Author's response

to reviewers on the initial submission of the preprint tc-2023-51

"Coupled thermo-geophysical inversion for permafrost monitoring",

by Soňa Tomaškovičová & Thomas Ingeman-Nielsen

1. June 2023

>> We are thankful to the reviewer for the thoughtful review and for acknowledging the value of the presented work. We are particularly thankful for the excellent suggestions on how to improve the discussion section of the paper. Our replies are indicated in ">> the blue paragraphs". All of the reviewer's suggestions were thoroughly considered and implemented in the revised manuscript, which we look forward to uploading upon the editor's invitation.

Reviewer 2

This paper describes the development and application of a fully-coupled inversion to retrieve thermal soil properties from geophysical and temperature data. The paper describes in detail how the models and inversion are setup, what their assumptions and limitations are, and by doing so provides a great reference on how to develop such a fully-coupled approach. The authors provide a detailed sensitivity study, showing that the most critical parameters for the estimation of subsurface thermal properties are the porosity and the soil grains thermal properties.

Their synthetic and field study shows that the soils thermal parameters can be estimated reasonably well using the temperature data, even though the soil is modelled as homogeneous layer. Adding the resistivity data is successful, but does not seem to contribute to improve the parameter estimates.

>> Indeed, it is true that in our study, the resistivity data does not provide a calibration superior to the calibration on borehole temperatures. This is because the intention of this study was 1) to evaluate the amount of information in geophysical data for calibration of a soil thermal model, 2) show that geophysical calibration data are useful as alternative calibration data and provide as good results as borehole temperature data. In certain situations, the use of geophysical data may have practical advantages that we discuss further in reply to the reviewer's comment below on "3. Value of geophysical data".

Although the paper presents the developed approach very clearly, and provides a significant amount of detail on the approachs performance, I'm missing a more detailed discussion on the limitations of the approach, which I would summarize as follows:

41 Modelling of a 1D distribution of thermal properties: While you state that your synthetic tests did not justify using a more complex thermal field, your discussion should address this issue. While it is well known that the thermal properties of the subsurface do vary with depth, why is the model not able to resolve this? Is it because you would require stronger temperature gradients, i.e. are the sensitivities to small to able to resolve this variability? And if resolving of vertical variations is not possible, how do your results improve current understanding of soil thermal property variations?

>> We distinguish between the bulk (effective) thermal properties of the ground vs. the specific thermal properties of the ground constituents (of water, ice, soil grains).

The model *is* able to resolve the effective thermal properties of the ground as they vary with depth; these properties are effectively changing with depth and with temperature in the modeled domain. The current implementation of the model can also handle prior constraining information in terms of known thermal parameters and known geological boundaries.

What the model - in the presented implementation - doesn’t optimize for, is different *specific* thermal properties of the respective soil constituents (eg. thermal conductivity and heat capacity of the soil matrix) that could be varying with depth if the geology varied. The reason for this is that the geology on our site is, based on geotechnical boreholes, homogeneous in terms of soil type (silty clays). Therefore it is justified to optimize for uniform specific soil thermal properties throughout the soil column. (but the bulk/effective thermal properties are still different, as they depend on temperature and phase distribution of the soil constituents in the soil column). It would be interesting to explore how e.g. inverting for varying porosity through depth would perform, but constraining information may need to be added (e.g. porosity has to be decreasing with depth). This would be an interesting question for a follow-up study.

Our model is not necessarily aiming at improving the current understanding of soil thermal properties variations, but at providing an alternative way of deriving it from surface measurements. Showing the sensitivity of parameters improves the understanding of what geological information may be necessary for constraining the model.

We edit the related statements in the revised version of the manuscript.

