Author response to editorial comments

Line numbers refer to the marked-up manuscript at the end of this document.

Thank you for your revised manuscript. There are many improvements, but there is still room for improvement.

My major concern is that after reading the abstract, many will wonder what the new insights are. This echoes comments from Reviewers 1 and 2. You must highlight these insights in the abstract. In the manuscript you suggest that magnitude, direction and response shapes provide important insights, but little of this jumps out in the abstract. I fear that many readers will not read beyond this point in the paper. If the title is new insights, then you must deliver the goods.

The second concern, raised by Reviewer 2, is that some of your results are at odds with findings from much of the literature. This is not necessarily a bad thing, but you will strengthen your manuscript if you can elaborate on why you find these differences. If is is a matter of scale, then say so more explicitly. For example, if vegetation and soil conditions are not that important, is this simply because the integration of the analysis is at a global scale and vegetation and soil condition are more important at regional scales? Are there specific regions that strengthen or weaken the overall relations?

These concerns must be addressed before the manuscript can be considered for publication. I have suggested major revisions to give you time to address the comments.

R: We thank the Editor for the overall positive views and for pointing out places where we can improve our manuscript. We agree that the abstract should highlight the new findings better and recognized the need to comprehensively revise the abstract and the conclusion of this study. Moreover, we agree that contradictions with previous study results could be considered more clearly.

Detailed responses concerning discrepancies with previous studies, scale-related issues, and the regional aspects addressed by the Editor are provided below. In addition, we have carefully checked the manuscript for typos as well as made some updates to the references (added/removed a few references and included DOIs wherever applicable) and modified caption in Tables 1 and 2 as requested.

We hope that we have succeeded in addressing all the concerns and refining the manuscript to fully describe the performed study and explicitly discuss the relevant findings and associated caveats.

Line 2: This title is misleading given the number of sites well outside of polar regions. Do you really mean northern hemisphere?

R: We agree that using the Northern Hemisphere is more unambiguous. Revised accordingly: *"New insights into the environmental factors controlling the ground thermal regime <u>in the Northern Hemisphere</u>"*

Abstract: What are the new insights? The findings presented here largely confirm what is already known and will not surprise the reader, especially Lines16-19. Perhaps the conclusions here are too general? Provide some detail. E.g., what are the important non-linear influences from soil properties? Are there regional influences that contribute to the break down of relations that many would have expected to be stronger?

R: We agree that our conclusions may be cautious and thus too general. In the revised abstract, we emphasized findings that our novel (statistical techniques/high resolution data combined with hemispheric extent) approach yielded. In particular, we stressed the magnitudes (effect size in °C) and importance of key predictors for MAGT and ALT. In addition, shapes of responses are briefly summarized by addressing the non-linearity found in responses between $MAGT_{\leq 0\ °C}$ /ALT and environmental factors. Moreover, we included discussion on the influence of scale raised by the Editor and reviewer 2 as well as addressed the uncertainties associated with the used soil data. We feel that disclosing this already in the abstract is important when relating our study to the lineage of cryospheric science. Revised parts (lines 17–25):

"Freezing (FDD) and thawing (TDD) degree-days were key factors for MAGT inside and outside the permafrost domain with average effect sizes of 6.7 °C and 13.6 °C, respectively. Soil properties had marginal effect on MAGT (effect size = 0.4–0.7 °C). For ALT rainfall (effect size = 181 cm) and solar radiation (161 cm) were most influential. Variable importance analysis further underlined the dominance of climate for MAGT and highlighted the role of solar radiation for ALT. Most response shapes for $MAGT_{\leq 0}$ *°C and ALT were non-linear indicating thresholds for the covariation. It is suggested that the factors with large global variation (i.e. climate) suppressed the effect of local-scale factors (i.e. soil properties and vegetation) owing to the extensive study area and limited representation of soil organic matter. Our approach facilitates hemispheric-scale cryospheric studies by offering new insights into the factors affecting the ground thermal regime at a 1-km scale."*

Given that the modelling of the circumpolar ground thermal regime uses very high resolution climatic and local environmental factors, what can you now say about spatial variation of the relative importance of these factors? At a global scale we expect the findings presented here, but are there regions where SOC or vegetation are very important, and other regions where they are not at all important to cryospheric conditions? The approach taken glosses over regional differences that are important and might provide deeper insights than achieved (will likely also address many of the comments from Reviewer 2), and not discussing the spatial component of your data is a missed opportunity.

R: The Editor presents a very interesting idea for future studies. We assume that spatial variation in the relative contributions could exist. It is not straightforward to point out any specific regions, yet in the discussion we address the complexities in vegetation effects (different effects of trees and shrubs that cannot be explicitly separated with the used vegetation index) that may average out some relations (lines 286–291).

We are in a view that regional comparisons would require a new study with additional regional partitions as well as abandoning our present idea of "permafrost vs. non-permafrost" examination. The current study setting provided a great deal of results (e.g. we used four statistical techniques to determine the effect sizes and variable importance for nine environmental factors). A division of the study area to several sub-regions could provide deeper insights but would substantially complicate the presentation of the results and main message of the study. Consequently, we decided not to extend our study by introducing new sub-region based results.

Lines 44–45: Here you describe the surface offset. Pleas add in a sentence about the thermal offet.

R: A sentence was added in lines 44–45: *Soils have different heat conductivities between frozen or thawed states, which can result in notable temperature differences between ground surface and top of permafrost, i.e. thermal offset (e.g. Smith and Riseborough, 1996)."* We also elaborated that the other described offset is specifically surface offset (line 49).

Smith, M. W. and Riseborough, D. W.: Permafrost monitoring and detection of climate change, Permafrost and Periglac., 7, 301–309, 1996.

Line 49: Please just use rainfall or snowfall in the text, tables and figures.

R: Done.

Line 51: Where are there temperate soils in the circumpolar regions?

R: We notice the contradiction here and replaced *circumpolar* with *hemispheric*. Also elsewhere in the text, terminology was updated in this regard.

Affects what more directly?

R: Revised (line 53): *"…climate signal affects* *the ground thermal regime* *more directly…"*

Lines 69–75: Where do you find observations of ALT in non-permafrost conditions? Reviewer 2 had a related question (R2C5). Revise this statement and make it reflect your response to R2C5 so that it is more clear to the reader what you are trying to examine. Perhaps you should include an investigation of seasonal frost depth, or simplify things and keep within

R: The sentence here was undoubtedly a little ambiguous. Naturally, ALT observations were confined to permafrost regions. The part was revised to reflect that only MAGT observations were compiled outside permafrost regions. Simultaneously, we aimed at better addressing the issues raised by reviewer 2 by emphasizing a central aspect to our study: to examine how the factor contributions for MAGT differ between the two thermal regimes.

"More specifically, we aim to (1) calibrate realistic models of the ground thermal conditions utilizing field observations of MAGT and ALT (the response variables) and geospatial data on climatic and local conditions (the predictors) across the Northern Hemisphere land areas, and (2) examine the relative importance, magnitude of effect, and response shapes of environmental factors at 1-km resolution. The focus of this study is on MAGT and ALT in permafrost regions but the analyses are also performed for sites with MAGT above 0 °C to compare factor importances, effect sizes and response shapes between the thermal regimes.

The proposed investigation of seasonal frost depth is another interesting idea. However, we have not compiled data on freezing depth and are not aware of any suitable datasets at this extent. Regional studies exist; e.g., Zhang et al. (2003) and Frauenfeld et al. (2004, 2011) studied freeze depth with data from Russian meteorological stations, and Wang & Zhang (2014) and Peng et al. (2016) in NW China. Moreover, Oelke et al. (2003) performed a coarse-resolution simulation the depth of seasonally frozen ground over the entire Arctic drainage basin using reanalysis data.

Zhang, Y., Chen, W., and Cihlar, J.: A process-based model for quantifying the impact of climate change on permafrost thermal regimes, J. Geophys. Res., 108, D22, 4695, doi:10.1029/2002JD003354, 2003.

Frauenfeld, O. W., Zhang, T., and Barry, R. G.: Interdecadal changes in seasonal freeze and thaw depths in Russia, J. Geophys. Res., VOL. 109, D05101, doi:10.1029/2003JD004245, 2004.

Frauenfeld, O. W. and Zhang, T.: An observational 71-year history of seasonally frozen ground changes in the Eurasian high latitudes. Environ. Res. Lett., 6, 044024, 2011.

Wang Q.F. and Zhang T.: Spatiotemporal variations of maximum seasonal freeze depth in 1950s–2007 over the Heihe River Basin, Northwest China, Sciences in Cold and Arid Regions, 6, 0209–0218, 2014.

Peng, X., Zhang, T., Cao, B., Wang, Q., Wang, K., Shao, W., and Guo, H.: Changes in freezing-thawing index and soil freeze depth over the Heihe River Basin, Western China, Arctic, Antarctic, and Alpine Research, 48:1, 161–176, 2016.

Oelke, C., Zhang, T., Serreze, M. C., and Armstrong, R. L.: Regional-scale modeling of soil freeze/thaw over the Arctic drainage basin, J. Geophys. Res., 108, D10, 4314, doi:10.1029/2002JD002722, 2003.

Line 92: corrected: meters → metres

Lines 129–130: The SoilGrids database reports soil organic carbon (fine earth fraction). What about soils with organics that have not substantially degraded (common inpermafrost peatlands)? Arguably, soils with the same SOC can have very different bulk densities/organic matter contents related to various stages of decomposition. Does SOC directly relate to Organic Matter Content? The two are not interchangeable. When we speak of the thermal offset and the role of the surface organic layer, we mean organic soil with a low bulk density, which is not the same as an organic rich soil with a high SOC. Is this adequately accounted for in your parameterization?

R: This is an important note, and we recognized the need to address the limitations of the SoilGrids SOC in the manuscript in a few places as described below.

We acknowledge that soil organic carbon content (SOC) does not equal soil organic matter content (SOM), and that thus SOC does not directly depict the amount of all organic material to which thermal offset is attributed. Moreover, we acknowledge that SOC and SOM are not interchangeable owing to properties of different soils although constant conversion factors between the two have been used (e.g. Nelson & Sommers 1996). However, suitable SOM data are not available, and physical fractionation of SOC is commonly used as a proxy owing to more straightforward measurement procedures (Bailey et al., 2017). In the development of SoilGrids data, SOM data (as well as total carbon observations) have been used to derive SOC using a conversion factor (Hengl et al. 2017).

Also included in the SoilGrids are SOC stock in tons per ha grids, which (in addition to SOC) employ bulk density and coarse fragments in their computation. Based on 10,000 randomly distributed sampling points over the study area (north of 30°N) the Spearman rank-order correlation (0.91, $p<0.001$) between SoilGrids SOC (g kg^{-1}) and SOC stock (t ha^{-1}) indicated that the used variable well depicts the spatial variability in density-considered SOC.

To address these issues we added a sentence in lines 281–285: *"It should be noted that the used variable depicts SOC in fine earth fraction and does not explicitly address incompletely decomposed or fresh organic matter, which are one of the central components of the thermal offset. However, suitable gridded data on soil organic matter content are not available, and physical fractionation of SOC has been commonly used as its correlative proxy owing to more straightforward measurement procedures (Bailey et al., 2017).*

Nelson, D. W. and Sommers, L. E.: Total Carbon, Organic Carbon, and Organic Matter, in: Methods of Soil Analysis. Part 3, Sparks, D. L., et al. (Eds.) Chemical Methods, SSSA Book Series No. 5, SSSA and ASA, Madison, WI, 961-1010, 1996.

