AUTHORS' RESPONSE TO THE COMMENTS OF THE REFEREE #2

RC2: The manuscript by Uxa et al. presents an approach for determining MAPT and ALT utilizing shallow ground temperatures at two depths. The MS is interesting and generally well written with a good description of the approach being proposed.

However, there are some concerns regarding the validation of the approach and evidence that it is novel given that the two variables being determined are commonly calculated by interpolation/extrapolation when shallow ground temperatures are available. It is unclear what advantage the method proposed has over this commonly used approach especially given that the authors acknowledge that their equation is in principle a linear extrapolation of the temperature indices. The MS would benefit from a comparison of their model results to those from interpolation/extrapolation of observed shallow ground temperatures. The authors may have done this when they compare their model results to observed MAPT and ALT, but it is not clear how the observed values were determined, and additional explanation is required (see additional comments below). The authors may also want to consult Riseborough (2008, ICOP) regarding use of interpolation and extrapolation to determine thaw depth and importance of spacing of sensor depths.

AC: The models are primarily intended to be used for MAPT or ALT estimates at places where ground temperature measurements are too shallow and MAPT or ALT cannot be determined directly or where the spacing between temperature sensors is too large (there are many such stations). Among other possible applications, they can be used to establish typical values of thermal conductivity ratio (for MAPT) and edaphic factor (for ALT), which can then be used to model MAPT and ALT in the past or in the future. Note that the thermal conductivity ratio has never been estimated this way. Edaphic factor has been estimated using the near-surface thawing index and active-layer thickness, but obviously this procedure cannot be used if ground temperatures are too shallow and active-layer thickness is unknown. Our procedure is applicable even in such situations.

The extrapolations have frequently been done rather intuitively and without a physical basis. We admit that the situation is somewhat better in the case of the active-layer thickness, but in principle none has been done for extrapolating the permafrost table temperature. The linear relationship between the thawing and freezing indices within the active layer is new, as is the whole procedure, which has a physical basis. We will emphasize these thoughts a bit more in the revised manuscript.

The ALT values were determined by continuous tracking/interpolating the 0 °C isotherm from measured temperatures (see e.g., Hrbáček et al., 2020, 2021; Kňažková and Hrbáček, 2024). The mean annual permafrost table temperature (MAPT) was the mean annual ground temperature interpolated to the depth corresponding to ALT (=permafrost table). We compared our model outputs directly with these measured/interpolated values. Thanks for providing the reference to Riseborough (2008). If it proves useful, we will consider including it in the revised manuscript.

Hrbáček, F., Cannone, N., Kňažková, M., Malfasi, F., Convey, P., Guglielmin, M. (2020). Effect of climate and moss vegetation on ground surface temperature and the active layer among different biogeographical regions in Antarctica. Catena, 190, 104562. https://doi.org/10.1016/j.catena.2020.104562

Hrbáček, F., Engel, Z., Kňažková, M., Smolíková, J. (2021). Effect of summer snow cover on the active layer thermal regime and thickness on CALM-S JGM site, James Ross Island, eastern Antarctic Peninsula. Catena, 207, 105608. https://doi.org/10.1016/j.catena.2021.105608

Kňažková, M., Hrbáček, F. (2024). Interannual variability of soil thermal conductivity and moisture on the Abernethy Flats (James Ross Island) during thawing seasons 2015–2023. Catena, 234, 107640. https://doi.org/10.1016/j.catena.2023.107640

RC2: The analysis and conclusions would benefit from better descriptions of the field sites including material properties, vegetation, climate etc. The limited range in their characteristics is a concern as all the sites are in cold permafrost of the continuous zone and likely tundra sites. This limits the conclusions that can be made regarding model performance and the broader applicability of the approach. Consideration of sites in warmer permafrost in the discontinuous zone including those in forested and peatland terrain would be useful as this would further back up statements regarding model performance including statements made regarding warmer permafrost.