51 Spatial variability: While you already discuss that there is a lack of model performance in the unfrozen state where water flow may contribute to temperature variations, you neglect the spatial variability of the electrical properties. In line 63 you state: "The relationship translating a certain ground electrical composition into apparent resistivity is unique", while this is true in the

way you state it, it is not true for the inverse, and thus provides a major limitation for your inversion that is not discussed. I.e. a homogenous subsurface distribution may provide the exact same apparent resistivity response than an arbitrarily layered medium and this will become even more complex when going from 1D to 3D. While this may not be a major limitation in some geological settings, in permafrost environments where the electrical properties are highly heterogenous, I would argue that this is a major limitation of your approach.

>> This concern is valid for a single geoelectrical measurement, or for several measurements on a homogeneous half-space, but not for a combination of electrode layouts on a heterogeneous half-space because of the different depth sensitivity of different layouts. This applies also to 2D and 3D scenarios, where different layouts are necessary to cover the part of the subsurface of interest.

A real concern is if the equivalencies observed in the inversion of resistivity data from permafrost impact this type of inversion. This is currently not known. Such a question is targeting a more complex situation than what we focused on in the simple conditions of this study. More work is necessary to understand how the method performs in more complex settings.

We've added this point to the Discussion in the revised manuscript.

61 Value of the geophysical data: You describe in much detail the performance of the thermal parameter inversion, which seems to provide very good results. Yet, when you add the geophysical data, the performance seems to degrade (i.e. you need to fix Cs to obtain reasonable estimates) and hence I am wondering what the rational is to include the resistivity data. Clearly, it would allow you to assess spatially varying parameter distributions, but this is not shown here.

>> We would like to stress that this study presents the results of an experimental phase where we investigated to which extent we can replace (not supplement) the borehole temperature data with geophysical data. Attempts at exploiting information in geophysical data that can be interpreted in terms of temperatures are also known from the Alps, where geophysical surveys are used to construct virtual boreholes. This study is another such approach to trying to exploit geophysical data in terms of their information content about ground temperatures.

In some situations, borehole temperature data may be the best calibration data. However in certain conditions, the following practical advantages of geophysics could be of interest:

1) Measurements collected from the surface rather than the need for drilling: This encompasses two advantages: larger depth reach, as well as the possibility to work in both sedimentary and bedrock settings. Hand-operated, engine-powered drilling tools are of limited depth penetration and restricted to sedimentary geology. Logistics associated with mobilizing a drilling rig able to reach larger depths or drilling through bedrock is often prohibitive in remote arctic areas. Meanwhile, the depth reach of a geoelectrical array can be more readily adjusted by the design of the largest spacing of the current electrodes.

2) Smaller impact on fragile ecosystems: Few roads exist in the Arctic, and the movement of drilling equipment on the tundra, especially outside of the frozen season, seriously damages the terrain, particularly in wetter and ice-rich permafrost areas. Arctic tundras are characterized by relatively low biological activity and diversity, and by short, cool and dry growing seasons. This leads to the natural re-vegetation process after surface disruption being very slow. The disruption of the surface organic layer then typically results in the accelerated thaw of permafrost. Together with the risk of pollution from engine-operated equipment, these factors may cause issues securing the necessary permits for drilling fieldwork. In comparison, the impact of the surface or airborne geophysical methods is minimal.
3) Assessment of spatially varying conditions: Geophysical mapping methods, unlike point borehole measurements, allow for a relatively quick assessment of ground conditions over comparatively large areas. Therefore, expanding the presented approach to three-dimensional mapping presents another potential for future development of the method.

We have added these points to the Discussion section of the revised manuscript.

In summary, while I think that the paper very nicely presents the develop approach, and the thermal inversion seems to provide reasonable results, it remains unclear what the benefit of including the geophysical data really is and how the limitating assumptions really affect the model outcome. I think that needs to be stated much more clearly, and will require a more detailed discussion section.

>> We thank the reviewer for acknowledging the presentation of the method. A discussion of the benefit of using the geophysical data has been added in reply to the previous comment (and added to the revised Discussion of the manuscript). Additionally, we think that this study, while presenting a working method, also has its value as a proof of concept and an exploration of possible pathways for future development.