Bailey, V. L., Bond-Lamberty, B., DeAngelis, K., Grandy, A. S., Hawkes, C. V., Heckman, K., Lajtha, K., Phillips, R. P., Sulman, B. N., Todd-Brown, K. E. O., and Wallenstein, M. D.: Soil carbon cycling proxies: understanding their critical role in predicting climate change feedbacks. Glob. Change Biol. 24, 895–905, 2017.

Hengl, T., Mendes de Jesus, J., Heuvelink, G.B.M., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M. N., Geng, X., Bauer-Marschallinger, B., Antonio Guevara, M., Vargas, R., MacMillan, R. A., Batjes, N. H., Leenaars, J. G. B., Ribeiro, E., Wheeler, I., Mantel, S., and Kempen, B.: SoilGrids250m – Global gridded soil information based on machine learning, PLoS ONE 12, e0169748, doi.org/10.1371/journal.pone.0169748, 2017.

If not, is this a potential reason why your results place minimal importance on soil conditions despite the findings of so many others?

R: Data on organic layer thicknesses/organic matter content inarguably would have been important for the study. It is also possible that SoilGrids SOC stock variable could have addressed thermal offset better than the used SOC variable but given the high correlation between the two datasets(0.91, $p<0.001$) the use of

SOC stock variable would have probably not affected the main outcome of our study. We added a sentence in the Uncertainties section (lines 310–311): *"It is also possible, that the used SOC data could not fully address the thermal offset albeit ALT modelling showed realistic and moderately strong effects."*

At this extent and resolution the used predictor is to our opinion a suitable estimate of amount of organic material and occurrence of peatlands with high SOC/SOM. Moreover, derivation of SOC stock from modelled SOC, bulk density and coarse fragments incorporates uncertainties in each of its component (Tifafi et al., 2018). We separately took into account coarse fragments (indicative of low organic content when abundant).

Tifafi, M., Guenet, B., and Hatté, C.:Large differences in global and regional total soil carbon stock estimates based on SoilGrids, HWSD, and NCSCD: Intercomparison and evaluation based on field data from USA, England, Wales, and France. Glob. Biogeochem. Cycles, 32, 42–56, 2018.

Lines 179–181: Refer to others with similar results.

R: References added: *"Pairwise correlations and the scatter plots revealed a strong association between MAGT and air temperature (see Smith and Burgess, 2000; Smith and Riseborough, 2002; Throop et al., 2012), especially in MAGT>0 °C (Fig. 2a–b, d)."*

Smith, S. and Burgess, M.: Ground temperature database for Northern Canada, Geological Survey of Canada, Open File Report 3954, 2000.

Smith, M. W. and Riseborough, D. W.: Climate and the limits of permafrost: a zonal analysis, Permafrost and Periglac., 13, 1–15, 2002.

Throop, J., Lewkowicz, A. G., and Smith, S. L.: Climate and ground temperature relations at sites across the continuous and discontinuous permafrost zones, northern Canada, Can. J. Earth Sci., 49, 865–876, 2012.

Line 219: Amended as suggested: *current permafrost occurrence → permafrost presence or absence*

Line 220: Amended as suggested: *is a prerequisite for the occurrence of permafrost → occurs*

Line 221: Amended as suggested: *the dominant nearly linear → a nearly linear dominant*

Line 230–232: Amended as suggested: *"mid-latitude sites predominantly locate in mountains (the Alps, central Asian mountain ranges) with thin soils…"*

Lines 243,244 and 254: *water precipitation → rainfall.* Also elsewhere in suitable places.

Lines 278–281: This is where I wonder if SOC should not be equated to soil organic matter content or surface organic layer thickness. Please look carefully at how SOC is defined in the SoilGrids database, and how that relates to the thermal properties of the soil. How do you related g/kg to density? Organic soils with the most seasonal differences in thermal properties are those that are pure peat, 1000 g/kg.

R: In SoilGrids SOC data, the highest values ~600 g/kg are located in the extensive wetlands of W Siberian Lowlands indicating large amounts of organic material. That being said, we acknowledge that SOC density is higher in organic horizons than in mineral soil horizons of permafrost-affected soils. We cannot explicitly relate SOC values to density, and their use is thus an indirect estimate of thermal effect of organic soils, which we consider to be adequate.

To avoid equating SOC and SOM, we replaced *organic material* with *organic carbon* (line 280) and made an addition in lines (279–285): *"It should be noted that the used variable depicts SOC in fine earth fraction and does not explicitly address incompletely decomposed or fresh organic matter, which are one of the central components of the thermal offset. However, suitable gridded data on soil organic matter content are* *not available, and physical fractionation of SOC has been commonly used as its correlative proxy owing to more straightforward measurement procedures (Bailey et al., 2017).*

Line 288: Amended as suggested: *vegetation → different vegetation canopy configurations.*

Lines 288–289: Reference added. Also, low vegetation was a little ambiguous, we now used tall shrubs *"In wintertime, ~~low~~ vegetation (e.g. tall shrubs) traps snow and thereby enhances insulation of the ground (Morse et al., 2012)"*

Morse, P. D., Burn, C. R., and Kokelj, S. V.: Influence of snow on near-surface ground temperatures in upland and alluvial environments of the outer Mackenzie Delta, Northwest Territories, Can. J. Earth Sci., 49, 895–913, 2012.

Line 305: Do you mean applicable or "appropriate".
"more applicable/appropriate than those of ALT" for what, or to what?

R: The text was revised (line 305): *"...suggests that ~~circumpolar~~ future ~~predictions~~ ~~of~~ MAGT ~~are~~ is more ~~applicable~~ feasible to predict than ~~those of~~ ALT, ..."*

Lines 311–315: As R2 suggests several times, many others have demonstrated the importance of soil soil and vegetation conditions. This paper contradicts those findings. Tell the reader what the new insight is, why soil and vegetation have minimal roles. What can you now tell us about the cryosphere that we didn't already know.

R: We added discussion about minimal contributions of soil properties and vegetation on MAGT (lines 306–311):*"This is incongruent with previous studies showing the high importance of soil properties for MAGT (e.g. Zhang et al., 2003; Throop et al., 2012). The discrepancies are argued to be partly attributed to the hemispheric study extent; large spatial variation in climatic parameters is suggested to have suppressed the effect of soil and vegetation properties locally. It is also possible that the used SOC data could not fully address the thermal offset albeit ALT modelling showed realistic and moderately strong effects."*

The low contribution of vegetation (NDVI) may stem from the reasons discussed in lines 286–291. The index is used to examine the amount of photosynthetic vegetation but it is unable to distinguish vegetation height, which generally defines whether vegetation traps snow (warming effect) or intercepts snow and shades the ground (tall canopies, cooling effect). However, MODIS NDVI has been shown to be closely related to fractional vegetation cover and has been used to obtain quantitative estimates of rainfall interception Galdos et al. (2012), and is thus suitable in estimating interception.

Please see the revised abstract and conclusions where we summarized the new insights more clearly than before.

Galdos, F. V., Álvarez, C., García, A., and Revilla, J. A.: Estimated distributed rainfall interception using a simple conceptual model and Model Resolution Imaging Spectroradiometer (MODIS), J Hydrol., 468–469, 213–228.

You need to explicitly discuss the thermal offset and how your approach treats it. the thermal offset is critical to MAGTs in discontinuous permafrost.

R: We agree that discussing offsets will position our work better in line with previous research. We introduced thermal offset in lines 44–45: *"Soils have different heat conductivities between frozen or thawed* *states, which can result in notable temperature differences between ground surface and top of permafrost, i.e. thermal offset (e.g. Smith and Riseborough, 1996).”* In lines 128–131, we clarify the inclusion of soil properties: *“To account for the thermal offset dictated by soil properties (e.g., Smith and Riseborough, 1996, 2002; Kuryluk et al., 2014) we extracted soil organic carbon content … from SoilGrids database (Hengl et al., 2017).”*

In the discussion, we further described how the used soil properties were attributed to the thermal offset (lines 281–283): *“It should be noted that the used variable depicts SOC in fine earth fraction and does not explicitly address incompletely decomposed or fresh organic matter, which are one of the central components of the thermal offset.*”

Kurylyk, B. L., MacQuarrie, K. T. B., and McKenzie, J. M.: Climate change impacts on groundwater and soil temperatures in cold and temperature regions: Implications, mathematical theory, and emerging simulation tools, Earth-Sci. Rev., 138, 313–334, 2014.

What about soil thickness? in SoilGrids, one property that is probably important is depth to bedrock. MAGT in bedrock with thin overburden will likely be very sensitive to climatic parameters. Much of the Canadian shield will be thus affected.

R: As discussed in lines 230–234, depth to bedrock is suggested to affect ALT through different thermal diffusivities of soils and bedrock. As the Editor points out, it also affects MAGT, and we briefly addressed this in lines 89–90 in the original manuscript.

However, we are not convinced about the suitability of SoilGrids depth-to-bedrock (DBT) variables in the present context. First, the censored DBT grids only consider bedrock surface (R horizon) found within 0-200 cm from surface, which is why values are heavily skewed with >90% of them being >200 cm (476 of 784 from all MAGT observations). Moreover, all the >200 cm values have been assigned a value of 200 making the variable problematic for examining statistical relationships. The absolute DBT variable, in turn, has an RMSE of > 8 metres, which to our opinion hinders the recognition of highly conductive consolidated materials in the critical first few metres from the surface.

In the early phases of the study, we tested a data on soil and sedimentary deposits thickness (Pelletier et al., 2016). This data shows DBT down to 50 m subsurface (hence encompassing all the used MAGT measurements). Owing to minimal variable importance and a flat response curve, we excluded it from further analyses. However, highly conductive soils were considered with the inclusion of the coarse sediments variable.

Pelletier, J. D., Broxton, P. D., Hazenberg, P., Zeng X., Troch, P. A., Niu, G.-Y., Williams, Z., Brunke, M. A., and Gochis, D.: A gridded global data set of soil, immobile regolith, and sedimentary deposit thicknesses for regional and global land surface modeling, J. Adv. Model. Earth Syst., 8, 41–65, 2016.

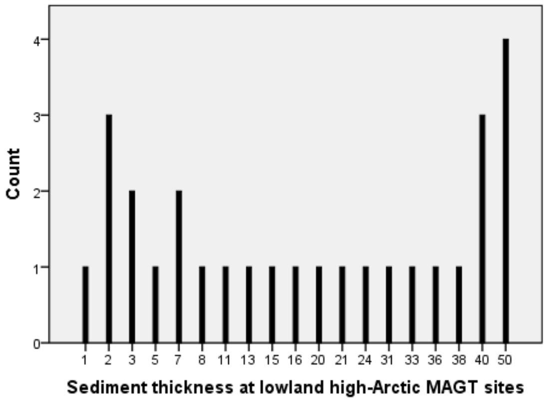
Is there a bias in your high-arctic/Lowland sites towards unconsolidated materials that should be noted?

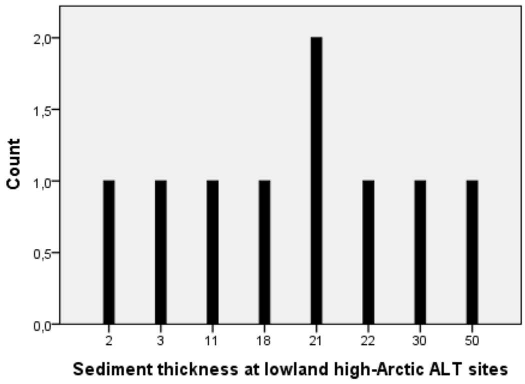
R: Pelletier et al. (2016) also distinguished uplands and lowlands at 30 arc-sec resolution. We used these data layers to define lowland sites in the high-Arctic (Canadian Archipelago, Northern Greenland, Svalbard, Arctic Russian islands; as defined in AMAP 2011) and then calculated average sediment (unconsolidated material) thickness, also Pelletier et al. (2016).