AC: We will roughly double the number of the validation sites in the revised manuscript, which will cover much of the world's major permafrost regions (Antarctica, Arctic, Tibetan Plateau and high mountains) and offer us greater heterogeneity in terms of permafrost table temperature and active-layer thickness (approximately −19 °C to −2 °C for MAPT and <50 cm to >200 cm for ALT), as well as in terms of surface cover, active-layer composition and stratigraphy, or permafrost zones. We will also provide more key information on the validation sites in the revised manuscript as suggested. This will allow us to make the validations more robust.

RC2: Additional comments related to the concerns raised above and other comments are provided below for the authors' consideration.

L21 – "indicators" might be better than "measures"

AC: We will change it as suggested.

RC2: L22-23 – suggested revision: "Climate change has resulted in permafrost warming and active-layer thickening throughout the permafrost regions". Biskaborn et al. is now out of date with respect to the trends. I suggest you include Smith et al. (2024, State of Climate- Arctic), along with Noetzli et al. (2024), as it provides the details for Arctic and is up to date.

AC: We will change it as suggested.

RC2: L29-30 – It is important to note that active layer thickness is not determined directly from geophysical surveys but is interpreted and it is difficult to determine ALT in warm permafrost with high unfrozen water contents.

AC: We totally agree and that is why we only state that geophysical surveys are among the methods used to investigate permafrost and active-layer thickness. We did not mention anywhere in the original manuscript that active-layer thickness is determined directly using geophysics.

RC2: L27-34 – Smith and Brown (2009) outline the various methods used as does Streletskiy et al. (2022).

AC: Thank you for these useful references. We will incorporate them into the revised manuscript.

RC2: L34-37 – Even if ground temperatures are measured within shallow permafrost and the active layer the permafrost table temperature or active layer thickness still needs to be determined/calculated. Interpolation and extrapolation is the method usually used. I suggest you consult Riseborough (2008 ICOP) which describes the appropriateness of interpolation/extrapolation approaches.

AC: Thank you for this reference. If it proves useful, we will consider including it in the revised manuscript.

RC2: L38-42 – The purpose of the model is important. The ones mentioned are generally used for predictive applications such as determining conditions with little information on the site conditions. What you seem to be proposing is away to determining ALT or MAPT based on having ground temperature measurements which is what we do when we use interpolation/extrapolation of shallow ground temperatures to determine ALT or MAPT (see comment above).

AC: The models are primarily intended to be used for MAPT or ALT estimates at places where ground temperature measurements are too shallow and MAPT or ALT cannot be determined directly or where the spacing between temperature sensors is too large (there are many such stations). Among other possible applications, they can be used to establish typical values of thermal conductivity ratio (for MAPT) and edaphic factor (for ALT), which can then be used to model MAPT and ALT in the past or in the future. Note that the thermal conductivity ratio has never been estimated this way. Edaphic factor has been estimated using the near-surface thawing index and active-layer thickness, but obviously this procedure cannot be used if ground temperatures are too shallow and active-layer thickness is unknown. Our procedure is applicable even in such situations. We will emphasize the above thoughts in the revised manuscript.

RC2: L45 – Is reference being made to air or ground temperatures here?

AC: It was meant to be both, because both air and ground temperatures are used to as model forcings (of course, for air temperatures, some procedures must be used to convert them to ground temperatures). We will explicitly state this in the revised manuscript.

RC2: L46-49 – Some of the approaches mentioned do consider variable properties including thermal conductivity for thawed and frozen conditions (e.g. ratio between them is included in TTOP equation) or the variation of conductivity with temperature (and unfrozen water content).

AC: Yes, some (but few) of the approaches mentioned indeed considered the temporal variations in ground physical properties, but these variations would have to be involved in the models as additional forcings, which is frequently not available. Hence, most models treat the ground physical properties as constants, which brings complications in terms of their representativeness (for instance, one measurement per year or more should represent the temporal variations over this whole period). We believe that our solutions are useful in that they can simply address this general lack and/or non-representativeness of ground physical data. We will a bit revise this sentence in the revised manuscript so that the above thoughts are clearer.

