

Dear Editor,

We want to thank both the reviewers for their constructive and helpful comments on manuscript TC-2018-144: “*New insights into the environmental drivers of the circumpolar ground thermal regime*”. We have carefully addressed all the comments and performed corresponding changes to the manuscript. This author’s response document includes detailed responses to both reviewers’ comments followed by a ‘track changes’ manuscript.

More precisely, we clarified the aim of our study and justified its place and novelty values in the long line of relevant research. In a few places, we provided a more detailed explanation of the methodology and the data used in the modelling. In addition, we included new discussions and supporting analyses concerning data-related issues pointed out by the reviewers.

Overall, we see that the revision has significantly improved the manuscript. We hope that our revised manuscript fully considered all the concerns raised by the reviewers and could be considered for publication in *The Cryosphere*.

Sincerely,

Olli Karjalainen (on behalf of all authors)

Authors' response to reviewers' comments on the manuscript TC-2018-144: “New insights into the environmental drivers of the circumpolar ground thermal regime”

Referee comments appear in gray,
author responses in black,
and suggested revisions to the original text are *italized*.

To facilitate effortless review we created a notation, in which each comment by the both referees was coded, e.g., **R1C1** = Referee#1, Comment#1.

Line numbers refer to the included track changes manuscript.

Referee #1

Comments on “New insights into the environmental drivers of the circumpolar ground thermal regime” by Olli Karjalainen et al. submitted to The Cryosphere

General

R1C1 This paper statistically related circumpolar observations of mean annual ground temperature (MAGT) and active-layer thickness (ALT) with climate, soil and vegetation variables. Based on the results, they provided some new insights into the major factors controlling the spatial distributions of MAGT and ALT. The analysis compiled a large number of circumpolar observations and the corresponding climate, soil and vegetation data, and the statistical modelling methods have not been seen often in permafrost studies. The results are interesting, especially by comparing the differences between permafrost and non-permafrost regions. I am not an expert of the statistical modelling methods. I assume they are valid and other reviewers can pay more attention to them.

R: We thank the reviewer for the positive views.

Major comments

R1C2 The analysis used thawing-degree-days (TDD) and freezing-degree-days (FDD) and other variables. It is valid for ALT since thawing occurs when air temperature (T_{air}) $> 0^{\circ}\text{C}$, and is related to TDD according to Stefan solution (especially in temporal variations). For AMGT, annual mean air temperature should be a major factor to consider. To assess the relative importance of cold season and warm season, winter mean and summer mean air temperatures are better choices than TDD and FDD since the length of the days is not a factor. I wonder why these factors were not chosen in the analysis. An important finding of this paper is that FDD were the main factor determining the spatial distribution of AMGT in the permafrost region while TDD dominated in the non-permafrost region. The days in a year when $T_{air} < 0^{\circ}\text{C}$ are longer in permafrost region than in non-permafrost region. This difference automatically contributes to your results. If this effect is the major reason, I feel it is quite natural or understandable (the longer the more important) and should not be treated so sensationally as a significant finding. Any way, it would be meaningful and interesting to see the relationships between AMGT and annual mean, winter and summer mean T_{air} .

R: We appreciate these comments and recognize the need to fully address the issue.

We agree that mean annual air temperature (MAAT) is highly relevant for MAGT. However, MAAT cannot alone explain the variations in MAGT attributed to seasonal differences in the response of ground to air temperatures (e.g. Zhang et al. 1997; Smith et al. 2009), which need to be accounted for as the reviewer suggested. We consider TDD and FDD as suitable both 1) for examining the seasonal effects (as discussed at

lines 37–39), and 2) covering year-round climate forcing better than summer and winter mean T, inevitably missing some of the variability important for long-term averages of MAGT and ALT. Smith et al. (2009), for example, showed that a considerable part of thawing occurred outside June to August period in Mackenzie Valley, Canada. Moreover, using the same climatic parameters with MAGT and ALT allowed for comparisons between their controlling factors, which was one of the contributions of this study.

We performed additional analyses to examine the contributions of mean annual air temperature (MAAT), summer (June to August, JJA) and winter temperatures (December to February, DJF) to $MAGT \leq 0^{\circ}C$. We tested the performances of models employing JJA+DJF in place of TDD+FDD, and also with MAAT as the only temperature predictor. Results are very similar to the original with TDD+FDD [average $R^2=0.91$ for calibration dataset, (0.85) for evaluation]; both JJA+DJF and MAAT models explain a marginally smaller part of variation in MAGT (Table I). Average RMSEs in both cases are higher than in the original models [0.95 (1.25)].

Table I. Adjusted coefficient of determination (R^2) and root mean square error (RMSE) between observed and predicted mean annual ground temperature (MAGT) in calibration and evaluation (in brackets) datasets averaged over 100 permutations. The results are provided for datasets employing average air temperatures for summer (June, July and August, JJA) and winter (December, January and February, DJF), and mean annual air temperature (MAAT) as predictors.

Method	R2 (JJA+DJF)	RMSE (JJA+DJF)	R2 (MAAT)	RMSE (MAAT)
GLM	0.84 (0.82)	1.34 (1.42)	0.85 (0.81)	1.33 (1.42)
GAM	0.86 (0.83)	1.26 (1.38)	0.86 (0.84)	1.25 (1.34)
GBM	0.93 (0.86)	0.92 (1.24)	0.92 (0.86)	0.92 (1.24)
RF	0.98 (0.87)	0.53 (1.19)	0.97 (0.87)	0.55 (1.21)
Average	0.90 (0.85)	1.01 (1.31)	0.90 (0.85)	1.01 (1.30)

TDD and JJA have almost perfect correlation, as do FDD and DJF (Figure I). Therefore, it is suggested that DD's well represent summer and winter conditions while also accounting for the climatic variability of the remaining year. In $MAGT \leq 0^{\circ}C$ dataset, MAAT had notably stronger correlation with DJF (0.86) than with JJA (0.40). This suggests that winter conditions contribute strongly to climatic forcing in permafrost regions even when length of the periods is not a factor. In non-permafrost conditions, MAAT had much more similar correlations with JJA (0.89) and DJF (0.94).

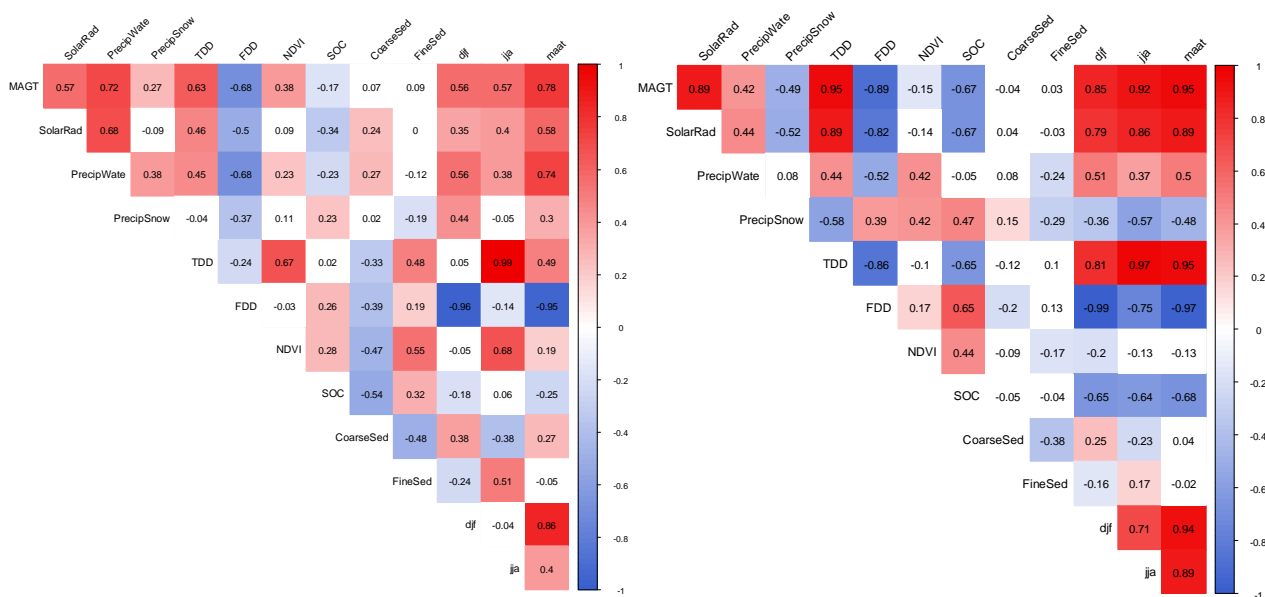


Figure I. Spearman correlations for MAGT in permafrost (a) and non-permafrost conditions (b).

Looking at effect sizes (Table II) and variable importance values (Table III) computed for DJF and JJA, however, it is evident that summer temperatures here have a larger contribution than winter. Should this be due to unaccounted variability outside these months or the buffering effect of snow cover during DJF, we conclude that both TDD+FDD and JJA+DJF can be used to model the ground thermal regime with similar performance (TDD+FDD was slightly better in the light of model performance). However, we consider it is important to take into account the full 12-month climatic variability especially when assessing long-term averages of ground thermal regime at circumpolar scale, and thus prefer TDD+FDD.