- Out of 52 high-Arctic boreholes, 22 located in lowlands with an average sediment thickness of 22.1 m, 30 on uplands (0.5 m).
- For ALT, out of 13 high-Arctic sites 10 were in lowlands (19.8 m), 3 on uplands (0 m).

Lowland sites, (also by definition: “In lowlands, we refer to all unconsolidated material above bedrock as sedimentary deposits” (Pelletier et al., 2016)), have thicker layers of unconsolidated sediments than uplands. Considering the entire high-Arctic, MAGT sites seem not to be biased toward unconsolidated materials, ALT sites possibly, but sample is very small and data uncertainties may affect.

Chart below shows that 6 out of 22 high-Arctic lowland MAGT sites have <= 3 m sediment cover indicating that relatively thin covers are usual also in lowland sites. Whatsoever, these data cannot be used to determine whether there is bias toward unconsolidated sediments in favor of bedrock outcrops or peatlands, for example. We consider it very difficult to give an explicit answer to the Editor’s comment, but consider it unlikely that the results are biased owing to the issue. Thus, we consider no need to mention this in the text.





AMAP, Arctic Climate Issues 2011: Changes in Arctic Snow, Water, Ice and Permafrost. SWIPA 2011 Overview Report, 2012.

Lines 329–330: You really did the opposite of this. You didn't use the field data to tune up a 1-km spatial resolution model of the circumpolar ground thermal regime, instead you figured out the relative importance climate and environmental factors at the nearly 800 field sites using the 1-km spatially averaged data.

R: The revised sentence puts focus on the used methodology (lines 329–330): “*We statistically related observations of MAGT and ALT to high-resolution (~1 km2) geospatial data of climatic and local environmental conditions to explore the factors affecting the ground thermal regime across the Northern Hemisphere.*

Line 334: Not really circumpolar. More like northern hemisphere.

R: Amended accordingly here and elsewhere including the abstract.

Line 340–344: These are not strong new insights. These are well known and should not constitute a key element of your core conclusions. Please highlight the new insights that you have developed herein.

R: We agree on this and revised this part of the conclusions to emphasize the new findings of our study (lines 334–347): *“In permafrost conditions, different key factors accounted for variation in MAGT and ALT; climate was paramount and soil properties showed marginal role for MAGT, while local environmental conditions precipitation factors and topography-controlled solar radiation were emphasized in case offor ALT. Where permafrost was not present, precipitation was less influential and MAGT was predominantly controlled by air temperatures above 0 °C.*

The relatively minor role of soil properties (especially organic carbon content) on MAGT and ALT may stem from the lack of global data with high local accuracy. The results also revealed distinct non-linear *relationships and thresholds between the ground thermal regime and environmental factors, especially in permafrost-affected regions. At sites without permafrost, responses were more often linear. In addition to providing these insights about effective magnitudes and response shapes of the key contributing factors at hemispheric scale, it is concluded that multi-variate modelling frameworks capable of employing high-resolution geospatial data will be valuable for the spatio-temporal prediction of ground thermal regimes from local to global scale."*

New insights into the environmental factors controlling the ~~circumpolar~~ ground thermal regime across the Northern Hemisphere

Olli Karjalainen[1], Miska Luoto[2], Juha Aalto[2,3], and Jan Hjort[1]

[1]Geography Research Unit, University of Oulu, FI-90014, Oulu, Finland
[2]Department of Geosciences and Geography, University of Helsinki, FI-00014, Helsinki, Finland
[3]Finnish Meteorological Institute, FI-00101, Helsinki, Finland

Correspondence to: Olli Karjalainen (olli.karjalainen@oulu.fi)

Abstract. The thermal state of permafrost affects Earth surface systems and human activity in the Arctic and has implications to global climate. Improved understanding of the local-scale variability in the ~~circumpolar~~ global ground thermal regime is required to account for its sensitivity to changing climatic and geoecological conditions. Here, we statistically related ~~circumpolar~~ observations of mean annual ground temperature (MAGT) and active-layer thickness (ALT) to high-resolution (~1 km^2) geospatial data of climatic and local environmental conditions across the Northern Hemisphere. The aim was to characterize the relative importance of key environmental factors and the magnitude and ~~direction~~ shape of their effects. ~~in predicting the circumpolar ground thermal regime at 1-km scale.~~ The multivariate models fitted well to MAGT and ALT observations with average R^2 values being ~0.94 and 0.78, respectively. Corresponding predictive performances in terms of root mean square error were ~1.31 °C and 87 cm. Freezing (FDD) and thawing (TDD) degree-days were key factors for MAGT inside and outside the permafrost domain with average effect sizes of 6.7 °C and 13.6 °C, respectively. Soil properties had marginal effect on MAGT (effect size = 0.4–0.7 °C). For ALT rainfall (effect size = 181 cm) and solar radiation (161 cm) were most influential. Variable importance analysis further underlined the dominance of climate for MAGT and highlighted the role of solar radiation for ALT. Most response shapes for $\text{MAGT}_{<0\ °C}$ and ALT were non-linear indicating thresholds for the covariation. It is suggested that the factors with large global variation (i.e. climate) suppressed the effect of local-scale factors (i.e. soil properties and vegetation) owing to the extensive study area and limited representation of soil organic matter. Our approach facilitates hemispheric-scale cryospheric studies by offering new insights into the factors affecting the ground thermal regime at a 1-km scale. ~~Freezing air temperatures was the main factor controlling MAGT in permafrost conditions while thawing temperatures dominated when permafrost was not present. ALT was most strongly related to solar radiation and precipitation with important non-linear influences from soil properties. Our findings suggest that in addition to climatic factors, local-scale variability in soil and topography need to be considered in order to realistically assess the current and future ground thermal regimes across the circumpolar region.~~

1 Introduction

In the face of changing Arctic, it is crucial to understand the mechanisms that drive the current geocryological dynamics of the region. Thaw of permafrost is expected to significantly attribute to hydrological and geoecological alterations in landscapes (Jorgenson et al., 2013; Liljedahl et al., 2016). In addition, greenhouse gas emissions from thawing permafrost soils have a potential to affect the global climate system (e.g. Grosse et al., 2016). Permafrost temperature and the depth of the overlying seasonally thawed layer, i.e. active layer, are key components of the ground thermal regime that govern various geomorphological and ecological processes (Frauenfeld et al., 2007; Aalto et al., 2017), as well as human activity in permafrost regions (Callaghan et al., 2011; Vincent et al., 2017; Hjort et al., 2018). Outside the permafrost domain, extensive regions undergo seasonal freezing, which in itself affects many aspects of natural and human activities (e.g. Shiklomanov, 2012; Westermann et al., 2015).

Climatic conditions account for large-scale spatial variation in mean annual ground temperature (MAGT) and active-layer thickness (ALT) (Bonnaventure and Lamoureux, 2013; Streletskiy et al., 2015; Westermann et al., 2015). From regional to local scales, topography-induced solar radiation input (Etzelmüller, 2013) and intercepting layers of snow, soil and vegetation mediate their effect (e.g. Osterkamp, 2007; Fisher et al., 2016; Gruber et al., 2017; Aalto et al., 2018a; Zhang et al., 2018). Soils have different heat conductivities between frozen or thawed states, which can result in notable temperature differences between ground surface and top of permafrost, i.e. thermal offset (e.g. Smith and Riseborough, 1996). Winter temperatures have been suggested to be most important for permafrost temperature (Smith and Riseborough, 1996; Etzelmüller et al., 2011), while ALT is essentially dependent on summer temperatures (Oelke et al., 2003; Melnikov et al., 2004; Luo et al., 2016). In wintertime, snow layer insulates the ground from cold air causing ~~an~~ surface offset, i.e. ground is warmer than air (e.g. Aalto et al., 2018b; Zhang et al., 2018). ~~Water precipitation~~Rainfall alters the thermal conductivity of near-surface layers through its control on, e.g., soil water balance (Smith and Riseborough, 1996; Callaghan et al., 2011; Marmy et al., 2013). Arguably, the responsiveness of the ~~circumpolar~~ hemispheric ground thermal regime to atmospheric forcing also depends on its initial thermal state. In permafrost conditions, temperature changes are lagged by the higher demand of energy for phase changes of water in the active layer (i.e. latent-heat exchange), whereas in temperate soils climate signal affects the ground thermal regime more directly (Romanovsky et al., 2010; Kurylyk et al., 2014). In addition to the effect of ground ice content on heat transfer, its development is an important geomorphic factor (e.g. Liljedahl et al., 2016).

Improved knowledge on hemispheric-scale ~~circumpolar~~ permafrost dynamics is required to understand various geoecological interactions and feedbacks associated with warming Arctic (e.g. Wu et al., 2012; Grosse et al., 2016; Yi et al., 2018). Such information is useful for climate change assessments (Zhang et al., 2005, Smith et al., 2009), infrastructure design and maintenance, as well as for adaptation to changing conditions (Romanovsky et al., 2010, Streletskiy et al., 2015; Hjort et al., 2018). Physically based ground thermal models can account for various biogeophysical processes acting in vegetation, snow and soil layers (e.g. Lawrence and Swenson, 2011) but are not applicable at high spatial resolutions over large areas owing to their tedious model parameterizations (Chadburn et al., 2017). For example, commonly used circumpolar 0.5° latitude/longitude resolution has been considered insufficient in characterizing spatial variation in soil properties and vegetation, thus leading to large mismatch between the simulations and observations (Park et al., 2013). Recently, Peng et al. (2018) assessed spatio-temporal long-term trends in circumpolar ALT with a large observational dataset stressing that ALT strongly depends on local topo-edaphic factors (e.g. Harlan and Nixon, 1978) and that thorough analyses of environmental factors controlling ALT at varying scales are urgently required.

Here, we use a statistical modelling framework employing multiple algorithms from regression to machine learning to examine the factors contributing to the spatial variation in the ~~circumpolar~~ hemispheric ground thermal regime. More specifically, we aim to (1) calibrate realistic models of the ground thermal conditions ~~MAGT and ALT (the responses)~~ utilizing field observations of MAGT and ALT (the response variables) and geospatial data on climatic and local conditions (the predictors) across the Northern Hemisphere land areas, and (2) examine ~~the nature of the contributing factors in~~ the relative importance, magnitude of effect, and response shapes of environmental factors at 1-km resolution. The focus of this study is on MAGT and ALT in permafrost regions but the analyses are also performed for sites with MAGT above 0 °C to compare factor importances, effect sizes and response shapes between the thermal regimes. ~~both permafrost and non-permafrost conditions using circumpolar field observations of MAGT and ALT.~~ ~~The analyses provide detailed insights into the importance of key environmental factors and the magnitudes and direction of their effect at 1-km resolution.~~

2 Methods

2.1 Study area and observational data

We compiled MAGT and ALT observations from the period 2000–2014 over the Northern Hemisphere land areas north of the 30^{th} parallel (Fig.1). To examine possible differences in the contribution of environmental factors between permafrost and non-permafrost conditions we used two separate MAGT datasets; observed MAGT at or below 0 °C, i.e. permafrost, ($\mathrm{MAGT}_{\leq 0\,°C}$, n = 469) and above 0 °C ($\mathrm{MAGT}_{>0\,°C}$, n = 315). For each MAGT and ALT site, averages over the study period were then calculated from available annual averages or suitable single measurements. The observations were standardized by requiring that MAGT was recorded at or near the depth of zero annual amplitude (ZAA) where annual temperature variation was less than 0.1 °C, and that ALT (n = 298) values represented the maximum thaw depth of a given year based on mechanical probing or derived from ground temperature measurements or thaw tubes (Brown et al., 2000; Aalto et al., 2018a). When ZAA depth was not reported or not retrievable from numeric data, we used the value at the depth of 15 m, where annual temperature fluctuation in most conditions is negligible (see French, 2007), although in thermally highly diffusive subsurface materials, such as bedrock, the depth can be greater (e.g. Throop et al. 2012). With some MAGT observations, ZAA depth was reportedly not reached but we chose to include these cases assuming that annual means calculated from year-round records from one or multiple years were representative of long-term thermal state. MAGT measured at less than two ~~meters~~ metres below the surface were excluded unless reported to be at the depth of ZAA.