RC2: L57 – Editorial suggestion – delete "Besides other solution (Garagulya, 1990)" – it is not adding anything.

AC: We will remove it from the revised manuscript.

RC2: L66 – Editorial suggestion – Delete first part of sentence: "Eq. (1) is also valid for temperatures measured…..layer, which is convenient because…."

AC: We will change it in the revised manuscript as suggested.

RC2: L68 – Note that usually the reference to surface temperature measurements used in these equations is from a sensor in upper 3-5 cm of the ground so not using exact surface temperature. The surface temperature can be estimated using n-factor to provide input into the equation.

AC: We agree and will consider this in the revised manuscript. However, the problems associated with ground surface temperature measurements (mentioned in the original manuscript) also relate to some extent to near-surface measurements.

RC2: L84 – If this is essentially extrapolation how is this different from the approach others use to determine the depth of the permafrost table and MAPT when they have temperatures at two or more depths?

AC: As detailed above, the major difference is that previous extrapolations have frequently been done rather intuitively and without a physical basis, which is not the case of our models. We will emphasize these thoughts a bit more in the revised manuscript.

RC2: L97 – Editorial suggestion - Delete first part of sentence: "ALT (m) can be calculated using the….

AC: This will require more changes to the text than this to make it understandable, but we will follow this suggestion in the revised manuscript.

RC2: L99 – missing word: "…simplest form is as…."

AC: We will add this to the revised manuscript.

RC2: L103 – See earlier comment regarding estimates of surface temperature used by others.

AC: We agree and will consider this in the revised manuscript. However, the problems associated with ground surface temperature measurements (mentioned in the original manuscript) also relate to some extent to near-surface measurements.

RC2: L136 – Smith et al. (2009) is also relevant - used observed ALT from sites in various regions and environments (tundra, forest, peatland and mineral and organic soil) to show the range in the Edaphic factor.

AC: Thank you for this useful reference. We will incorporate it in the revised manuscript.

RC2: L148 – See earlier comment regarding extrapolation

AC: The major difference is that previous extrapolations were frequently done rather intuitively and without a physical basis. We will emphasize these thoughts a bit more in the revised manuscript.

RC2: L159-197 – It seems that there are several assumptions being made as well as simplifications. For example, thermal conductivity changes with temperature due to change in unfrozen water but it appears that constant frozen and unfrozen conductivity are assumed. Are the results of the two models really comparable?

AC: Yes, there are several assumptions and simplifications that needed to be made so that the numerical model can mimic the behaviour of the analytical–statistical models together with their (simplifying) assumptions and boundary conditions, which is a standard practice. We think the numerical model does a right (and required) job in this respect because the numerical validations are not obscured by processes that the analytical–statistical models do not account for. We believe that the numerical simulations for idealized scenarios are relevant because they are meant to evaluate if the analytical–statistical models were derived correctly.

RC2: Table 2 – For years and seasons is the 2nd number the total record length and the first number the number of years utilized in analysis? It might be clearer to refer to number of years used and refer to it as e.g. 6 of 6. Are the ALT values determined from temperature or through probing? How is MAPT determined? It is unclear what you are comparing your modelled values with? I might have missed something here but maybe there needs to be a clearer explanation

AC: We used three depth combinations in our models based on temperatures from the depth intervals of 0–10 cm, 25–35 cm and 45–55 cm. However, there were occasional gaps in the datasets, which caused that some of the depth combinations could not sometimes be used for validations or that the number of years for MAPT and ALT validations differed. We admit this is not very intuitive, and we will rework it to make it fully understandable in the revised manuscript.

The ALT values were determined by continuous tracking/interpolating the 0 °C isotherm from measured temperatures (see e.g., Hrbáček et al., 2020, 2021; Kňažková and Hrbáček, 2024). The mean annual permafrost table temperature (MAPT) was the mean annual ground temperature interpolated to the depth corresponding to ALT (=permafrost table). We compared our model outputs directly with these measured/interpolated values.