Table II. The effect size of individual predictors and their four-model averages

	MAGT ≤ 0°C (°C)				
	GLM	GAM	GBM	RF	Avg
DJF	7.8	2.1	2.3	2.2	3.6
JJA	10.0	10.4	2.7	3.2	6.6
PrecipWater	2.9	3.1	5.2	3.5	3.7
PrecipSnow	4.9	4.6	0.1	0.3	2.5
SolarRad	3.6	4.0	0.0	0.3	2.0
CoarseSed	1.1	2.0	0.1	0.1	0.8
FineSed	0.8	0.6	0.1	0.4	0.5
SOC	0.4	0.6	0.6	1.0	0.6
NDVI	0.6	0.3	0.1	1.0	0.5

Table III. Variable importance values for individual predictors.

MAGT pf	#FineSed	#CoarseSed	#NDVI	#SOC	#SolarRad	#PrecipWater	#PrecipSnow	#djf	#jja
GLM	0.00	0.01	0.00	0.00	0.06	0.01	0.09	0.18	0.50
GAM	0.00	0.02	0.00	0.00	0.04	0.04	0.08	0.23	0.42
GBM	0.00	0.00	0.00	0.00	0.02	0.41	0.00	0.17	0.05
RF	0.00	0.00	0.01	0.00	0.04	0.17	0.01	0.09	0.06

R1C3 This study is to understand the factors affecting the spatial distributions of MAGT and ALT. The factors and mechanisms could be very different from that controlling the temporal variations. The paper should make that clearer, including the title. It should be cautious about assuming factors controlling spatial distribution will automatically controlling the temporal changes (Lines 194-199). The paper used “drivers”, “driving” frequently. The words usually have a sense for temporal changes in climate change studies. For spatial distribution, it is better to avoid it. The relationships and impact indicators are based on statistical analysis. They depend on data, methods, and factors selected for analysis. It should be cautious to use the word “drive”, just say “a factor has a close relationship with ... or has large impacts statistically on ...”, especially when no strong physical processes and mechanisms to support the results.

R: Our focus indeed is on spatial variation of MAGT and ALT rather than temporal dynamics. Therefore, we agree on avoiding “drivers”, and preferring “factors” and other ways to express the relationships between the predictors and responses. We revised the text in any places where temporal changes were discussed (mainly the Abstract, Discussion and Conclusions), stressing the spatial focus of this study and the need to remain cautious when discussing temporal dynamics. However, we decided to leave some cautious discussions about the potential effects of warming climate on MAGT and ALT (lines 225–230, 234–237).

To follow the account we modified the title accordingly: *“New insights into the environmental factors controlling the circumpolar ground thermal regime”*.

R1C4 I like the phrase “new insights” in the title. The text should keep that cautious sense in the text.

R: We thank the reviewer for this view and strive at remaining insightful.

Some minor points

R1C5 Line 9: “The thermal dynamics of permafrost shape Earth surface systems and human activity in the Arctic ...”. “The thermal dynamics of permafrost” means temporal changes, which is different from the focus of the paper (spatial distribution). The word “shape” probably overstated the importance of the thermal dynamics.

R: As agreed upon ([R1C3](#)), we focus on examining the spatial variation of the ground thermal regime and revised accordingly (line 9–10): *“The thermal state of permafrost affects Earth surface systems and human activity in the Arctic and has...”*

R1C6 As mentioned above, the title: “...driver of the circumpolar ground thermal region”, Line 16: “main driver of MAGT in permafrost conditions” and similar sentences other places. These sentences give me a sense that they are drivers of temporal changes rather than factors influencing or determining spatial distributions of MAGT and ALT. The paper should make that clearer.

R: Great thanks for pointing out these occurrences. We revised these and related sentences throughout the manuscript to clarify the study’s focus. Please see [R1C3](#).

R1C7 Line 17-19: The last sentence of the abstract is about temporal changes the authors like to infer from spatial patterns to temporal changes. It is problematic as I mentioned above. The term “initial ground thermal conditions” is not very clear, probably should say “the current ground thermal conditions”. “local-scale topography-soil-driven variability”, probably should be “local-scale variability in soil and topography” or simply “local-scale soil and topography”.

R: These are highly valuable suggestions. The last sentence was revised accordingly (lines 19–22): *“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.”*

R1C8 Line 21: “geocryological development”, the word “development” probably should be “dynamics”.

R: We agree that “dynamics” is more unambiguous here. Replacement made.

R1C9 Line 28: “activity”, using plural.

R: Replaced “activity” → “activities”

R1C10 Line 36: “ground temperatures are higher than air”, adding “temperature” after “air”, or “ground is warmer than air”.

R: Revised accordingly (line 40): *“ground is warmer than air”*

R1C11 Line 59: “geographically comprehensive datasets of field-quantified MAGT ($n = 784$) and ALT ($n = 298$) observations.”. Feels strange. How about “circumpolar field observations of MAGT and ALT”. The number of sites in brackets can be described in methods section.

R: The suggested simplification reads well and was revised with accordingly (line 66): “...*circumpolar field observations of MAGT and ALT.*” The numbers of ALT sites were added in the Methods, line 77: “*and that ALT ($n = 298$) ...*”

R1C12 Line 63: “possible variation ...”, not very clear/direct. Using “differences” instead of “variation”.

R: We agree that “differences” is better here and have made a replacement (line 72): “*possible differences...*”

R1C13 Lines 71: “MAGT values shallower than two meters ...” should be “MAGT measured at less than two meters ...”. Delete “systematically”.

R: Very appreciable suggestions, the revised sentence (lines 84–85) reads: “*MAGT measured at less than two meters below the surface were excluded unless reported to be at the depth of ZAA.*”

R1C14 Line 85: “presenting”, should be “representing”

R: Prefix added.

R1C15 Lines 94–98: You calculated TDD and FDD based on monthly climate data. Did you interpolated to daily or directly based on monthly averages? It is generally ok directly using monthly data based on the test of Frauenfeld et al. (2007, doi: 10.1002/joc.1372). You may refer to this paper for proof.

R: We calculated the indices based on monthly temperature averages utilising the WorldClim data. It indeed was our intention to cite Frauenfeld et al. to show that using monthly data provides very similar values to those derived from daily observations. We considered it necessary to elaborate the original manuscript (lines 109–110): “*Frauenfeld et al. (2007) showed that their use instead of daily temperatures accounts for less than 5 % error for most high-latitude land areas*”.

R1C16 The tables and the figures are quite interesting. However, I feel the result section is a bit weak. I hope it can provide more detailed description, explanation and analysis of the tables and Figures.

R: We appreciate the reviewer’s views here. To give a more detailed account, we added some further explanations. However, we preferred to focus on main findings to not unnecessarily lengthen the manuscript or repeat the information conveyed by the figures and tables.

(lines 170–171): “*Coarse sediments and SOC, especially, were important and showed clear, yet non-linear, responses to ALT, respectively (Fig. 4c).*”

(177–181): “*On average, RMSEs were low (~ 1 °C) in $MAGT \leq 0$ °C and $MAGT > 0$ °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.*”

(195–198): “*Considering the remaining predictors, clear differences were observed in cases of SOC and NDVI, both higher in $MAGT > 0$ °C dataset. [...] In contrast to variable importance results (Fig. 3c), snow precipitation had a larger average effect than coarse sediments and SOC, both of which nevertheless had a considerable effect.*”

R1C17 Line 184: This study did not include any sites with permanent snow cover, you may delete “or permanent snow cover”.

R: This is a spot-on notion. Deleted “*or permanent*” at line 210.

R1C18 In discussion section, temporal changes were inferred from the spatial statistical results. The author should be cautious about that and clearly indicate the assumption.

R: Please see [R1C3](#). We clarified the original text with a follow-up sentence (underlined, lines 223–224): “*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.*”

R1C19 Figures 2a-c: one color legend probably is enough. Figure 2d: the units of TDD and FDD should be °C d.

R: Two-color legend was used to show whether the significant correlations are positive (red) or negative (blue). This was to allow more easy visual interpretation of the interrelationships within and between a, b and c panels without having to compare the numbers. Therefore, we preferred not to remove the colors, but changed the unit of TDD/FDD to °C d here and in Supplementary Figures 1 and 2.

R1C20 Figure 4: I am not familiar with the GAM. It would be useful to briefly describe how the response shapes are calculated and what do they mean?

R: This an important remark and we agree that describing response curve derivation will improve legibility. We described the calculation and interpretation of GAM response curves in the Methods (lines 134–135) “*The curves show smoothed fit between response and a predictor while all other predictors are fixed at their average (Hjort and Luoto, 2011).*”

R1C21 What is the unit of solar radiation?

R: The unit of solar radiation was added at line 118: “*to estimate the potential incident solar radiation (PISR, $W\ cm^{-1}\ a^{-1}$)...*”

Interactive comment on “New insights into the environmental drivers of the circumpolar ground thermal regime” by Olli Karjalainen et al.
Anonymous Referee #2

Received and published: 3 August 2018

General Comments

R2C1 This paper uses ground temperature and active layer data acquired from various sources to determine their relationships with various climate and other parameters to gain insights into the environmental drivers of the circumpolar ground thermal regime. While the analysis of this rather large data set is interesting (although others e.g. Peng et al. 2018 have made use of similar data sets) some of the insights regarding the various relationships are not necessarily new and have been reported elsewhere. In addition, some of the conclusions would appear to be at odds with those of other studies, which may be partly an issue of scale. A number of comments are offered below. These concerns should be addressed before the manuscript is considered for publication.