The Global Terrestrial Network for Permafrost database (GTN-P, Biskaborn et al., 2015) was the principal constituent of our datasets (~60 % of MAGT and ~67 % of ALT observations). Additionally, data were gathered from open Internet databases (e.g. Roshydromet, meteo.ru; Natural Resources Canada, GEOSCAN database; National Geothermal Data System) and previous studies to cover a maximal range of climatological and environmental conditions (see Table S1 and S2 for sources)

A minimum geopositional location precisions of two decimal degrees (~1,110 m at the Equator) for MAGT and a commonly used arc minute (~1,800 m) for often less accurately geopositioned ALT sites were adopted both to ascertain adequate spatial match with geospatial data layers and to moderate the need to exclude lower precision observations. Nonetheless, almost 90 % of MAGT and more than two-thirds of ALT observations had a precision of at least three decimal degrees (~110 m at the Equator). Further exclusions were made when the ground thermal regime was evidently disturbed by recent forest fire, anthropogenic heat source, large water bodies or the effect of geothermal heat in temperature-depth curve (Jorgenson et al., 2010; Woo, 2012) as revealed by source data or cartographical examination of the site.

2.2 Predictor variables

Nine geospatial predictors representing climatic (air temperature and precipitation) and local (potential incident solar radiation, vegetation and soil properties) conditions at 30 arc-second spatial resolution were selected to examine their potential effects on MAGT and ALT at the ~~circumpolar~~ hemispheric scale (e.g. Brown et al., 2000; French, 2007; Jorgenson et al., 2010; Bonnaventure & Lamoureux, 2013; Streletskiy et al., 2015). Climatic parameters were derived from the WorldClim dataset (Hijmans et al., 2005). The temporal coverage of WorldClim is 1950–2000, so we adjusted the data to match our study period of 2000–2014 using the Global Meteorological Forcing Dataset for land surface modelling (GMFD, Version 2, Sheffield et al., 2006) at a 0.5-degree resolution (see Aalto et al., 2018a). Monthly averages over this 15-year period were then used to derive the following climate parameters.

Previous studies have suggested that using indices representing the length or magnitude of thawing and freezing season could be more suitable than annual mean of air temperature (e.g. Zhang et al., 1997; Smith et al., 2009). Thus, thawing (TDD) and freezing (FDD) degree-days were determined as cumulative sums of mean monthly air temperatures above and below 0 °C, respectively. Frauenfeld et al. (2007) showed that their use instead of daily temperatures ~~accounts~~ accounted for less than 5 % error for most high-latitude land areas. Since available global data on snow thickness or snow-water equivalency have relatively coarse spatial resolutions (Bokhorst et al., 2016), we examined the snow cover's contribution indirectly using derivatives of the climate data. We estimated annual precipitation as water droplets (hereafter rainfall) or snow particles (snowfall) ~~snow and rainfall~~ by summing up precipitation (mm) for months with mean monthly temperature below and above 0 °C, respectively (Zhang et al., 2003).

MODIS Terra-based normalized difference vegetation indices (NDVI, Didan, 2015) at a 1-km resolution were used to assess the amount of photosynthetic vegetation. We averaged monthly summertime (June to August) NDVI values over the study period of 2000–2014 and screened for only high-quality pixels based on the MODIS pixel reliability attribute. Potential incident solar radiation, computed after McCune and Keon (2002, Equation 2, p. 605) utilizing slope angle and aspect, along with latitude, was used to estimate the potential incident solar radiation (PISR, W cm^{-1} a^{-1}) that affects the energy balance of the ground thermal regime (e.g. Hasler et al., 2015; Streletskiy et al., 2015). To account for the thermal offset dictated by soil properties (e.g., Smith and Riseborough 1996, 2002; Kurylyk et al., 2014) we extracted ~~S~~soil organic carbon content (SOC, g kg^{-1}), and fractions of coarse (CoarseSed, > 2 mm) and fine sediments (FineSed, ≤ 50 µm) for 0–200 cm subsurface~~, were extracted~~ from SoilGrids database (Hengl et al., 2017).

2.3 Statistical modelling

2.3.1 Calibration of MAGT and ALT models

We used four statistical techniques, namely generalized linear modelling (GLM, McCullagh and Nelder, 1989), generalized additive modelling (GAM, Hastie and Tibshirani, 1990), and regression-tree based machine-learning methods generalized boosting method (GBM, Friedman et al., 2000) and random forest (RF, Breiman 2001) to calibrate MAGT and ALT models by using the nine geospatial predictors. Multi-model framework was adopted to control for uncertainties related to the choice of modeling algorithm (e.g. Marmion et al., 2009). GLM is an extension of linear regression capable of handling non-linear relationships with an adjustable link function between the response and explanatory variables. The GLM models were fitted including quadratic terms for each predictor. In GAM, alongside linear and polynomial terms, smoothing splines can be applied for more flexible handling of non-linear relationships. For smoothing spline, a maximum of three degrees of freedom were specified, which was further optimized by the model fitting function. To examine the direction and possible non-linearity of the relationship between predictors and responses, we used GAM to plot model-based response curves. The curves show smoothed fit between response and a predictor while all other predictors are fixed at their average (Hjort and Luoto, 2011). Both GLM and GAM were fitted without interactions between predictors using a Gaussian error distribution with an identity link function.

GBM was specified with the following parameters: number of trees = 3,000, interaction depth = 6, shrinkage = 0.001. Bagging fraction was set to 0.75 to select a random subset of 75 % of the observations at each step, without replacement. As for RF, 500 trees, each with a minimum node size of five were grown. The final prediction is the average of individual tree predictions. Both GBM and RF automatically consider interaction effects between predictors (Friedman et al., 2000). All statistical analyses were executed in R (R Core team, 2015) using auxiliary R packages; *mgcv* (Wood, 2011) for GAM, *dismo* (Hijmans et al., 2016) for GBM, and *randomForest* for RF (Liaw and Wiener, 2002).

2.3.2 Model evaluation

To evaluate the models, we split the response data randomly into calibration (70 % of the observations) and evaluation (30 %) datasets (Heikkinen et al., 2006). This was repeated 100 times, at each step fitting models with the calibration data and then using them to predict to both the calibration and evaluation datasets. Model performance was assessed with adjusted coefficient of determination (R^2) and root mean square error (RMSE) between observed and predicted values in these datasets.

2.3.3 Variable importance computation

A measure of variable importance was computed to determine the relative importance of each predictor to the models´ predictive performance (Breiman, 2001). In the computation, each modelling technique was first used to fit models with the MAGT and ALT datasets using all the nine predictors. The variable importance was then computed based on Pearson's correlation between predictions from two models produced with the fitted model; one with unchanged variables, and another where the values of one variable were randomized while others remained intact. In the procedure, each predictor was randomized in successive model runs. The measure of variable importance was computed as follows:

Variable importance = 1 – corr($\text{Prediction}_{\text{intact variables}}$, $\text{Prediction}_{\text{one variable randomized}}$) (1)

On a range from 0 to 1, high variable importance value, i.e. high individual contribution to MAGT or ALT, was returned when any randomized predictor had a substantial impact on the model's predictive performance, and consequently resulted low correlation with predictions from the model with intact variables (Thuiller et al., 2009). Each modelling method was run 100 times for each response with each predictor shuffled separately. For each run, different subsample from the original data was randomly bootstrapped with replacement.

2.3.4 Effect size statistics

Effect sizes for each predictor were determined based on the range between the predicted minimum and maximum MAGT and ALT values over the observation data while controlling for the influence of other predictors by fixing them at their mean values (see Nakagawa and Cuthill, 2007). The procedure was repeated with each dataset and modelling method.

3 Results

MAGT in permafrost conditions was on average –3.1 °C while the minimum was –15.5 °C. $\text{MAGT}_{>0\,°C}$ had an average of 8.0 °C and a maximum of 23.2 °C. ALT had an average of 141 cm and ranged from 23 to 733 cm. The extreme values, apart from the ALT maximum, were based on one year of measurements. Pairwise correlations and the scatter plots revealed a strong association between MAGT and air temperature (see Smith and Burgess, 2000; Smith and Riseborough, 2002; Throop et al., 2012), especially in $\text{MAGT}_{>0\,°C}$ (Fig. 2a–b, d). In contrast to MAGT, ALT was not significantly correlated with TDD, but had stronger associations with soil properties (Fig. 2c). Coarse sediments and SOC, especially, were important and showed clear, yet non-linear, responses to ALT~~, respectively (Fig. 4c)~~. Statistical descriptives of the predictors in respective datasets are presented in Fig. S1.

3.1 Model performance

$\text{MAGT}_{>0\,°C}$ models had the highest R^2 values between predicted and observed MAGT (Table 1). In permafrost conditions, all the models had high R^2 values for MAGT, whereas in case of ALT between-model variation was large and R^2 on average lower. A decrease in the fit was identified when predicting ALT to evaluation datasets, especially with GBM and RF, whereas MAGT models retained their high performance. On average, RMSEs were low (~1 °C) in $\text{MAGT}_{\leq 0\,°C}$ and $\text{MAGT}_{>0\,°C}$ calibration datasets. When predicted over evaluation datasets, the average increased slightly more in non-permafrost conditions. A similar increase of 40 % was documented with ALT. For each response, GBM and RF had lower RMSEs (i.e. higher predictive performance) than GLM and GAM, but also larger change between calibration and evaluation datasets, indicating that GLM and GAM produced more robust predictions.

3.2 Relative importance of individual ~~variables~~predictors

FDD and TDD were the most important factors affecting MAGT; FDD (variable importance score = 0.27) where permafrost was present, TDD (0.53) in non-permafrost conditions (Fig. 3a–b). Precipitation predictors, especially ~~water precipitation~~rainfall, had a moderate importance (0.10) on $\text{MAGT}_{\leq 0\,°C}$ but were marginal when permafrost was not present (0.01). Climatic factors were followed by solar radiation (0.02, both MAGT datasets) and finally by NDVI and soil properties with minimal importance (each ≤0.01). The importance of both ~~water~~ rainfall and snowfall ~~precipitation~~ was higher in permafrost conditions.

Solar radiation was the most important predictor (0.37) explaining variation in ALT (Fig. 3c). ~~Water precipitation~~Rainfall had second highest importance (0.05) followed by soil properties SOC (0.04) and coarse sediments (0.03). The remaining climate variables (~~snow precipitation~~snowfall, TDD and FDD) had low importance scores that were comparable to those of NDVI (each 0.01–0.02).