Below are some more specific remarks:

Lines 20 - 21: I find this misleading as it seems like there are only 3 studies that look into petrophysical relationships, but there are a number of papers, e.g. Olhoeft (1978), Magnin et al. (2015), Hoekstra and McNeil (1973), Scott and Kay (1988), Holloway and Lewkowicz (2019), Tang et al. (2018), Uhlemann et al. (2021), Wu et al. (2017)

>> We had no intention of making it look like only three studies were available. More relevant references were listed in the discussion. We have reviewed the suggested references and added them to the revised version of the manuscript.

Lines 54-56: Would this require you to know the composition of the ground? If so, how would you obtain that information, which likely is spatially varying too.

>> We appreciate the reviewer's positive attitude about expanding the method into more dimensions. The purpose of this study is not to investigate 2-3D variability, but rather whether resistivity contains information to invert for the thermal properties, and whether

it can replace borehole temperatures in 1D setting. The resistivity method already has its limitations and in 2D, the resistivity inversion relies on constraining info to resolve 2D variations (smoothness constraints). We are of the opinion that first, we needed to find out if the approach was possible in 1D before expanding into more dimensions. With the successful results reported here, it would be interesting to expand the analysis to 2D and 3D. It is conceivable that in such cases, there may be a need to combine resistivity data with other constraining or calibration information (other geophysics, remote sensing).

"Composition of the ground" - does it refer to different soil types? Or different proportions of ground constituents (water, ice, soil grains)? The latter is solved by the model. Regarding different soil types, it would be of course very interesting to test the performance of the method at a site of different geology; for this, at least one freezing season of resistivity data from a different site would be needed.

Lines 146 - 149: Wouldn't this have two explanations: (1) you are not sensitive to these variations, or (2) the uncertainty of your results are larger than the vertical variability?

>> We think this is addressed in the reply to the reviewer's comment above "1.Modelling of a 1D distribution of thermal properties". Also, the statements are clarified in the revised version of the manuscript and discussion on the topic is added.

Figure 2: Here and elsewhere (also in the text), you first refer to the thermal conductivity as k, but then change its annotation to lambda.

>> Notation changed to lambda throughout the revised version of the manuscript.

References:

Olhoeft, G. R. (1978). Electrical properties of permafrost. Proceedings of the Third International Conference on Permafrost, 127–131.

Magnin, F., Krautblatter, M., Deline, P., Ravanel, L., Malet, E., & Bevington, A. (2015). Determination of warm, sensitive permafrost areas in near-vertical rockwalls and evaluation of distributed models by electrical resistivity tomography. Journal of Geophysical Research, 120, 745–762. https://doi.org/10.1002/2014JF003351

Hoekstra, P., & McNeill, D. (1973). Electromagnetic probing of permafrost. North AmericanContribution to the Second International Conference on Permafrost, 517–526.

Scott, W. J., & Kay, A. E. (1988). Earth Resistivities of Canadian Soils.

Holloway, J. E., & Lewkowicz, A. (2019). Field and laboratory investigation of electrical resistivity-temperature relationships, southern Northwest Territories. Cold Regions Engineering, 64–72. https://doi.org/10.4324/9780203210536

Tang, L., Wang, K., Jin, L., Yang, G., Jia, H., & Taoum, A. (2018). A resistivity model for testing unfrozen water content of frozen soil. Cold Regions Science and Technology, 153, 55–63. https://doi.org/10.1016/j.coldregions.2018.05.003_chapter_9

Uhlemann, S., Dafflon, B., Peterson, J., Ulrich, C., Shirley, I., Michail, S., & Hubbard, S. S. (2021). Geophysical monitoring shows that spatial heterogeneity in thermohydrological dynamics reshapes a transitional permafrost system. Geophysical Research Letters, 48(6), 1–11.

https://doi.org/10.1029/2020gl091149

Wu, Y., Nakagawa, S., Kneafsey, T. J., Dafflon, B., & Hubbard, S. (2017). Electrical and seismic response of saline permafrost soil during freeze - thaw transition. Journal of Applied Geophysics, 146, 16–26. https://doi.org/10.1016/j.jap