R: We thank the reviewer for highly expertized comments across the manuscript. Peng et al. (2018), along with Park et al. (2013, 2015), Luo et al. (2016), Guo & Wang (2017) and Zhang et al. (2018), have indeed used similar data sets. In addition to the unprecedented geographical coverage of MAGT sites, our dataset allowed for assessing the differences between permafrost and non-permafrost regions, to our knowledge, previously not (semi)quantitatively studied at this extent. We consider that the novelty of our work lies in its implementation of multiple statistical modelling techniques from regression to decision-tree-based machine learning, and the high spatial resolution (~1 km² grid-cell size) combined with circumpolar extent the approach offers.

Our view to ground thermal regime modelling implies that we break the system into components (predictors; climatic and local factors) and assess their correlative relationships with MAGT and ALT. Some advantages of statistical models are that they are more cost-efficient than mechanistic models (which currently have limited high-resolution applicability in hemisphere scale investigations), and enable examining permafrost-climate relations without pre-defined parameters, e.g., thermal diffusivity. Unlike in mechanistic transient models (which can arguably provide more accurate regional predictions than statistical methods) we do not model processes, such as phase transition in the Stefan equation, but focus on the individual predictors' effects. In addition, it can account for variables related to topography and land cover (vegetation) that could be difficult to otherwise parametrize.

Importantly, our analyses go beyond examining the relative contributions of the predictors. The effect size analysis provides numerical information about the effective magnitudes of the relationships. In addition, the response curves provide means to assess the shape of the response (direction and non-linearity) facilitating the understanding of the observed responses. To better point out the novelties of this study, we reflected these aspects in the Abstract (lines 11–15, edits underlined): *“Here, we statistically related circumpolar observations of mean annual ground temperature (MAGT) and active-layer thickness (ALT) to high-resolution (~1 km²) geospatial data of climatic and local environmental conditions. The aim was to characterize the relative importance of key environmental factors and the magnitude and direction of their effects in predicting the circumpolar ground thermal regime at 1-km scale.”*

Introduction (lines 62–68): *“More specifically, we aim to (1) calibrate realistic models of MAGT and ALT (the responses) utilizing 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 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.”*

and in the Conclusions (lines 313–315): *“In permafrost conditions, different key factors accounted for variation in MAGT and ALT; climate was paramount for MAGT, while local environmental conditions were emphasized in case of ALT.”* and lines 320–323: *“In addition to providing theoretical insights about effective magnitudes and directions of the key contributing factors at circumpolar scale, multi-variate modelling frameworks capable of employing high-resolution geospatial data are valuable for the spatio-temporal prediction of ground thermal regime at the circumpolar scale. ...”*

The scale, as the reviewer suggests, presumably is behind some discrepancies with the previous studies, which is one reason why we think it is interesting and important to do research from this viewpoint. Climate and ground temperature relations differ between sites in different regions as shown by e.g. Throop et al. (2012), and some of these may average-out, but our aim was to quantify how the relevant factors affect at circumpolar scale, the contribution of which provides new information for future research.

R2C2 Some of the relationships considered in this paper particularly those concerning air temperature and soil conditions have been well summarized in key equations such as the Stefan equation and the TTOP equation and their variants (see for eg. Brown et al. 2000; Harland and Nixon, 1978; Hinkel and Nelson, 2003; Nelson and Outcalt 1993; Romanovsky and Osterkamp, 1995; Risborough and Smith 1998; Smith and Riseborough 2002). There have also been a number of studies over the last decade, including those at local to continental scales, that have considered permafrost-climate relations (i.e. consideration of ground temperature and active layer thickness) and role of various local factors (e.g. Romanovsky et al. 2010, 2017; Smith et al. 2009, 2010, 2012; Burn and Kokelj 2009; Palmer et al. 2012; Throop et al. 2012; Morse et al. 2012 etc).

R: We appreciate the reviewer’s efforts in providing an extensive listing of relevant references. We have acquainted with most of this literature and used it as a basis for our modelling framework. We acknowledge the findings of the large-scale studies cited by the reviewer here (Romanovsky et al. 2010, Smith et al. 2010; Throop et al. 2012) as well as those in [R2C1](#) and its response, but argue that our analyses provide new detailed information (relative importance, effect size, shape of response) about the contributing factors. Please see [R2C1](#).

R2C3 The broad scale of the analysis and lack of site specific data likely obscures some of the important relationships between MAGT and various local factors such as vegetation, snow cover and terrain conditions (including properties of the earth materials). Studies over 40 years ago showed the relevance of these factors and their influence on the ground thermal regime and also the occurrence of permafrost, i.e. whether MAGT is above or below 0_C (e.g. Brown 1965, 1973; Nicholson and Granberg 1973; Thie 1974). The importance of substrate conditions (thermal properties, moisture content) is described in the thermal offset component in the TTOP model. The thermal offset which, under equilibrium conditions, is due to a difference between frozen and unfrozen thermal conductivity, can result in subsurface temperatures being below 0_C, and therefor the existence of permafrost, even though the ground surface temperature is above 0_C (see Romanovsky and Osterkamp, 1995; Risborough and Smith 1998; Smith and Riseborough 2002). This effect along with latent heat effects can result in the persistence of permafrost under warm climate conditions (e.g. Romanovsky et al. 2010; James et al. 2013).

R: This is an enjoyable summary of decades’ worth of research. For discussions about the potential effect of scale, please see ([R2C1](#)). The lack of site-specific data is an obvious source of uncertainty, and it would be indeed interesting to see how geospatial data compares to measured values at the used sites should they be sufficiently available. However, we would like to point out that vegetation, snow cover and terrain conditions indeed had an effect on the ground thermal regime in permafrost conditions albeit it was clearly smaller than that of air temperature. As pointed out above (see [R2C1](#) for performed edits) our results do not just echo the relevance of, for example air temperature, but also show the magnitude and shape of the relationship between ground thermal regime and environmental factors. Thus, we consider that our results have substantial added value to the study of the permafrost-environment relationships.

We decided to diverge from the TTOP model and its offset components by independently addressing the determinants of these offsets (soil properties, snow). Therefore, also in our analyses, joint effect of all considered factors is suggested to be able to predict subzero MAGT even when surface temperature is above zero, as happens when thermal offset is strong. As a sign of this, the latent-heat effect can be discerned in the response shapes (Fig. 4a) as a flattened curve near 0 °C, that is, weakened relationship between FDD and MAGT.

R2C4 This paper largely considers spatial variation in ALT and MAGT rather than temporal variations and the authors should be careful in making conclusions regarding future changes in these variables in response to a changing climate. Also, a number of papers (such as Romanovsky et al. 2010, 2017; Smith et al. 2010 and others mentioned above) have considered the temporal variation in the ground thermal regime in the permafrost region and the factors affecting the response to a changing climate. In particular, these other studies have made conclusions regarding the importance of the initial ground thermal regime (i.e. how close MAGT is to 0_C and the importance of latent heat effects), the effect of snow cover, vegetation and substrate or soil conditions.

R: This is a highly valuable argument, and was pointed out by the reviewer #1 ([R1C3](#)) as well. We recognize the need to more clearly state that our focus is in spatial variation in ALT and MAGT and not on temporal dynamics of permafrost. See [R2C1](#) for discussions about the added information from our study compared to the previous. We carefully revised each sentence where temporal effects were assessed based on our results (lines 220–221, 315–318; [R1C5](#), [R1C7](#), [R1C18](#)).

R2C5 A large part of the paper appears to focus on the permafrost regions. However, the MAGT data utilized extends well beyond the permafrost regions and the cryospheric aspect (such as the seasonal frost depth) is not really considered in these more southerly regions and might be negligible in some areas. Given this is a journal focussed on the cryosphere and there appears to be a significant focus in the MS on permafrost, it is not clear why these additional sites were included in the analysis.

R: Seasonal frost depth would be another important issue to address at broad scale using e.g. statistical modelling framework. Here, we focus on MAGT because it can provide comparable information on ground thermal conditions inside and outside the permafrost regions. Although our focus is on permafrost, we performed similar analyses for non-permafrost regions to test the hypothesized influence of current ground thermal conditions (presence or absence of permafrost) on the effect of controlling factors. This information is important in the context of changing future permafrost extent; if currently frozen areas thaw, their response to environmental forcing is altered.

Specific Comments

R2C6 Line 25-26 – One could argue that it is the presence of ground ice that influences the geomorphological processes and the impact of changing permafrost conditions.

R: At this early stage of the Introduction, we wanted to first point out broader factors and not specific factors such as ground ice, soil properties or topography. However, ground ice is central for geomorphological processes, and thus we added a mention on this (lines 46–47): *“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).”*

R2C7 Line 29 – Snow cover or snow depth is as (or perhaps more) important as precipitation with respect to the ground thermal regime.