3.3 Effect size of individual ~~variables~~predictors

FDD had the highest individual effect size of 6.7 °C averaged over the four methods in case of $\text{MAGT}_{\leq 0\,^\circ\text{C}}$, whereas in $\text{MAGT}_{>0\,^\circ\text{C}}$ dataset TDD accounted for a dominant 13.6 °C effect (Table 2). Precipitation had the second highest effect, albeit snowfall ~~precipitation~~ was less effective in non-permafrost conditions. Considering the remaining predictors, clear differences were observed in cases of SOC and NDVI, both higher in $\text{MAGT}_{>0\,^\circ\text{C}}$ dataset. In case of ALT, ~~water precipitation~~rainfall exerted the greatest effect (181 cm) despite large between-model variation. In contrast to variable importance results (Fig. 3c), snowfall ~~precipitation~~ had a larger average effect than coarse sediments and SOC, both of which nevertheless had a considerable effect. Solar radiation had a central role with a highly non-linear shape of response (Fig. 4c). A varying degree of non-linearity is also visible in the responses between $\text{MAGT}_{\leq 0\,^\circ\text{C}}$ and the key predictors, whereas in case of $\text{MAGT}_{>0\,^\circ\text{C}}$ the responses are more often linear (Fig. 4a–b).

4 Discussion

4.1 ~~Circumpolar f~~Factors affecting MAGT and ALT

Our results are in line with previous understanding that climatic conditions are the primary factors affecting the long-term averages of ~~circumpolar~~ MAGT across the Northern Hemisphere at 1-km resolution but also indicate that the effects of TDD and FDD on MAGT are dependent on permafrost presence or absence~~the current permafrost occurrence~~. As anticipated, FDD has higher influence on MAGT in permafrost conditions where strong freezing occurs ~~is a prerequisite for the occurrence of permafrost~~ (e.g. Smith & Riseborough, 1996). At sites without permafrost, TDD has a nearly linear dominant ~~the dominant nearly linear~~ (Fig. 4b) effect, which is suggested to be mostly attributed to the lack of the buffering effect of the freeze-thaw processes and latent-heat exchange in the active layer (e.g. Osterkamp, 2007), and to the absence of seasonal snow cover in the warmest parts of the study region. In permafrost conditions, the warming effect of TDD and especially the cooling effect of FDD on MAGT show flattening in response shapes where MAGT is close to 0 °C owing to the latent-heat effects associated with thawing and freezing of water in the active layer (Fig. 4a).

The minimal effect of TDD on ALT contradicts with the documented strong regional scale (spatio)temporal connection (e.g. Zhang et al., 1997; Oelke et al., 2003; Frauenfeld et al., 2004; Melnikov et al., 2004; Yi et al., 2018). According to our results, the spatial linkage is more elusive at a broader scale and could be attributed to the great ~~circumpolar~~ hemispheric variation in ALT. The majority of high-Arctic sites locate on low-lying tundra overlaid by mineral and organic soil layers, whereas ~~at~~ mid-latitude~~s~~ sites ~~(the Alps, central Asian mountain ranges) permafrost~~ predominantly ~~occurs~~ locate in mountains (the Alps, central Asian mountain ranges) with thin soils and thermally diffusive bedrock. This difference partly explains generally small and large ALT within the respective regions notwithstanding that they can have similar average climatic conditions (e.g. TDD, see Fig. 2d). Moreover, large inconsistencies between observed ALT and climate-warming trends have been documented (e.g. Wu et al., 2012; Gangodagamage et al., 2014). Although temporal dynamics of ALT are beyond our analyses, this suggests that thaw depth and air temperatures are, to a degree, decoupled by local conditions.

Recent warming trends in the atmosphere (Guo et al., 2017) are already well visible in circumpolar permafrost temperature observations (Romanovsky et al., 2017) implying that the permafrost system will remain dynamic in future's changing climate. Warmer air temperatures will occur mostly during winters (AMAP, 2017; Guo et al., 2017), which, given the presented high contribution of FDD on MAGT, suggests that changes are foreseeable. Projected warmer winters can also affect ALT through changing snow conditions and subsequent changes in hydrology and vegetation (Park et al., 2013; Atchley et al., 2016; Peng et al., 2018).

In line with new studies (Peng et al., 2018; Zhang et al., 2018), our results highlight the notable role of ~~water precipitation~~ rainfall on both MAGT and ALT. Projected greater proportion of ~~liquid precipitation~~ rainfall (e.g. AMAP, 2017; Bintanja and Andry, 2017) potentially has a direct effect on the ground thermal regime through its influence on latent heat exchange (Westermann et al., 2011), and convective warming during spring (Kane et al., 2001) and summertime (Melnikov et al., 2004; Marmy et al., 2013). However, abundant summer rains arguably also cool the ground surface through increased evaporation and heat capacity, and thus limit the heat conduction into the ground (Zhang et al., 1997, 2005; Frauenfeld et al., 2004; Park et al., 2013). ~~Moreover, extreme climatic events, such as wintertime rain events can have a distinct effect on soil temperature (Westermann et al., 2011) although the long-term sensitivity of permafrost to them is not fully clear yet (Marmy et al., 2013). According to Kurylyk et al. (2014), permafrost studies often consider only conductive heat propagation in the ground. Vincent et al. (2017), however, stress the need to acknowledge processes associated with liquid water and advective heat in efforts to understand rapidly changing cryosphere.~~

The dominant contribution of ~~water precipitation~~rainfall over snowfall observed here contradicts with some previous regional scale studies (e.g., Zhang et al., 2003, 2005). However, the elevated effect of snowfall on MAGT in permafrost conditions (effect size of 2.3 °C compared to 0.8 °C in non-permafrost conditions) underlines the role of snow cover's control over the ground thermal regime. Similarly, Zhang et al. (2018) found that the offset between air and surface temperatures was weaker in temperate regions (mean annual air temperature >0 °C) than in low-Arctic and boreal permafrost regions, although also high-Arctic had small surface offsets owing to small amount of snow. Despite the complexity involved in the role of snow conditions (e.g. Fiddes et al., 2015; Aalto et al., 2018b), thick snow cover has been shown to increase also ALT at site (Atchley et al., 2016), regional (Zhang et al., 1997; Frauenfeld et al., 2004) and circumpolar scale (Park et al., 2013).

Incoming solar energy can be considered central for soil thawing (see Biskaborn et al., 2015), but the high contribution of solar radiation on ALT stands out. Arguably, the effect is emphasized because ALT observation sites in cold permafrost conditions are mostly sparse in vegetation and lack tree canopy (Zhang et al., 2003; Biskaborn et al., 2015). Moreover, most of the ALT sites have been established on flat terrain (Biskaborn et al., 2015), meaning that local topographic shading is less significant. Thus, ALT is suggested to follow poleward decrease in solar radiation and associated shorter thaw seasons (see Luo et al., 2016). The weaker association of solar radiation with MAGT suggests that its direct effect is limited to the near-surface permafrost, i.e. intensified thawing during thawing seasons, and that the influence to deeper temperatures is more indirect and associated with the relationship between annual solar radiation and air temperatures. Moreover, given that MAGT sites are usually located in more topographically heterogeneous terrain than ALT sites, the local exposure to solar radiation is suggested to be more important than the latitudinal trend (e.g. Romanovsky et al. 2010).

The weak connection between TDD and ALT is additionally explained by soil factors that influence the heat transfer between the lower atmosphere and the ground (Smith et al., 2009). According to the response shapes from GAM, coarse sediments increase ALT when enough prevalent (~25 % fraction) in the soils. The effect of soil texture on ALT has been implied to occur largely through its effects on hydrological conditions (Zhang et al., 2003; Yin et al., 2017) and conductivity (Callaghan et al., 2011). More efficient water transfer in coarse-grained material could impose convective heat into soils during the thawing season or promote latent-heat effect during the freeze-up, which both contribute to deeper thaw (see Romanovsky and Osterkamp, 2000; Frauenfeld et al., 2004). Thermal ~~I~~insulation by soil organic layers has been demonstrated to effectively decouple air-permafrost connection resulting in thinner active layer and lower soil temperatures (e.g. Johnson et al., 2013; Atchley et al., 2016). The GAM response shape illustrates a thinning of ALT with increasing SOC until ~150 g kg^{-1}, after which additional organic ~~material~~ carbon does not attribute to enhanced insulation. It should be noted that the used variable depicts SOC in fine earth fraction and does not explicitly address incompletely decomposed or fresh organic matter, which are one of the central components of the thermal offset. However, suitable gridded data on soil organic matter content are not available, and physical fractionation of SOC has been commonly used as its correlative proxy owing to more straightforward measurement procedures (Bailey et al., 2017).

NDVI has a small contribution on ALT and MAGT in permafrost conditions, but outside the permafrost region it has a moderate cooling effect. The low contribution of NDVI in permafrost conditions could be attributed to the intra- and inter-seasonal differences in the effects of different vegetation canopy configurationsvegetation. In wintertime, low vegetation (e.g. tall shrubs) traps snow and thereby enhances insulation of the ground (Morse et al., 2012). Taller tree canopies of evergreen boreal forests, in turn, intercept snow and allow more heat loss from the ground in winter, while in summer their shading cools the ground surface (Lawrence and Swenson, 2011; Fisher et al., 2016).

4.2 Uncertainties

Large-scale scrutinization of factors affecting ground thermal dynamics is often hindered by data deficiencies or unavailability. More precisely, many data lack adequate spatial or temporal accuracy, geographical consistency, methodological robustness or thematic detail (Bartsch et al., 2016; Chadburn et al., 2017). Some of these shortcomings are exacerbated in remote permafrost regions with low-density observational networks of, e.g., climatic parameters (Hijmans et al., 2005) or soil profiles (Hengl et al., 2017). The fine-scale spatial variability of ALT and MAGT called for a high spatial resolution data to assess the local factors that mediate the atmospheric forcing. Here, the availability of geospatial data largely determined the resolution of 30 arc seconds, which could be considered the highest currently attainable resolution at a near-global scale. While not adequate to account for all potential sources of sub-grid spatial heterogeneity in, e.g. microclimatic conditions, especially in topographically complex conditions (Fiddes et al., 2015; Aalto et al., 2018b; Yi et al., 2018), the implemented resolution is a step forward in making a distinction in between-site conditions and revealing local relationships relevant at the hemispheric-circumpolar scale.

In general, the sensitivity of MAGT to the climatic parameters along with the minimal role of soil and vegetation properties suggests that circumpolar future predictions of MAGT are is more applicable feasible to predict than those of ALT, even without addressing, for example, future vegetation or soil organic carbon content, whose response to climate change is extremely challenging to project (Jorgenson et al., 2013). This is incongruent with previous studies showing the high importance of soil properties for MAGT (e.g. Zhang et al., 2003; Throop et al., 2012). The discrepancies are argued to be partly attributed to the hemispheric study extent; large spatial variation in climatic parameters is suggested to have suppressed the effect of soil and vegetation properties locally. It is also possible that the used SOC data could not fully address the thermal offset albeit ALT modelling showed realistic and moderately strong effects. However, the effects of soil properties on MAGT have been shown to be statistically significant when predicting future circumpolar hemispheric ground thermal conditions (Aalto et al., 2018a), and should thus be considered. In addition, Throop et al. (2012), for example, concluded that substrate greatly affects the spatial distribution of permafrost, and that bedrock is expected to respond more rapidly to changes in climate than unconsolidated sediments. Given the pronounced role of precipitation, more direct information on fine-scale soil moisture conditions controlled by local soil and land surface properties (see Kemppinen et al., 2018), as well as more comprehensive and finer resolution data on circumpolar global snow thickness are required for improved ground thermal regime modelling. Fine-scale biophysical factors affecting drainage conditions and distribution of wind-drifted snow (e.g. vegetation and small topographic depressions) are largely averaged-out and cannot be accounted for at 1-km resolution.

Although the main factors were identified as important and effective by each modelling technique, notable inter-modal variability suggested that using only one method could have led to disputable results. A multi-model approach was in this sense safer, although not all the methods may have worked optimally with the present observational and environmental data owing to their different abilities to handle collinearity, spatial autocorrelation or non-linearity. For example, interactions between variables were not included in regression-based modelling (GLM and GAM), while being intrinsically considered by tree-based methods (GBM and RF) (Friedman et al., 2000). Differences such as this could have attributed to the dissimilar performances of the models; GBM and RF were overall less stable when comparing R^2 and RMSE values between the observed and predicted values in calibration and evaluation settings.