RC2: L200-201 – No information on the sites is provided so the reader doesn't know how diverse they are. There is no information provided on material characteristics or vegetation. The Alaskan sites are all on the North Slope in the continuous permafrost zone and likely in tundra environments, so conditions are not that diverse with respect to climate and vegetation. Using field data from sites in warmer permafrost in discontinuous zone and for forested sites would provide more diverse conditions. This would help show if your approach is valid for a wide range in conditions.

AC: We will roughly double the number of the validation sites in the revised manuscript, which will cover much of the world's major permafrost regions (Antarctica, Arctic, Tibetan Plateau and high mountains) and offer us greater heterogeneity in terms of permafrost table temperature and active-layer thickness (approximately −19 °C to −2 °C for MAPT and <50 cm to >200 cm for ALT), as well as in terms of surface cover, active-layer composition and stratigraphy, or permafrost zones. We will also provide general information on the validation sites in the revised manuscript as suggested.

RC2: L204 – Since you are referring to a depth it would be better to refer to permafrost table or base of the active layer. Do you mean the base of the active layer was above the shallowest sensor?

AC: We will revise this sentence in the revised manuscript so that it is clearer. Please note that we used temperatures measured at the depth intervals of 0–10 cm, 25–35 cm and 45–55 cm as model forcings so that they are comparable across the study sites, but the depths at each site were constant, for instance, 5 cm, 30 cm and 50 cm. If the active layer is thin, there can be some years when the base of the active layer was shallower than the deepest sensor used. This means that the active-layer thickness was less than 50 cm. But definitely, we did not mention anywhere that the base of the active layer was above the shallowest temperature sensor.

RC2: L206-2011 – See Riseborough et al. (2008 ICOP) regarding errors associated with different approaches (interpolation, extrapolation) to determine thaw depth/top of permafrost etc. and guidance on the best approach to use.

AC: Thank you for this reference. If it proves useful, we will consider including it in the revised manuscript. Please note that we used linear interpolation based on measured temperatures to determined MAPT and ALT, which we also used in numerous previous publications.

RC2: L222 – Wasn't this exponential decrease already fairly well known? Doesn't the magnitude of the decrease depend on the material properties?

AC: It was known for thawing indices (e.g., Riseborough, 2003), but rather neglected for freezing indices because permafrost studies have dominantly focused on summer active-layer dynamics and/or annual means. However, the linear relationship between the thawing and freezing indices within the active layer is new. And yes, the magnitude of the decrease mostly depends on the thermal conductivities and the amount of latent heat. We will emphasize these points a bit more in the revised manuscript.

Riseborough, D. (2003). Thawing and freezing indices in the active layer, in: Proceedings of the 8th International Conference on Permafrost, Zurich, Switzerland, 21–25 July 2003, 953-–958, 2003.

RC2: L235 – See earlier comment – How were observed values determined?

AC: The observed MAPT values were determined by a linear interpolation of the mean annual ground temperatures observed at sensors just above and below the observed active-layer thickness, which was briefly described in Sect. 3.3. Still, we will make this a bit clearer in the revised manuscript so that it is easily understandable.

RC2: L260 – See earlier comment – How were observed values determined?

AC: The ALT values were determined by continuous tracking/interpolating the 0 °C isotherm from measured temperatures (see e.g., Hrbáček et al., 2020, 2021; Kňažková and Hrbáček, 2024), which was briefly described in Sect. 3.3. Still, we will make this a bit clearer in the revised manuscript so that it is easily understandable.

RC2: L265-268 – Does the difference in error between Antarctica and Alaska sites have anything to do with the material properties. Was latent heat more of a factor for the AK sites?

AC: We believe that it does. We think this is mainly caused by the active-layer stratigraphy, which is almost exclusively one-layer without any organic material in Antarctica and two-layer in Alaska. Hence, it definitely also has something to do with larger amount of latent heat at the Alaskan sites.