R: Here, we considered snowfall to be included in “precipitation” related to our method of deriving snowfall variable (PrecipSnow) from precipitation data. To reduce ambiguity, we decided to only refer to climatic conditions here (line 33): *“Climatic conditions account for large-scale...”*. Also at line 36, we moved snow

before soil and vegetation to stress its importance: “... *intercepting layers of snow, soil and vegetation mediate their effect...*”

R2C8 Line 37-38 – One could argue it is the moisture content and drainage that are the important factors.

R: This is very true, but in the Introduction we would prefer characterizing the studied factors and their major effects. However, we added a sentence to elaborate how fine-scale factors affect soil moisture (and snow) distribution in the Discussions (lines 298–300): “*Fine-scale biophysical factors affecting drainage conditions and distribution of wind-drifted snow (e.g. vegetation and small topo-graphic depressions) are largely averaged-out and cannot be accounted for at 1-km resolution.*”

R2C9 Line 39-41 – Romanovsky et al. (2010) is probably a better reference to use here for the role of latent heat in determining the response of the ground thermal regime to changes in air temperature.

R: We replaced Ekici et al. (2015) with Romanovsky et al. (2010) (line 45).

R2C10 Line 46-47 – As mentioned above, there have been circumpolar and continental analyses of the environmental drivers.

R: Although our approach offers new ways to examine these environmental factors (variable importance, effect size, shape of response; please see [R2C1](#)) with very comprehensive observational data over the Northern Hemisphere north of 30th latitude, we acknowledge that the present study and relevant previous efforts are hard to compare related to varying extent, spatial resolution, used methods, observational data etc. Therefore, statements concerning lack of relevant studies can be ambiguous, and we thus remove the sentence (lines 51–53). We believe that the novelty of our study becomes obvious elsewhere.

R2C11 Line 52-54 – This observation wasn’t unknown prior to Peng et al (2018) and as mentioned above, these relationships and the relevance of the “edaphic factors” are describe in variants of the Stefan Equation (e.g Harlan and Nixon, 1978; Nelson et al. 2000). Also, in an investigation of air temperature – ALT relationships across a range of ecoclimate zones, Smith et al. (2009) showed that the relationship varied according to vegetation and soil conditions (i.e. the edaphic factors).

R: Our intention was not to claim that Peng et al were the first to stress this. Instead, we wanted to highlight the research need with recent pan-Arctic study and the recommendations given therein. We slightly modified the sentence (lines 58–60): “*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.*” A reference to Harlan and Nixon (1978, line 59) was added to acknowledge the long history of this observation.

Smith et al. study is very interesting in its setting, and would be interesting to reproduce with our modelling methods. We believe that here lies one reason for the discrepancies between our results and Smith et al. (and some others); at circumpolar scale, some region-specific controls can be averaged out. Therefore, we argue that moderately weak circumpolar ALT/TDD connection is valid, given the highly heterogeneous environmental conditions across the observed ALT sites. Nevertheless, our results show the multivariate nature of ALT and strongly point out the effects of soil conditions. Vegetation’s effect, in turn, was vague possibly owing to the inadequacy of NDVI in depicting complex (seasonal) involved processes (see Anisimov & Sherstiukov 2016) as discussed in the original manuscript (lines 272–276).

R2C12 Line 67 – Was ALT only obtained through mechanical probing or were some values acquired through analysis of shallow ground temperature records. In the results section you give a maximum value of ALT of >7 m and it is unlikely that this was determined through mechanical probing. Some of the reports used for sources of ALT data may report ALT determined by methods other than probing (including thaw tubes and ground temperature measurements). Note also that probing does not necessarily capture the maximum thaw depth.

R: We agree that the expression in the original manuscript was incomplete and see the need to elaborate the text (lines 77–79): “...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).” The deepest values were measured from borehole temperatures.

R2C13 Line 68 – The depth of ZAA can be much greater than 15 m and will depend on thermal properties of the subsurface materials. ZAA depth can be greater than 20 m for example in bedrock (see for eg. Romanovsky et al. 2010; Smith et al. 2010; Throop et al. 2012).

R: This is a valid point and should be disclosed in the text. We chose 15 m as a compromise value (to be systematic, only one depth was chosen), because it is usually included in the depth ranges for ZAA in general (e.g. French 2007). We elaborated the issue accordingly (underlined, lines 80–82): “...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 (Throop et al. 2012).” We added a reference to Throop et al. because it was an important reference work when writing the original manuscript but for some reason was not included in the submitted manuscript.

R2C14 Line 60-83 – It is unclear whether the analysis utilizes a mean value for the entire 2010- 2014 period for ground temperature, ALT, air temperature etc.

R: We acknowledged the need to clarify the issue. MAGT and ALT values used in modelling were calculated from averages of all available full years of observations (or appropriate single measurements, i.e. at or near ZAA). This is now detailed in the text (lines 73–74): “For each MAGT and ALT site, averages over the study period were then calculated from available annual averages or suitable single measurements.”

The WorldClim data were adjusted to represent 15-year monthly climate averages from the same period. We clarified this (lines 104–105): “Monthly averages over this 15-year period were then used to derive the following climate parameters.”

NDVI was calculated from June to August imagery from 2000 to 2014, as stated at lines 113–115.

R2C15 Line 95-98 – Snow depth can be highly variable in northern environments depending on exposure to wind and vegetation. This is a site specific factor and its influence is probably not adequately considered by only utilizing precipitation records.

R: We strongly agree on this, and consider that the lack of data on specific snow thickness or snow water equivalency is a limitation in our approach. However, suitable data on snow depth or water equivalent at this extent (i.e. the whole pan-Arctic area) and resolution (ca. 1 km) unfortunately are not available. Moreover, at this resolution fine-scale biophysical factors affecting wind-drifted snow are largely smoothed out as discussed earlier ([R2C8](#)).

R2C16 Line 104-106 – What is the resolution?

R: All the predictor variables have a 30 arc-second resolution (~1 km²) as stated at lines 98-100 (edits underlined): “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 scale."

R2C17 Line 151-152 – This relationship was not unknown and has been shown by others (a couple of examples Brown, 1967, Throop et al. 2012 and GSC Open File 3954 available through GEOSCAN).

R: Great thanks for pointing out the references. The air temperature-permafrost relationship was reported here because it is central to the study and for the subsequent discussions, even though it is not a novel finding. Thus, we see no need to revise the text here.

R2C18 Line 153-154 – As shown in Smith et al. (2009), there is a more direct relationship between TDD and ALT for tundra sites compared to vegetated sites or organic terrain.

R: Although the ALT-TDD relationship was not very strong at circumpolar scale, the moderately high contribution of soil organic content on ALT represents the strong thermal offset at sites where organic layer is thick (Table 2, Fig. 4). This, along with addressing other factors affecting the TDD-ALT relationship, were discussed in the Discussion section (lines 262–271). The study by Smith et al. was also cited therein, and thus no changes were seen necessary.

R2C19 Line 161-169 – Aren't these factors inter-related?

R: Effect size analysis is capable of addressing the individual predictor contributions by recursively averaging the values of the others in the computation (described in Section 2.3.4.). Thereby, each predictors' individual effect can be assessed. No changes were considered necessary.

R2C20 Line 180-187 – I would disagree that this finding about the effects of TDD and FDD is all that significant. Cold conditions are a requirement for permafrost so FDDair will have a higher value in permafrost environments compared to non permafrost environments. This is described by the Frost Index model of Nelson and Outcalt (1983).

R: We agree that it was anticipated that freezing temperatures would dominate in a colder area. We think it is important to report the effectiveness of FDD in permafrost regions, and TDD elsewhere, because these findings confirm previous understanding of climate-permafrost relationship at circumpolar setting. However, based on our results we can also characterize these relationships (please see discussions in [R2C1](#)) and thereby improve previous understanding rather than only confirming it.

Consequently we revised the text at lines 204–206: *"Our results show are in line with previous understanding that climatic conditions are the primary factors affecting the long-term averages of circumpolar MAGT at 1-km resolution but also indicate that the effects of TDD and FDD on MAGT are dependent on the current permafrost occurrence."* and added a notion (underlined) on the directness of the response between $MAGT < 0^{\circ}C$ and TDD (line 208–209): *"At sites without permafrost, TDD has the dominant nearly linear (Fig. 4b) effect..."*

R2C21 Line 181 – Do you really mean there is a negative energy balance or do you mean $FDD > TDD$ which is not the same thing (a negative energy balance would mean there is cooling over time).

R: Great thanks for your comment. We have improved the text, we completely revised this sentence. It is true that we cannot make statements about the current state of energy balance at the sites. Here, with negative energy balance we referred to the initial process behind the conditions that permafrost exists and did not mean to argue that $FDD > TDD$ means negative energy balance. Revised at lines 206–208: *"As anticipated, FDD has*

higher influence on MAGT in permafrost conditions where strong freezing is a prerequisite for the occurrence of permafrost (e.g. Smith & Riseborough, 1996)."

R2C22 Line 188-190 – See earlier comment regarding relationship between TDD and ALT and its variability with vegetation etc.

R: Please see [R2C18](#).

R2C23 Line 189-193 – High Arctic sites do not necessarily have decimeter thaw depths. Greater thaw depths can be found in bedrock so the material type is important. Also, if thaw depths are largely obtained by probing there may be some bias in the data set as the method is limited by soil type (difficult or impossible in granular material and bedrock) and the depth of probing.