5 Conclusions

We statistically related observations of MAGT and ALT to high-resolution (~1 km^2) geospatial data of climatic and local environmental conditions to explore the factors affecting the ground thermal regime across the Northern Hemisphere. ~~We assessed the factors affecting the circumpolar ground thermal regime at an unprecedentedly high 1-km spatial resolution using comprehensive field-quantified observational datasets on MAGT and ALT.~~ Our ~~statistical~~ modelling framework efficiently captured the multi-variate nature of ground thermal regime and highlighted the difference between the contributions of climatic factors on MAGT inside and outside the permafrost domain. In permafrost conditions, ~~different key factors accounted for variation in MAGT and ALT;~~ climate was paramount and soil properties showed marginal role for MAGT, while ~~local environmental conditions~~ precipitation factors and topography-controlled solar radiation were emphasized ~~in case of~~for ALT. Where permafrost was not present, precipitation was less influential and MAGT was predominantly controlled by air temperatures above 0 °C.

The relatively minor role of soil properties (especially organic carbon content) on MAGT and ALT may stem from the lack of global data with high local accuracy. The results also revealed distinct non-linear relationships and thresholds between the ground thermal regime and environmental factors, especially in permafrost-affected regions. At sites without permafrost, responses were more often linear. ~~Our 1-km scale findings are congruent with previous process- and broad-scale studies stressing that, in addition to reliably addressing the key climatic factors, realistic modelling of Earth surface systems should take into account local-scale variation in solar radiation and ground properties.~~ In addition to providing ~~theoretical~~ these insights about effective magnitudes and ~~directions~~ response shapes of the key contributing factors at ~~circumpolar~~ hemispheric scale, it is concluded that multi-variate modelling frameworks capable of employing high-resolution geospatial data ~~are~~ will be valuable for the spatio-temporal prediction of ground thermal regimes ~~at circumpolar~~ from local to global scale.

Author contribution

OK, ML and JH developed the original idea. OK led the compilation of observational data and geospatial data processing with contributions from all the authors. ML, OK and JA performed the statistical analyses. OK wrote the manuscript with contributions from all the authors.

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Competing interests

The authors declare that they have no conflict of interest.

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Table 1: Adjusted coefficient of determination (R^2) and root mean square error (RMSE) between observed and predicted mean annual ground temperature (MAGT) and active-layer thickness (ALT) in calibration and evaluation (in brackets) datasets averaged over 100 permutations. ~~**GLM = generalized linear modelling, GAM = generalized additive modelling, GBM = generalized boosting method and RF = random forest.**~~

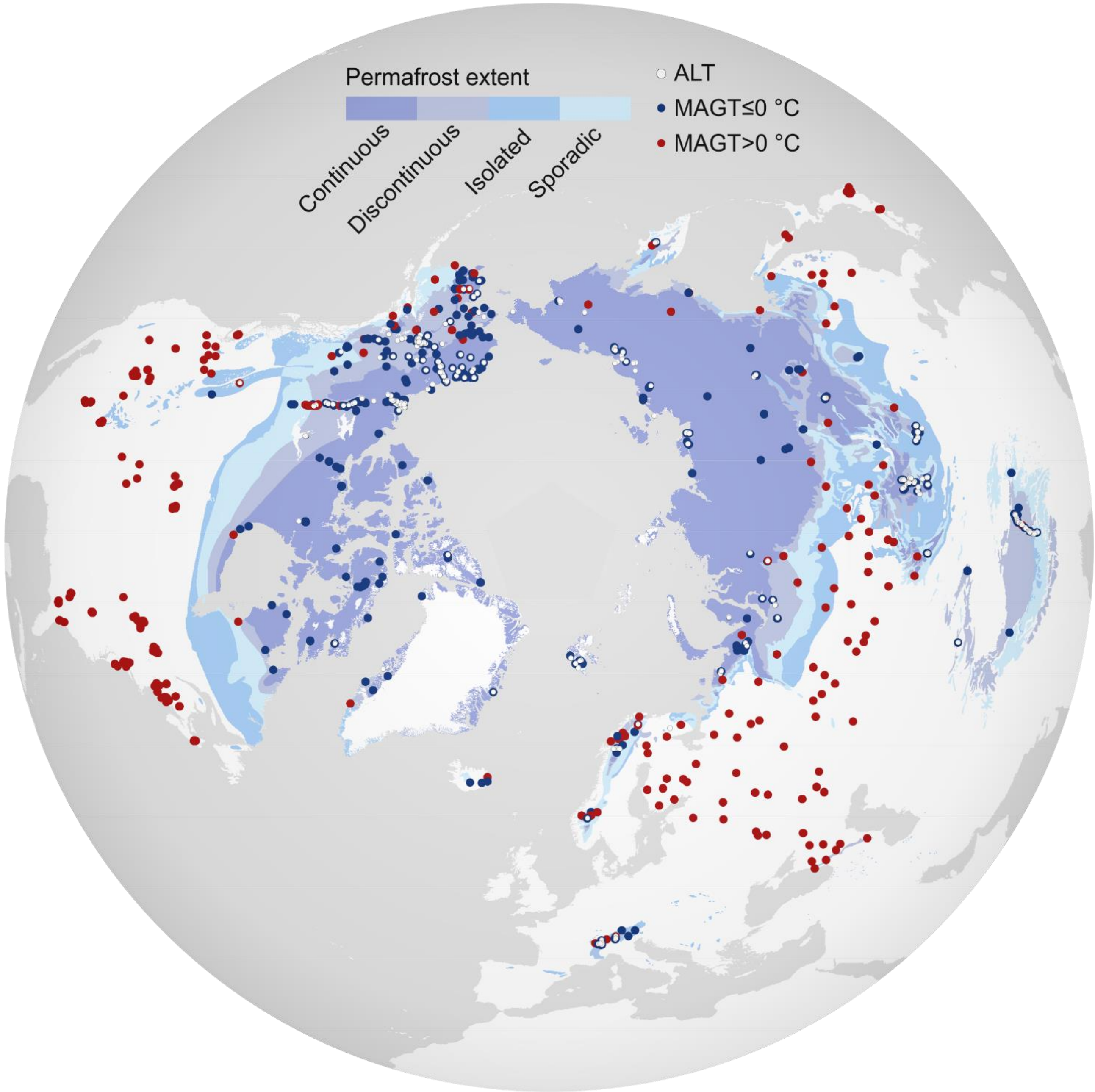
	$MAGT_{\leq 0\,°C}$		$MAGT_{>0\,°C}$		ALT	
Method	R^2	RMSE (°C)	R^2	RMSE (°C)	R^2	RMSE (cm)
GLM	0.86 (0.83)	1.24 (1.33)	0.95 (0.92)	1.20 (1.44)	0.65 (0.50)	80 (93)
GAM	0.88 (0.84)	1.17 (1.29)	0.95 (0.92)	1.18 (1.37)	0.70 (0.54)	74 (89)
GBM	0.93 (0.86)	0.88 (1.22)	0.97 (0.92)	0.91 (1.37)	0.84 (0.59)	55 (84)
RF	0.98 (0.87)	0.51 (1.17)	0.99 (0.93)	0.55 (1.27)	0.93 (0.62)	36 (82)
Average	0.91 (0.85)	0.95 (1.25)	0.96 (0.92)	0.96 (1.36)	0.78 (0.56)	61 (87)

GLM = generalized linear modelling, GAM = generalized additive modelling, GBM = generalized boosting method and RF = random forest.

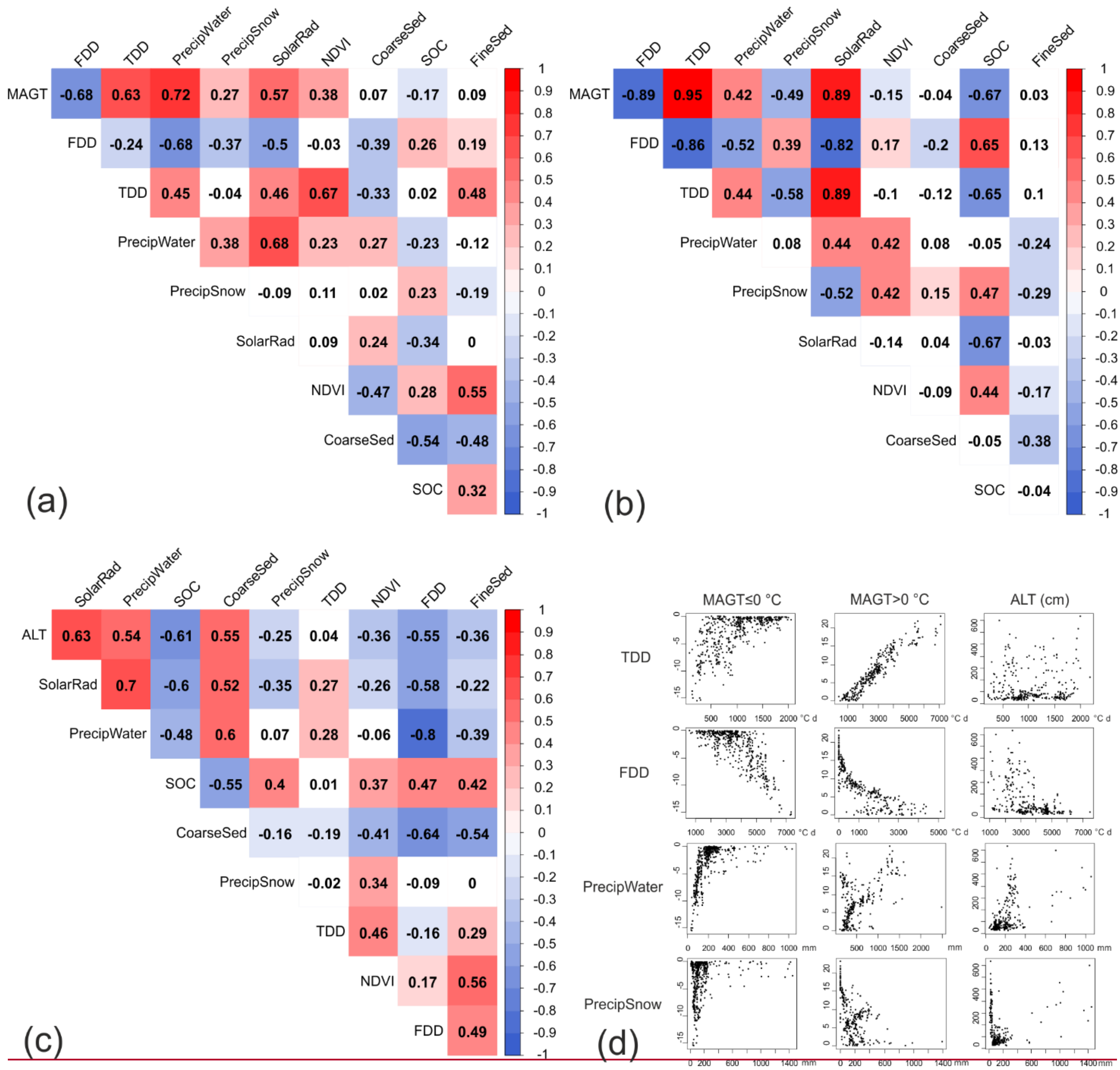
Table 2: The effect size of individual predictors and their four-model averages (see Sect. 2.2 for abbreviations) in the original scale of the responses, °C for (mean annual ground temperature) MAGT and cm for active-layer thickness (ALT). ~~**The values are shaded with increasing blue ($MAGT_{\leq 0\,°C}$), red ($MAGT_{>0\,°C}$) and yellow (ALT) hues relative to the magnitude of the effect. GLM = generalized linear modelling, GAM = generalized additive modelling, GBM = generalized boosting method and RF = random forest. See Sect. 2.2 for predictor abbreviations.**~~