RC2: L264-292 – The thermal offset depends on the ratio of thawed and frozen thermal conductivity which depends on the amount of moisture/ice in the ground. If the moisture content is low or arid conditions exist, then the offset will be low or positive. Is the site in McMurdo Sound a dry site? It would be useful to know this. It would have been good to use sites with warmer permafrost in your analysis to back up the comment that deviation in MAPT estimates would be larger.

AC: Yes, the sites in McMurdo Sound experience hyperarid conditions, which most likely produce positive thermal offsets. Please note that we will roughly double the number of the validation sites in the revised manuscript, which will cover much of the world's major permafrost regions (Antarctica, Arctic, Tibetan Plateau and high mountains) and offer us greater heterogeneity in terms of permafrost table temperature and active-layer thickness (approximately −19 °C to −2 °C for MAPT and <50 cm to >200 cm for ALT), as well as in terms of surface cover, active-layer composition and stratigraphy, or permafrost zones. Hence, we will be able to back up or revise our statement that larger deviations in MAPT would be expected in warmer conditions.

RC2: L306-310 – It would be useful to have information on the material properties at the field sites to back up these statements.

AC: We totally agree that it would be useful, but unfortunately the information on the material properties are scattered or rather general/descriptive from the validation sites. Hence, we can draw only general conclusions in this respect. If we wanted to have detailed information on the material properties, the number of validation sites would have to be much smaller, which is, however, undesirable in terms of robustness of the validations.

RC2: L315-330 – Although these other approaches make assumptions regarding thermal properties etc. based on general site characteristics, information on ground temperature is not required and the models determine the ground temperatures. This makes them useful for determining current and future conditions. This might make them more broadly applicable.

AC: Unfortunately, we do not understand this comment clearly. Anyway, it is important to note that all other models for permafrost table temperature and active-layer thickness require information on ground (surface or near-surface) temperature, which is used as their upper boundary condition.

RC2: L327-330 – If temperature below the permafrost table was available would it be used if there were only one sensor at a shallower depth? You state that inputs can be any depth combination within the active layer based on temperature data availability and site characteristics. What are the site characteristics being referred to?

AC: Unfortunately, temperatures below the permafrost table cannot be used because thawing indices must have non-zero (=positive) values; otherwise the outputs would be erroneous. We will explicitly state this in the revised manuscript.
By the site characteristics we meant that specific depth combinations may work better under specific site characteristics. However, we acknowledge that this is unclear and rather misleading, and therefore we will remove it from the revised manuscript.

RC2: L331-334 – Aren't these products based on modelling with various assumptions made regarding ground properties etc.

AC: Yes, but these assumptions and/or ground properties are largely unknown for these products, which considerably impedes model applications. Consequently, for instance, the active-layer thickness estimates are limited by the deepest ground temperature level (node) available in these products, which is frequently shallow and situated within the active layer. However, our models can deal with such situations. We will emphasize this a bit further in the revised manuscript.

RC2: L338-340 – This is likely one of the primary sources of error especially with respect to moisture/ice contents and latent heat effects as discussed in Riseborough (2003).

AC: Yes, it certainly is, as in any analytical model, and we think it is only fair to admit it.

RC2: L340-348 – Riseborough (2008) is probably relevant here especially with respect to spacing of temperature measurements etc. in determining thaw depth.

AC: We think this is much more relevant, for instance, to interpolating the active-layer thickness or calculating the permafrost table temperature from measured ground temperatures. In terms of this paper, this is therefore particularly relevant to the validation data used to evaluate the models. However, the models themselves are in principle independent of the spacing of temperature measurements. More important is the sensor position with respect to the active-layer stratigraphy.

RC2: References

Riseborough, D.W. 2008. Estimating active layer and talik thickness from temperature data: implications from modeling results. In Ninth International Conference on Permafrost. Edited by D.L. Kane and K.M. Hinkel. Fairbanks, Alaska. Institute of Northern Engineering, University of Alaska Fairbanks, Vol.2, pp. 1487-1492.

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