R: We recognized the need to clarify the text. By high-Arctic sites we referred to low-lying regions in the circumpolar north. High latitudes obviously also have mountains with highly conductive ground and therefore thick ALT. The revised sentence reads (lines 215–222): *“According to our results, the spatial linkage is more elusive at a broader scale and could be attributed to the great circumpolar variation in ALT. The majority of high-Arctic sites locate on low-lying tundra overlaid by mineral and organic soil layers, whereas at mid-latitudes (the Alps, central Asian mountain ranges) permafrost predominantly occurs in mountains 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).”*

As discussed ([R2C12](#)), ALT measurements have been performed by probing or derived from boreholes and thaw tubes. We would like to point out that compiled data came from established sources often cited in permafrost science. We nevertheless acknowledged the potential source of uncertainty in probing in coarse material. Therefore, we excluded all the probing measurements that reportedly did not reach the maximum depth of thaw as reported by sources. To our opinion there is no need revise the text here.

R2C24 As mentioned in previous comments, site specific factors are an important influence on ALT and its relationship with TDD and this is likely masked in your analysis.

R: Our aim was to examine the individual influences of climate and local factors on MAGT and ALT. The results show that soil factors indeed had notable individual contributions on ALT. TDD-ALT relationship therefore is not necessarily masked, but rather stress that at this scale TDD is not the major control of spatial variability. The weak connection between observed ALT and TDD is also visible in Figure 2d. Please see [R2C18](#).

Based on the comment, we discussed this issue in more detail (lines 216–219) in [R2C23](#).

R2C25 Line 200-209 – The results presented don't really allow attribution of the effect of precipitation to advection over latent heat. Drainage will be an important factor.

R: This is an important point; we need to be cautious when assessing any subsurface processes as they were not directly studied. Here we relate our findings to previously documented connections including the effects discussed in the original manuscript. The role of precipitation and related mechanisms at this scale needs more studying (cf. Peng et al. 2018).

We revised this paragraph (lines 230–242) by moving the discussions about advective heat to the end of the paragraph and by giving a stronger emphasis on latent heat effect reinforced by the amount of water precipitation. Westermann et al. (2011) was cited to accompany this (lines 234–237, underlined): *“Projected*

greater proportion of liquid precipitation (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)."

R2C26 Line 210-217 – As mentioned above, the amount of snow on the ground (snow depth) is probably the more important factor and is highly variable. Other studies have utilized winter n-factors to account for this effect in investigations of climate-ground temperature relationships. (see for example Morse et al. 2012; Palmer et al. 2012; Throop et al. 2012 as well as those cited in the MS).

R: As discussed in the original manuscript, the relatively low contribution of snowfall contradicted with previous studies. Please see discussion concerning data limitations ([R2C15](#)).

R2C27 Line 218-225 – A general northward decrease in MAGT which is associated with decreasing solar radiation and air temperature has been reported elsewhere (e.g Brown 1967, Smith et al. 2010; Romanovsky et al. 2010). As others have pointed out (see various papers already cited) the relationship is modulated by local factors. The incoming solar radiation that reaches the ground surface, and therefore influences the ground surface temperature and the deeper thermal regime, is probably the more important variable and probably not well captured in your data set.

R: We argue that here used estimate of potential incident solar radiation reaching the ground surface is not as important factor for MAGT as air temperature, because its effect in high latitudes is minimal for most of the year. Local topography also greatly affects the received amount of solar radiation at site. However, our results show that it still was more important (Fig. 3) and had a greater average effect (Table 2) than local soil and vegetation properties.

The amount of solar radiation is obviously a major control of climate in any area but conditioned regionally; Tibet plateau has high solar radiation but still low air temperatures, whereas e.g. the Nordic countries receive less solar radiation but are still mostly permafrost free. These anomalies clearly disrupt the northward decrease in MAGT and its association with solar radiation. We added a sentence to address the MAGT-solar radiation relationship (lines 259–261): *"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).*

R2C28 Line 223-224 – Other studies (see those cited earlier) conclude that vegetation and soil properties are an important influence on the response of MAGT to changes in climate and therefore predictions of future conditions. Also, soil properties are an important influence on the thermal offset (which is not mentioned in this MS) which can be an important factor determining whether permafrost exists or not under warmer conditions (See previous comments).

R: We suppose the reviewer refers to lines 253-254. The effect of soil on MAGT was indeed small in our study but still not negligible. At this scale, it was anticipated that air temperature patterns would account for the greatest effect but the analyses were still able to point out their contribution, especially the effect size analysis, implicating that on average soil properties exerted a 0.4–0.7°C effect on MAGT. We modified the text to address these issues (lines 292–295): *"However, the effects of soil properties have been shown to be statistically significant when predicting future ground thermal conditions (Aalto et al., 2018), and should thus be considered. In addition, Throop et al. (2012), for example, concluded that substrate greatly affects the spatial distribution between permafrost, and that bedrock sites are expected to respond more rapidly to changes in climate than unconsolidated sediments."*

Concerning offsets, please see [R2C3](#) and [R2C18](#).

R2C29 271-272 – This has been concluded in other studies as mentioned in earlier comments.

R: We completely revised this sentence to acknowledge this has been concluded previously, and to focus on the new aspects of this study (lines 315–318): *“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.”*

R2C30 Line 273-275 – See earlier comments regarding importance of substrate conditions (soil or rock properties) in influencing the response of the ground thermal regime (and future permafrost conditions) to changes in climate.

R: We significantly modified the Conclusions to better reflect the findings of this study, and consequently removed this part (lines 318–320). This issue was discussed elsewhere (lines 292–295; [R2C28](#)).

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New insights into the environmental drivers of factors controlling the circumpolar ground thermal regime

Olli Karjalainen¹, Miska Luoto², Juha Aalto^{2,3}, and Jan Hjort¹

¹Geography Research Unit, University of Oulu, FI-90014, Oulu, Finland

²Department of Geosciences and Geography, University of Helsinki, FI-00014, Helsinki, Finland

³Finnish Meteorological Institute, FI-00101, Helsinki, Finland

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

Abstract. The thermal dynamics-state of permafrost shape-affects Earth surface systems and human activity in the Arctic and have-has implications to global climate. Improved understanding of the fine-local-scale variability in the circumpolar ground thermal regime is required to account for its sensitivity to changing climatic and geoeological conditions. Here, we statistically related circumpolar observations of mean annual ground temperature (MAGT) and active-layer thickness (ALT) to high-resolution (~1 km²) geospatial data of climatic and local environmental conditions. The aim was to identify-characterize their relative importance of key environmental drivers-factors and the magnitude and direction 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 R² 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 air temperatures were-was the main driver-of 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 an-important (non-linear) influences from soil properties. Our findings suggest that in addition to climatic factors, initial ground thermal conditions and local-scale topography-soil-driven-variability in soil and topography need to be considered in order to realistically assess the impacts-of climate-change on current and future ground thermal regimes across the circumpolar region. cold-climate-geoeosystems.

1 Introduction

In the face of changing Arctic, it is crucial to understand the mechanisms that drive the current geocryological development-dynamics of the region. Thaw of permafrost is expected to significantly attribute to hydrological and geoeological 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). 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).

Air-temperature-and-precipitationClimatic conditions account for large-scale spatial variation in mean annual ground temperature (MAGT) and active-layer thickness (ALT) (Bonnaveure 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 and-snow-mediate their effect (e.g. Osterkamp, 2007; Fisher et al., 2016; Gruber et al., 2017; Aalto et al., 2018a; Zhang et al., 2018). 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

Commented [A1]: R1C5 Line 9: “The thermal dynamics of permafrost shape Earth surface systems and human activity in the Arctic ...”. “The thermal dynamics of permafrost” means temporal changes, which is different from the focus of the paper (spatial distribution). The word “shape” probably overstated the importance of the thermal dynamics.

Commented [A2]: R1C7 Line 17-19: The last sentence of the abstract is about temporal changes the authors like to infer from spatial patterns to temporal changes. It is problematic as I mentioned above. The term “initial ground thermal conditions” is not very clear, probably should say “the current ground thermal conditions”. “local-scale topography-soil-driven variability”, probably should be “local-scale variability in soil and topography” or simply “local-scale soil and topography”.

R2C4 This paper largely considers spatial variation in ALT and MAGT rather than temporal variations and the authors should be careful in making conclusions regarding future changes in these variables in response to a changing climate. Also, a number of papers (such as Romanovsky et al. 2010, 2017; Smith et al. 2010 and others mentioned above) have considered the temporal variation in the ground thermal regime in the permafrost region and the factors affecting the response to a changing climate. In particular, these other studies have made conclusions regarding the importance of the initial ground thermal regime (i.e. how close MAGT is to 0 °C and the importance of latent heat effects), the effect of snow cover, vegetation and substrate or soil conditions.

Commented [A3]: R1C8 Line 21: “geocryological development”, the word “development” probably should be “dynamics”.

Commented [A4]: R1C9 Line 28: “activity”, using plural.

Commented [A5]: R2C7 Line 29 – Snow cover or snow depth is as (or perhaps more) important as precipitation with respect to the ground thermal regime.