	MAGT≤ 0°C (°C)					MAGT> 0°C (°C)					ALT (cm)				
	GLM	GAM	GBM	RF	Avg	GLM	GAM	GBM	RF	Avg	GLM	GAM	GBM	RF	Avg
FDD	8.6	10.7	4.3	3.2	6.7	3.8	4.3	2.6	2.8	3.4	117	86	15	36	64
TDD	7.1	6.6	2.4	2.8	4.7	19.1	19.5	9.0	6.6	13.6	30	23	19	31	26
Rainfall	1.6	2.6	4.3	3.0	2.9	4.8	3.6	0.2	0.7	2.3	372	249	28	74	181
Snowfall	4.4	4.4	0.1	0.2	2.3	0.8	1.4	0.3	0.5	0.8	195	146	44	94	120
SolarRad	2.6	2.5	0.2	0.3	1.4	2.0	2.3	0.9	1.6	1.7	135	193	178	139	161
CoarseSed	0.8	1.8	0.1	0.2	0.7	0.6	2.6	0.1	0.3	0.9	129	137	69	65	100
FineSed	0.5	0.7	0.2	0.4	0.4	0.6	0.7	0.1	0.1	0.4	17	20	7	9	13
SOC	0.5	0.4	0.3	0.8	0.5	1.7	1.4	0.1	0.6	0.9	121	129	30	28	77
NDVI	0.4	0.3	0.1	0.8	0.4	2.6	2.3	0.2	0.1	1.3	68	36	15	34	38

The values are shaded with increasing blue ($MAGT_{\leq 0\,°C}$), red ($MAGT_{>0\,°C}$) and yellow (ALT) hues relative to the magnitude of the effect. GLM = generalized linear modelling, GAM = generalized additive modelling, GBM = generalized boosting method and RF = random forest. See Sect. 2.2 for predictor abbreviations.



585 **Figure 1: The observational network of the used mean annual ground temperature (MAGT) and active-layer thickness (ALT) across the circumpolar region. Blue symbols indicate the locations of boreholes where MAGT (averaged over the period 2000–2014) was at or below 0 °C and red symbols for those above 0 °C. White symbols depict the ALT measurements sites. The underlying permafrost zonation is from Brown et al. (2002).**


(a)
(b)
(c)
(d)
MAGT≤0 °C
MAGT>0 °C
ALT (cm)
TDD
FDD
PrecipWater
PrecipSnow
SolarRad
NDVI
CoarseSed
SOC
FineSed
MAGT
ALT

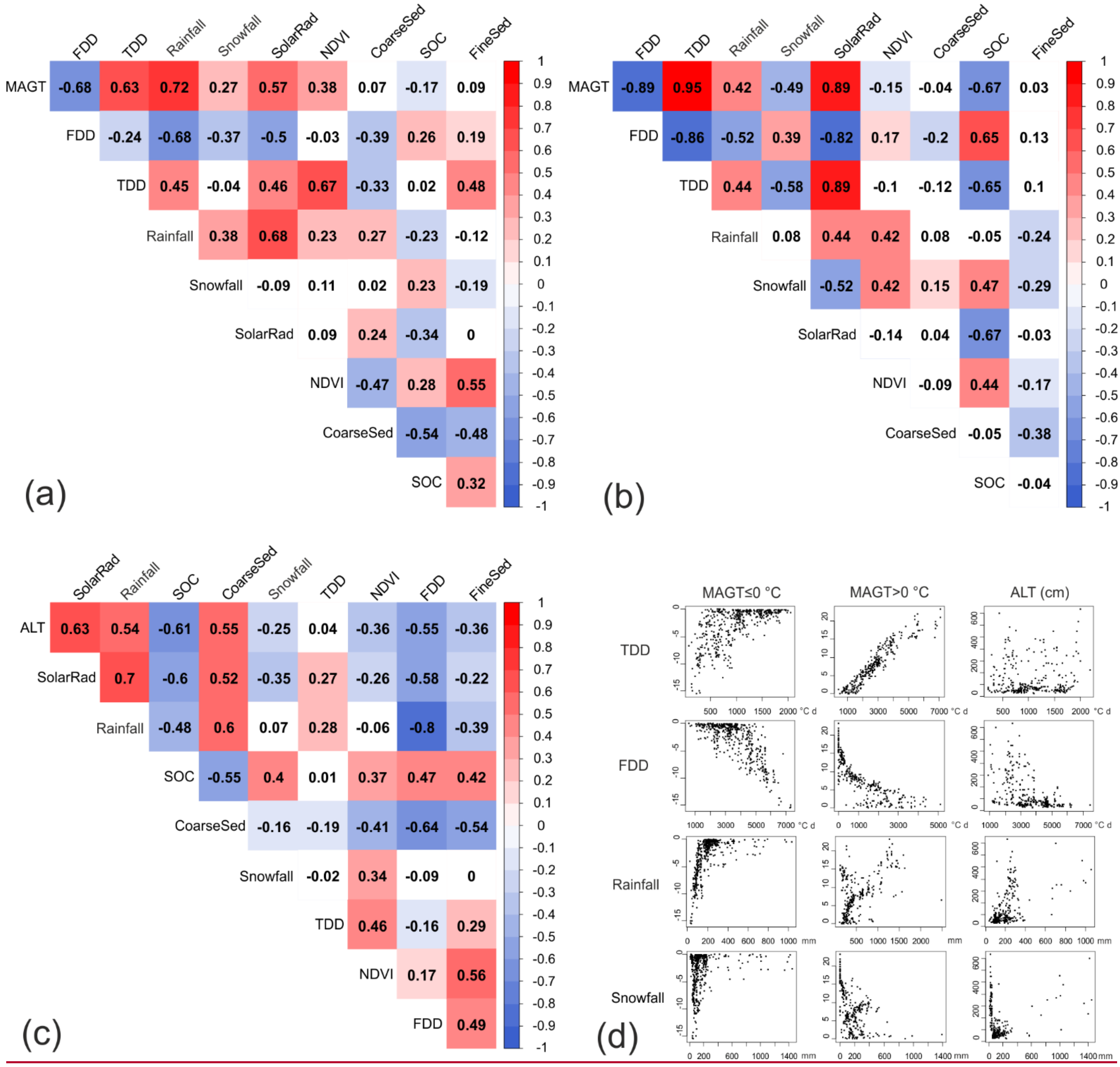
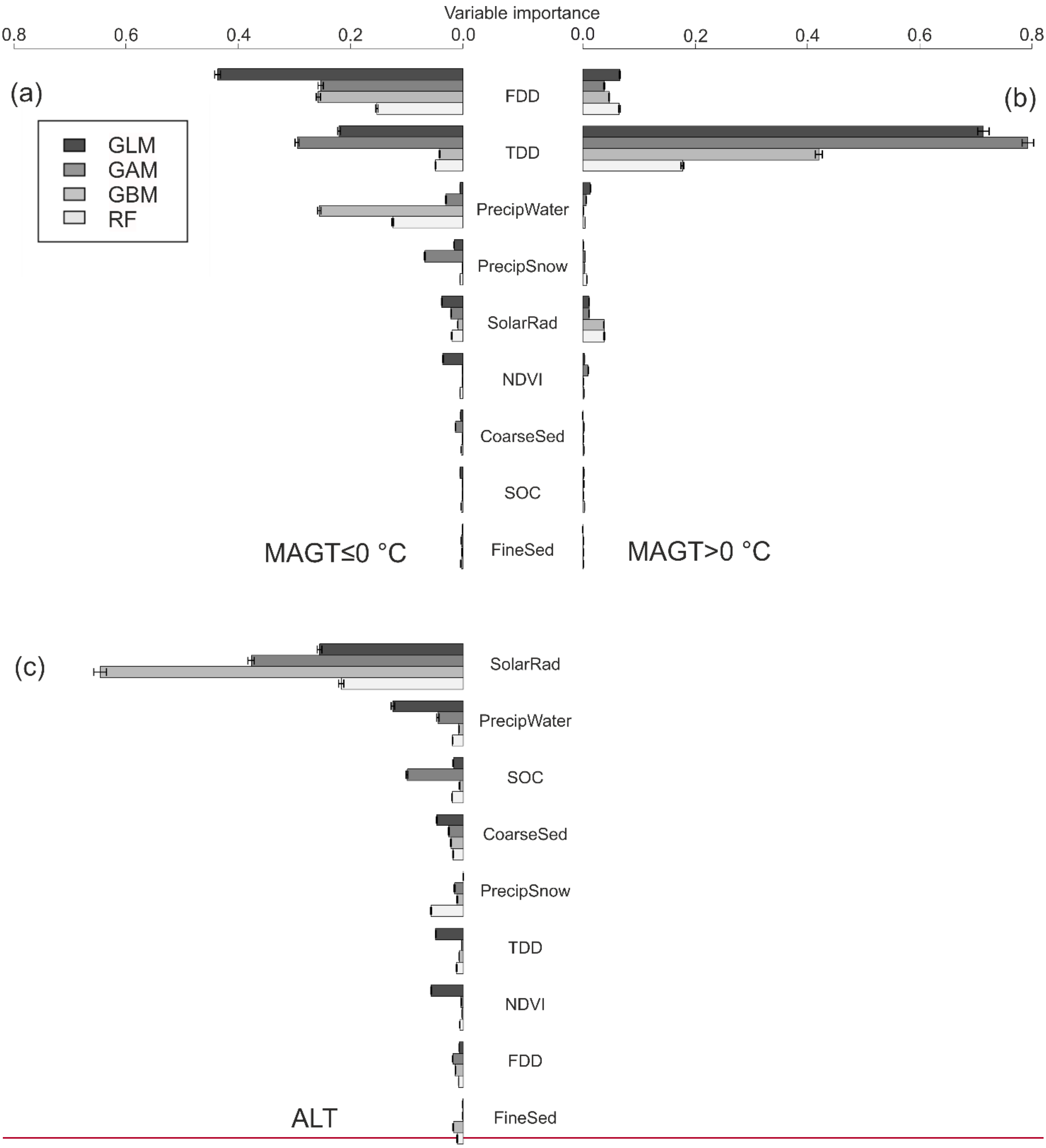


Figure 2: Spearman rank-order correlations between the predictor variables (see Sect. 2.2 for abbreviations) and MAGT$_{\leq 0\,°C}$ (mean annual ground temperature) (a), MAGT$_{>0\,°C}$ (b) and ALT (active-layer thickness) (c). Red hue stands for positive correlations, blue for negative, and white indicates non-significant ($p > 0.01$) correlations. Panel (d) shows MAGT and ALT observations plotted against the climatic predictors.


