is related to this in Figure 3.

265: It is an open question what the influence of convection is, but we need to answer the question...” → in the introduction, it is mentioned that convection is reduced in wind slabs on sea ice. More context is required to understand why we refer to convection here.

Removed this sentence to read “We need to answer the question...”

292 “As snow undergoes metamorphism, we expect its thermal conductivity to increase as the density increases.” → Not all types of metamorphism involve a density increase; temperature gradient metamorphism can keep snow at about constant density. Explanation needs improvement.

Removed this sentence, I agree this was incorrect.

293 “We now work to understand the process causing a reduction in density after March.” → provide order of magnitude of the reduction in density. Are we trying to understand a gap of 5 or 100 kg/m³?

We have found that there are not enough measurements in May to draw and concrete statistical analysis. As a result we have excluded May and mention this in the discussion.

298 “Fresh snowfall as input would lower the average density. A layer with low thermal conductivity $k_{Mac(l)eff}$ leads to a drastic decrease in the average thermal conductivity. We can see in Wagner et al. (2022) that we had fresh snowfall during this period.” → Be more specific that “we had snowfall”. It could be mentioned that this is not seen in the snow height data in Figure 5, as there is no increase. Also, snowfalls are always fresh.

Removed this section from the discussion, see the above comment.

312 “Penetration of the hard density layers at the snow-ice interface became thinner due to sublimation” → not understandable.

This has been removed and the discussion has been restructured accordingly.

318 “Crocus and SNOWPACK simulate lower layers with high density and high thermal conductivity, and surface layers with low values for both variables (Domine et al., 2019), whereas we have presented the opposite.” → It is not shown in the paper that you have opposite results. There is no clear trend in the vertical profile of thermal conductivity, as seen in Figure 1, and it is not described in the text. No density profiles are shown. So additional data / figure should be provided to support this comment or this paragraph should be deleted. Also, SNOWPACK and Crocus are not defined.

I have removed this paragraph

321 “Due to the combination of this seasonal trend in density and $k_{Mac(l)eff}$ snow depths, we see no change of R” → wording

Re-worded this sentence

340 “It was found that a combination of fresh snowfall, high wind speeds causing erosion and re-deposition (initiating a SWE reduction during a storm event, as shown in Wagner et al. (2022)), vapour diffusion within the snow and changes at the snow-ice interface (further analysis of this interface is needed to draw concrete conclusions. However, this is not in the scope of this study), could all result in the density reduction across the snow profile.” → this sentence should be shortened.

Thank you for the suggestion the sentence is now shortened

Conclusion: The conclusion could be improved to provide a clearer picture of the main contributions / findings of the paper.

Introduction, discussion and conclusions have been adapted according to the changes and suggestions above. Thank you for your help improving this manuscript.