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 offset, i.e. ground ~~temperatures are higher is warmer~~ than air (e.g. Aalto et al., 2018b; Zhang et al., 2018). Water precipitation 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; Marny et al., 2013). Arguably, the responsiveness of the circumpolar 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 more directly (Romanovsky et al., 2010; Kurylyk et al., 2014; Ekiei et al., 2015). ~~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 circumpolar permafrost dynamics is required to understand various geocological 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). ~~Despite the increased availability of MAGT and ALT measurements (Biskaborn et al., 2015) and global geospatial data, fine-scale analyses of the environmental drivers over the circumpolar area are largely lacking.~~ 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 fine-high spatial resolutions ~~for 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 ~~drivers controlling factors contributing to~~ the spatial variation in the circumpolar ground thermal regime. More specifically, we aim to (1) calibrate realistic models of MAGT and ALT (the responses) utilizing geospatial data on climatic and local conditions (the predictors) ~~across the Northern Hemisphere land areas, and (2) assess the relative contribution of the drivers~~ ~~examine the nature of the contributing factors in both permafrost and non-permafrost conditions using geographically comprehensive circumpolar field observations of MAGT and ALT, datasets of field-quantified MAGT (n = 784) and ALT (n = 298) observations.~~ 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 30th parallel (Fig. 1). To examine possible ~~variation 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, (MAGT_{≤0} °C, n = 469) and above 0 °C (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~~

Commented [A6]: R1C10 Line 36: “ground temperatures are higher than air”, adding “temperature” after “air”, or “ground is warmer than air”.

Commented [A7]: R2C9 Line 39–41 – Romanovsky et al. (2010) is probably a better reference to use here for the role of latent heat in determining the response of the ground thermal regime to changes in air temperature.

Commented [A8]: R2C6 Line 25–26 – One could argue that it is the presence of ground ice that influences the geomorphological processes and the impact of changing permafrost conditions.

Commented [A9]: R2C10 Line 46–47 – As mentioned above, there have been circumpolar and continental analyses of the environmental drivers.

Commented [A10]: R2C11 Line 52–54 – This observation wasn't unknown prior to Peng et al (2018) and as mentioned above, these relationships and the relevance of the “edaphic factors” are describe in variants of the Stefan Equation (e.g. Harlan and Nixon, 1978; Nelson et al. 2000). Also, in an investigation of air temperature – ALT relationships across a range of ecoclimate zones, Smith et al. (2009) showed that the relationship varied according to vegetation and soil conditions (i.e. the edaphic factors).

Commented [A11]: R1C11 Line 59: “geographically comprehensive datasets of field-quantified MAGT (n = 784) and ALT (n = 298) observations.”. Feels strange. How about “circumpolar field observations of MAGT and ALT”. The number of sites in brackets can be described in methods section.

Commented [A12]: R2C1 This paper uses ground temperature and active layer data acquired from various sources to determine their relationships with various climate and other parameters to gain insights into the environmental drivers of the circumpolar ground thermal regime. While the analysis of this rather large data set is interesting (although others e.g. Peng et al. 2018 have made use of similar data sets) some of the insights regarding the various relationships are not necessarily new and have been reported elsewhere. In addition, some of the conclusions would appear to be at odds with those of other studies, which may be partly an issue of scale. A number of comments are offered below. These concerns should be addressed before the manuscript is considered for publication.

Commented [A13]: R1C12 Line 63: “possible variation ...”, not very clear/direct. Using “differences” instead of “variation”.

Commented [A14]: R2C14 Line 60–83 – It is unclear whether the analysis utilizes a mean value for the entire 2010–2014 period for ground temperature, ALT, air temperature etc.

probing or derived from ground temperature measurements or thaw tubes was measured at the end of thawing season during the maximum thaw (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 values shallower measured at less than two meters below the surface were systematically 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 geospatial 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 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). Frauenfeld et al. (2007) showed that their use instead of daily temperatures accounts 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 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

Commented [A15]: R2C12 Line 67 – Was ALT only obtained through mechanical probing or were some values acquired through analysis of shallow ground temperature records. In the results section you give a maximum value of ALT of >7 m and it is unlikely that this was determined through mechanical probing. Some of the reports used for sources of ALT data may report ALT determined by methods other than probing (including thaw tubes and ground temperature measurements). Note also that probing does not necessarily capture the maximum thaw depth.

Commented [A16]: R2C13 Line 68 – The depth of ZAA can be much greater than 15 m and will depend on thermal properties of the subsurface materials. ZAA depth can be greater than 20 m for example in bedrock (see for eg. Romanovsky et al. 2010; Smith et al. 2010; Throop et al. 2012).

Commented [A17]: R1C13 Lines 71: “MAGT values shallower than two meters ...” should be “MAGT measured at less than two meters ...”. Delete “systematically”.

Commented [A18]: R1C14 Line 85: “presenting”, should be “representing”

Commented [A19]: R2C14 Line 60-83 – It is unclear whether the analysis utilizes a mean value for the entire 2010-2014 period for ground temperature, ALT, air temperature etc.

Commented [A20]: R1C15 Lines 94-98: You calculated TDD and FDD based on monthly climate data. Did you interpolated to daily or directly based on monthly averages? It is generally ok directly using monthly data based on the test of Frauenfeld et al. (2007, doi: 10.1002/joc.1372). You may refer to this paper for proof.

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, $\text{W cm}^{-2} \text{ a}^{-1}$) that affects the energy balance of the ground thermal regime (e.g. Hasler et al., 2015; Streletskiy et al., 2015). Soil organic carbon content (SOC, g kg^{-1}), and fractions of coarse (CoarseSed, $> 2 \text{ mm}$) and fine sediments (FineSed, $\leq 50 \mu\text{m}$) 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. Heikkinen–Marmion et al., 2006, 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 univariate-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 (Breiman, 2004). In the procedure, each predictor was randomized in successive model runs. The measure of variable importance was computed as follows:

Commented [A21]: R1C21 What is the unit of solar radiation?

Commented [A22]: R1C20 Figure 4: I am not familiar with the GAM. It would be useful to briefly describe how the response shapes are calculated and what do they mean?

155 Variable importance = $1 - \text{corr}(\text{Prediction}_{\text{intact variables}}, \text{Prediction}_{\text{one variable randomized}})$ (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 . $\text{MAGT}_{>0^{\circ}\text{C}}$ 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, especially in $\text{MAGT}_{>0^{\circ}\text{C}}$ (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 with box-plots (in Fig. S1).

3.1 Model performance

$\text{MAGT}_{>0^{\circ}\text{C}}$ 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 ($\sim 1^{\circ}\text{C}$) in $\text{MAGT}_{\leq 0^{\circ}\text{C}}$ and $\text{MAGT}_{>0^{\circ}\text{C}}$ 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. According to changes in RMSE between calibration and evaluation datasets, indicating that GLM and GAM produced more accurate-robust predictions, than GBM and RF for each response.

3.2 Relative importance of individual variables

FDD and TDD were the most important drivers-of-factors affecting MAGT; FDD (0.27) where permafrost was present, TDD (0.53) in non-permafrost conditions (Fig. 3a–b). Precipitation predictors, especially water precipitation, had a moderate importance (0.10) on $\text{MAGT}_{\leq 0^{\circ}\text{C}}$ but were marginal when permafrost was not present (0.01). Climatic drivers-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 and snow precipitation was higher in permafrost conditions.

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

Commented [A23]: RIC16 The tables and the figures are quite interesting. However, I feel the result section is a bit weak. I hope it can provide more detailed description, explanation and analysis of the tables and Figures.

Commented [A24]: RIC16 The tables and the figures are quite interesting. However, I feel the result section is a bit weak. I hope it can provide more detailed description, explanation and analysis of the tables and Figures.

3.3 Effect size of individual variables

FDD had the highest individual effect size of 6.7 °C averaged over the four methods in case of MAGT_{≤0} °C, whereas in MAGT_{>0} °C dataset TDD accounted for a dominant 13.6 °C effect (Table 2). Precipitation had the ~~next-second~~ highest effect, albeit snow 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 MAGT_{≤0} °C dataset.~~ In case of ALT, water precipitation exerted the greatest effect (181 cm) despite large between-model variation. ~~In contrast to variable importance results (Fig. 3c), snow 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 MAGT_{≤0} °C and the key predictors, whereas in case of MAGT_{>0} °C the responses are more linear (Fig. 4a–b).

4 Discussion

4.1 Circumpolar ~~drivers-factors affecting of~~ MAGT and ALT

Our results ~~show are in line with previous understanding~~ that climatic conditions are the primary ~~drivers-of factors affecting~~ the long-term averages of circumpolar MAGT at 1-km resolution but also indicate that the effects of TDD and FDD on MAGT are dependent on ~~initial-the current ground thermal conditions~~ permafrost occurrence. ~~As anticipated,~~ FDD has higher influence on MAGT in permafrost conditions where strong freezing ~~leads to negative surface energy balance and is a prerequisite for~~ the occurrence of permafrost (e.g. Smith & Riseborough, 1996). At sites without permafrost, TDD has 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 ~~or-permanent~~ 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 variation in ALT. ~~high-Arctic sites have decimeter thaw depths, while ALT in similar average climatic conditions can be several meters in mountainous areas (e.g. Bonnaventure and Lamoureux, 2013; Luo et al., 2016).~~ The majority of high-Arctic sites locate on low-lying tundra overlaid by mineral and organic soil layers, whereas at mid-latitudes (the Alps, central Asian mountain ranges) permafrost predominantly occurs in mountains 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).