Variable importance
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
(a)
(b)
GLM
GAM
GBM
RF
FDD
TDD
PrecipWater
PrecipSnow
SolarRad
NDVI
CoarseSed
SOC
FineSed
MAGT≤0 °C
MAGT>0 °C
(c)
SolarRad
PrecipWater
SOC
CoarseSed
PrecipSnow
TDD
NDVI
FDD
FineSed
ALT

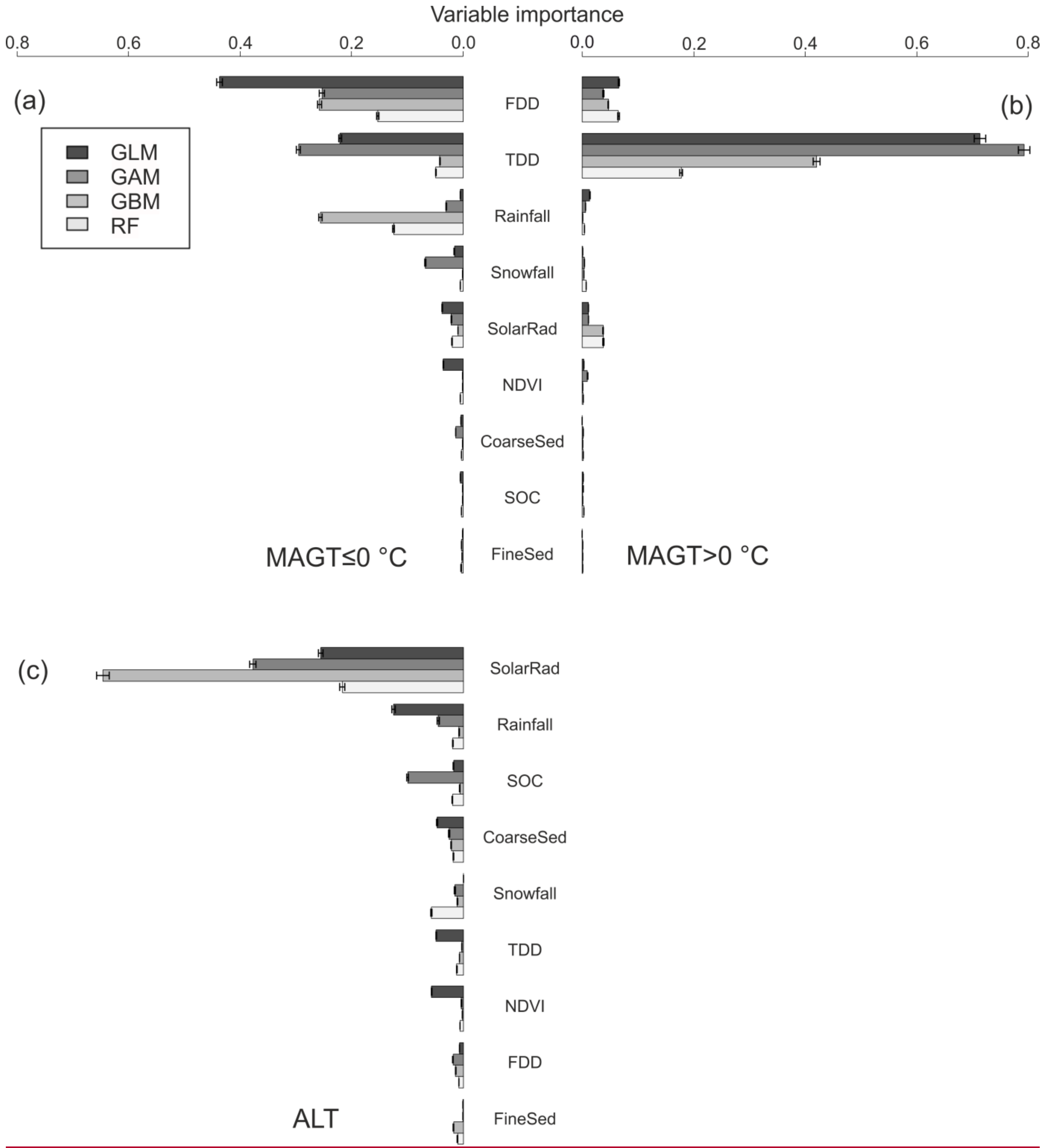
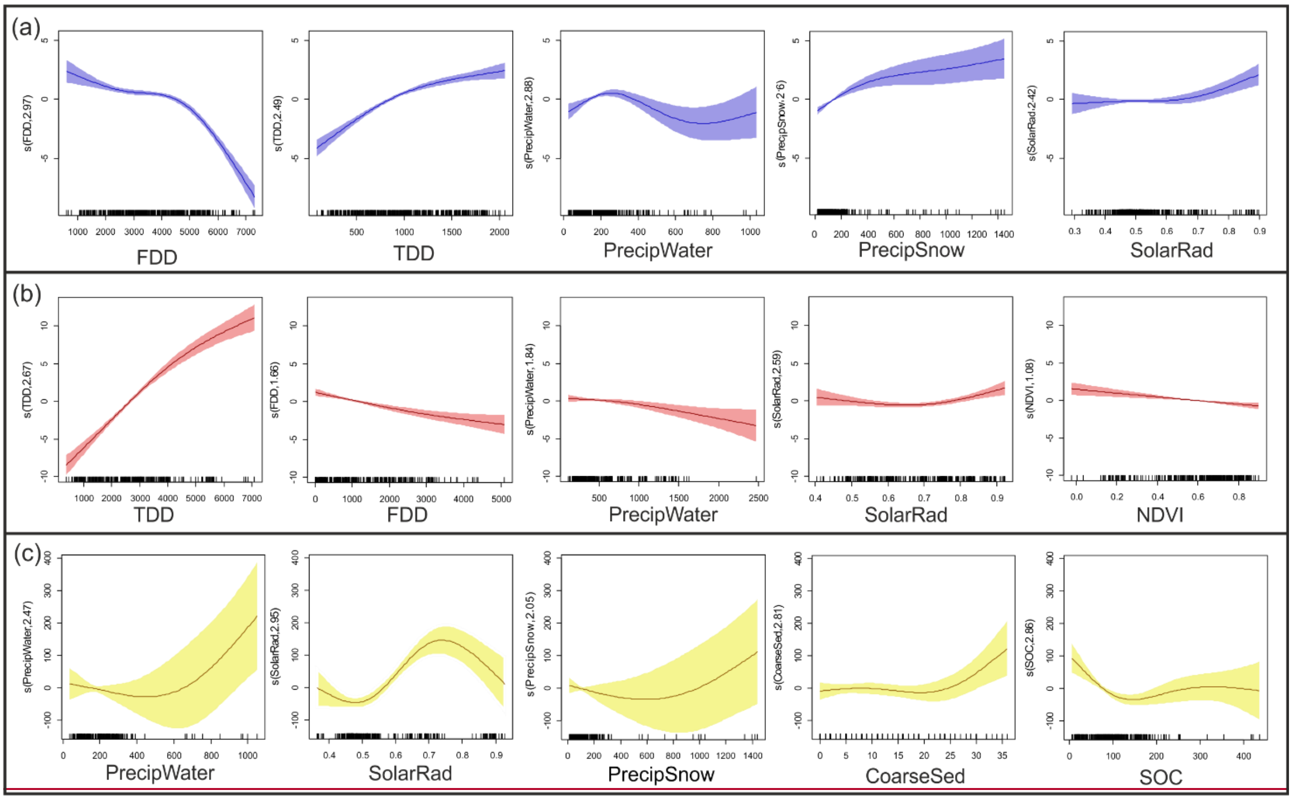


Figure 3: Variable importance values in $MAGT_{\leq 0\,°C}$ (mean annual ground temperature) (a) and $MAGT_{>0\,°C}$ (b) datasets arranged in the descending order of four-model average in $MAGT_{\leq 0\,°C}$ conditions, and for ALT (active-layer thickness) (c), arranged likewise based on ALT results. The whiskers depict 95 % confidence intervals (over 100 bootstrapping rounds). GLM = generalized linear modelling, GAM = generalized additive modelling, GBM = generalized boosting method and RF = random forest. See Sect. 2.2 for predictor abbreviations.



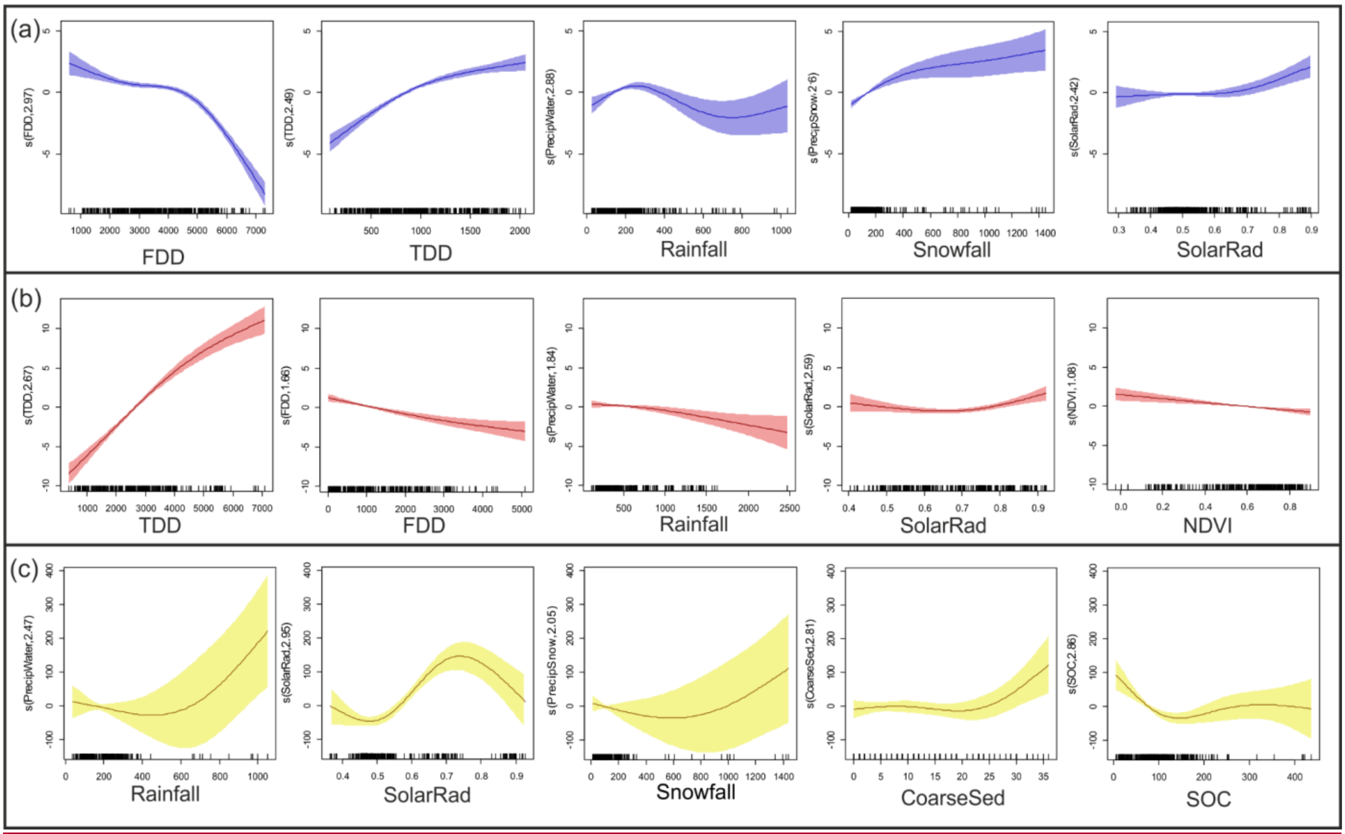


Figure 4: Response shapes of the five predictors with most contribution in $MAGT_{\leq 0\,°C}$ (a) (mean annual ground temperature, blue curves), $MAGT_{>0\,°C}$ (b) (red curves) and ALT (c) (active-layer thickness, yellow curves) datasets obtained from generalized additive modelling (GAM). Response shapes for the remaining predictors are illustrated in Figure S2. Predictors (see Sect. 2.2 for abbreviations) are presented in the descending order of their effect size in respective datasets. X-axis units appear in the original scale of the predictors. Y-axis displays partial residuals and labels the estimated degrees of freedom used in fitting the respective predictors to a response. Shaded areas depict 95 % confidence limits.