Commented [A25]: R1C16 The tables and the figures are quite interesting. However, I feel the result section is a bit weak. I hope it can provide more detailed description, explanation and analysis of the tables and Figures.

Commented [A26]: R2C20 Line 180-187 – I would disagree that this finding about the effects of TDD and FDD is all that significant. Cold conditions are a requirement for permafrost so FDDair will have a higher value in permafrost environments compared to non permafrost environments. This is described by the Frost Index model of Nelson and Outcalt (1983).

Commented [A27]: R2C21 Line 181 – Do you really mean there is a negative energy balance or do you mean FDD>TDD which is not the same thing (a negative energy balance would mean there is cooling over time).

Commented [A28]: R1C17 Line 184: This study did not include any sites with permanent snow cover, you may delete "or permanent snow cover".

Commented [A29]: R2C23 Line 189-193 – High Arctic sites do not necessarily have decimeter thaw depths. Greater thaw depths can be found in bedrock so the material type is important.

Commented [A30]: R2C24 As mentioned in previous comments, site specific factors are an important influence on ALT and its relationship with TDD and this is likely masked in your analysis.

Commented [A31]: R1C18 In discussion section, temporal changes were inferred from the spatial statistical results. The author should be cautious about that and clearly indicate the assumption.

235 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. In line with new studies (Peng et al., 2018; Zhang et al., 2018), our results highlight the notable role of water precipitation on both MAGT and ALT. Projected greater proportion of liquid precipitation (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.](#)

245 The dominant contribution of water precipitation 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 offsets owing to small amount of snow. Despite the complexity involved in [snow's 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).

255 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 [as well](#). 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 \(e.g. Romanovsky et al. 2010\).](#)

265 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). 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 does not attribute to enhanced insulation.

Commented [A32]: R2C25 Line 200-209 – The results presented don't really allow attribution of the effect of precipitation to advection over latent heat. Drainage will be an important factor.

Commented [A33]: R2C27 Line 218-225 – A general northward decrease in MAGT which is associated with decreasing solar radiation and air temperature has been reported elsewhere (e.g Brown 1967, Smith et al. 2010; Romanovsky et al. 2010). As others have pointed out (see various papers already cited) the relationship is modulated by local factors. The incoming solar radiation that reaches the ground surface, and therefore influences the ground surface temperature and the deeper thermal regime, is probably the more important variable and probably not well captured in your data set.

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 vegetation. In wintertime, low vegetation traps snow and thereby enhances insulation of the ground. 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 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 more applicable 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). However, the effects of soil properties on MAGT have been shown to be statistically significant when predicting future circumpolar 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 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 topo-graphic depressions) are largely averaged-out and cannot be accounted for at 1-km resolution.

Although the main ~~drivers-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.

Commented [A34]: R2C28 Line 223-224 – Other studies (see those cited earlier) conclude that vegetation and soil properties are an important influence on the response of MAGT to changes in climate and therefore predictions of future conditions. Also, soil properties are an important influence on the thermal offset (which is not mentioned in this MS) which can be an important factor determining whether permafrost exists or not under warmer conditions (See previous comments).

Commented [A35]: R2C8 Line 37-38 – One could argue it is the moisture content and drainage that are the important factors.

R2C15 Line 95-98 – Snow depth can be highly variable in northern environments depending on exposure to wind and vegetation. This is a site specific factor and its influence is probably not adequately considered by only utilizing precipitation records.

5 Conclusions

We assessed the ~~drivers of~~ factors affecting the circumpolar ground thermal regime at an unprecedentedly ~~fine~~-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 ~~MAGT and ALT~~ 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 for MAGT, while local environmental conditions were emphasized in case of ALT.~~ ~~The~~ Our 1-km scale findings ~~imply~~ are congruent with previous ~~process- and broad-scale studies stressing~~ that, in addition to reliably addressing the key climatic factors, realistic modelling ~~future climate change assessments~~ of Earth surface systems should take into account ~~local-scale variation in solar radiation and ground properties, initial ground thermal conditions.~~ Furthermore, the thermal state of permafrost in terms of MAGT and ALT was controlled by distinctive factors. ~~Although of little importance for MAGT, soil properties had a momentous effect on ALT and should thus be accounted for in simulations of permafrost thaw.~~ In addition to providing theoretical insights ~~about effective magnitudes and directions of the key contributing factors at circumpolar scale,~~ multi-variate modelling frameworks capable of employing ~~global-high-resolution geospatial data at fine spatial resolution;~~ are valuable for the ~~spatio-temporal prediction of ground thermal regime at circumpolar scale.~~ Arctic research, e.g. greenhouse gas emissions from thawing permafrost soils.

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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Commented [A36]: R2C29 271-272 – This has been concluded in other studies as mentioned in earlier comments.

Commented [A37]: R2C30 Line 273-275 – See earlier comments regarding importance of substrate conditions (soil or rock properties) in influencing the response of the ground thermal regime (and future permafrost conditions) to changes in climate.

Commented [A38]: R2C1 This paper uses ground temperature and active layer data acquired from various sources to determine their relationships with various climate and other parameters to gain insights into the environmental drivers of the circumpolar ground thermal regime. While the analysis of this rather large data set is interesting (although others e.g. Peng et al. 2018 have made use of similar data sets) some of the insights regarding the various relationships are not necessarily new and have been reported elsewhere. In addition, some of the conclusions would appear to be at odds with those of other studies, which may be partly an issue of scale. A number of comments are offered below. These concerns should be addressed before the manuscript is considered for publication.

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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.

Method	MAGT $\leq 0^\circ\text{C}$		MAGT $> 0^\circ\text{C}$		ALT	
	R^2	RMSE ($^\circ\text{C}$)	R^2	RMSE ($^\circ\text{C}$)	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)

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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, $^\circ\text{C}$ for (mean annual ground temperature) MAGT and cm for active-layer thickness (ALT). The values are shaded with increasing blue (MAGT $\leq 0^\circ\text{C}$), red (MAGT $> 0^\circ\text{C}$) 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 $\leq 0^\circ\text{C}$ ($^\circ\text{C}$)					MAGT $> 0^\circ\text{C}$ ($^\circ\text{C}$)					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
PrecipWater	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
PrecipSnow	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

520

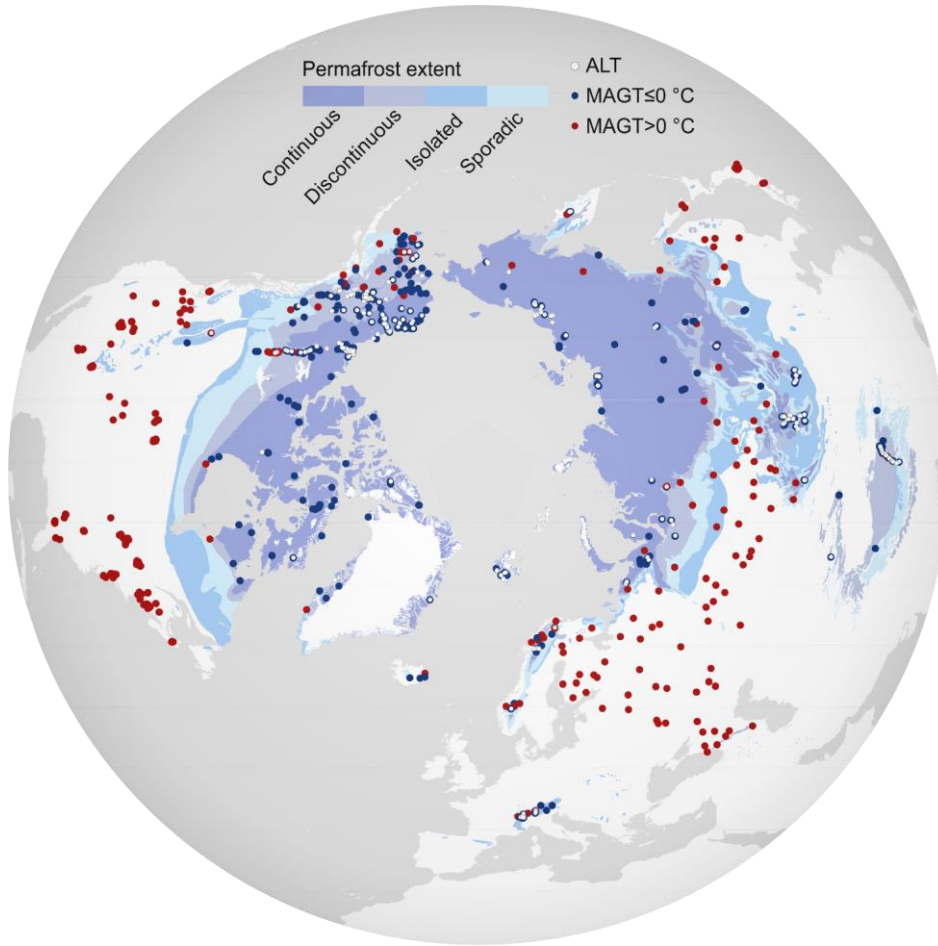


Figure 1: The observational network of the used mean annual ground temperature (MAGT) and active-layer thickness (ALT) across the circumpolar region. Blue symbols indicate the locations of boreholes where MAGT (averaged over the period 2000–2014) was at or below 0 °C and red symbols for those above 0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

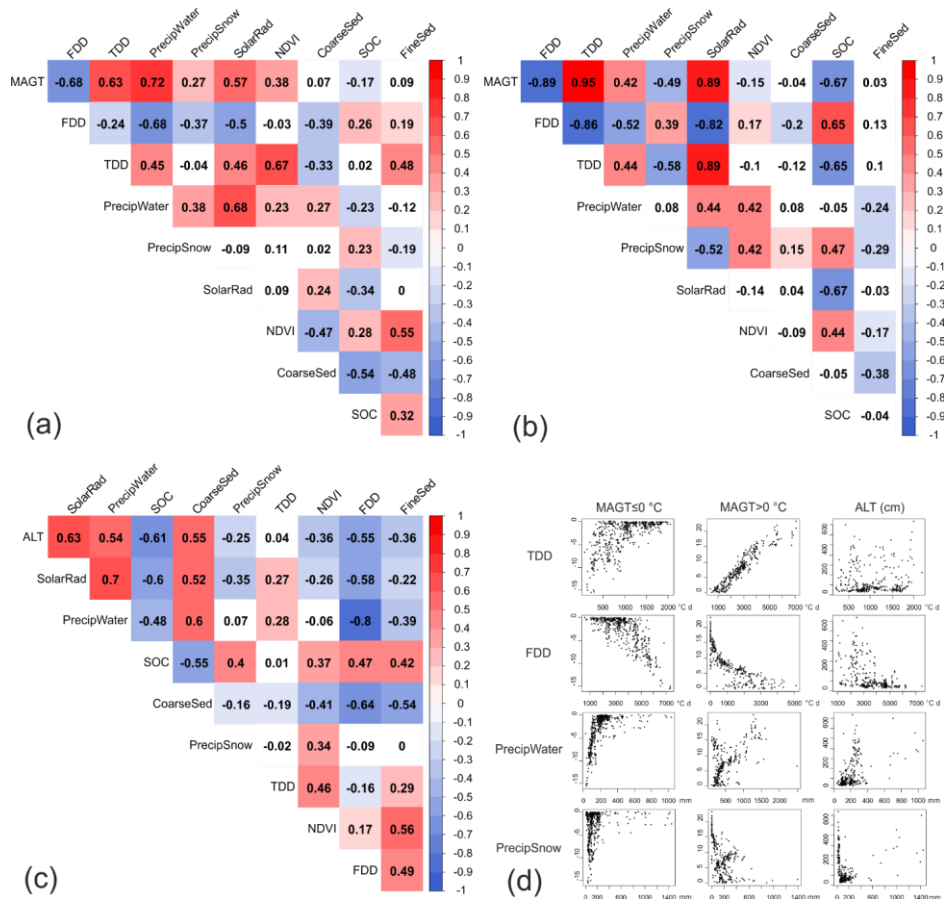


Figure 2: Spearman rank-order correlations between the predictor variables (see Sect. 2.2 for abbreviations) and MAGT ≤ 0 °C (mean annual ground temperature) (a), MAGT > 0 °C (b) and ALT (active-layer thickness) (c). Red hue stands for positive correlations, blue for negative, and white indicates non-significant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

Commented [A39]: RIC19 Figures 2a-c: one color legend probably is enough. Figure 2d: the units of TDD and FDD should be °C d.

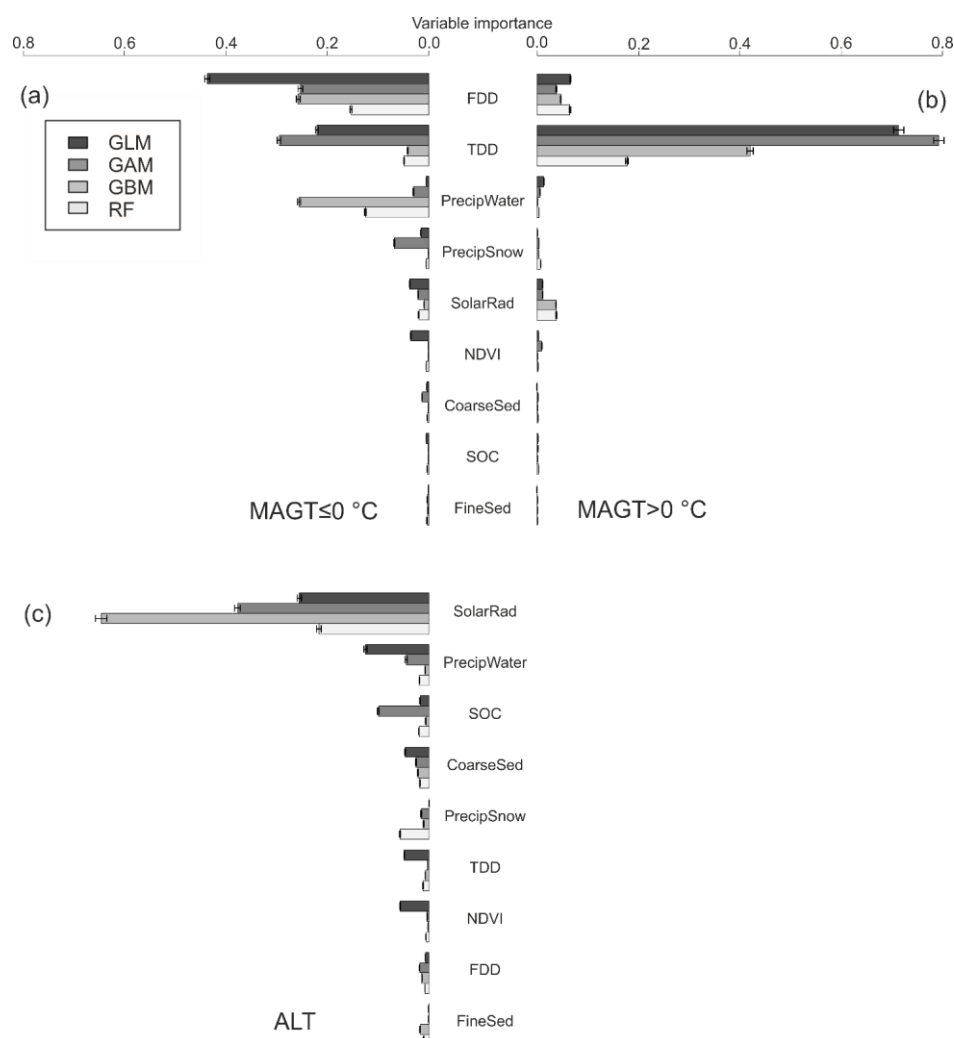


Figure 3: Variable importance values in MAGT₀ °C (mean annual ground temperature) (a) and MAGT>0 °C (b) datasets arranged in the descending order of four-model average in MAGT₀ °C conditions, and for ALT (active-layer thickness) (c), arranged likewise based on ALT results. The whiskers depict 95 % confidence 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.

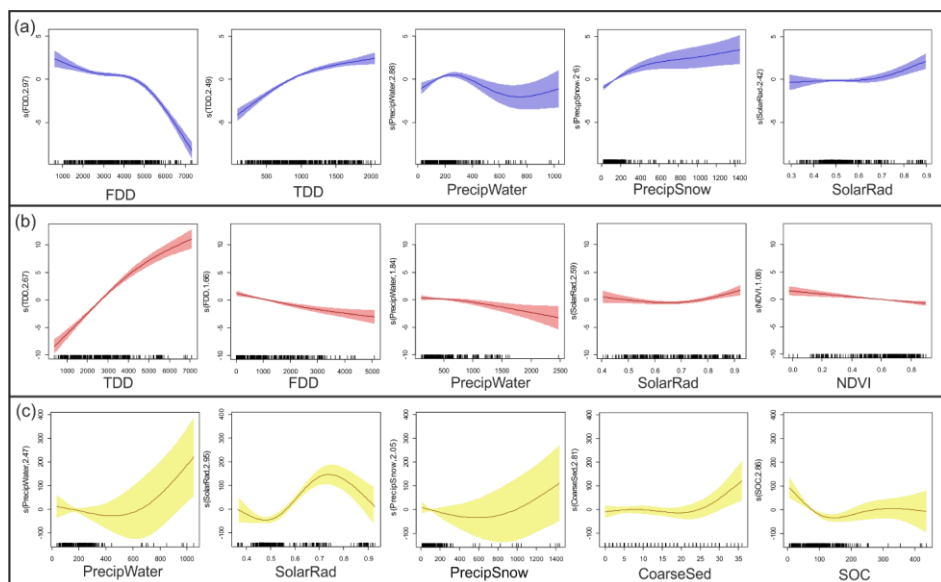


Figure 4: Response shapes of the five predictors with most contribution in $MAGT_{\leq 0} \text{ } ^\circ\text{C}$ (a) (mean annual ground temperature, blue curves), $MAGT_{>0} \text{ } ^\circ\text{C}$ (b) (red curves) and ALT (c) (active-layer thickness, yellow curves) datasets obtained from generalized 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.