

Answer to the reviewers comments on *Linking tundra vegetation, snow, soil temperature, and permafrost*

Inge Grünberg, Evan J. Wilcox, Simon Zwieback, Philip Marsh, Julia Boike

Anonymous Referee #2

We thank the anonymous referee #2 for his/her helpful and knowledgeable comments on our manuscript. Please find our answers to all specific points below in black after the original comments (in grey). We also attached the track-changed manuscript with new text in blue and text of the old version in red and small. We updated all figures as the reviewer #1 requested a change of colours. We also added some more details such as regression lines. We removed the old graphics from the track-changed version to limit the file size. The line numbers refer to the track-change version.

This paper uses two years of topsoil temperature, snow, and active layer data from six vegetation types within a heterogeneous Low Arctic landscape in the northwestern Canadian Arctic to evaluate the relationships among these variables – vegetation, snow, soil temperature, and active layer depth. With changes in arctic vegetation being readily observed, there needs to be a greater understanding of how vegetation influences snow dynamics, ground temperature, and ultimately active layer depth and permafrost. Several papers in the literature do exist on this topic, however, the results collectively are not incredibly clear and consistent, and more data and analyses are needed. With a soil temperature dataset as robust as the one from this study, there are unlimited ways to analyze the data, and everyone will have their own opinion on how best to do that. The analysis presented here is generally a fine one, and is informative, and therefore I will not give opinions on other ways in which the analysis could have been done, but rather will provide some constructive comments on the existing analysis.

The following are some general, more specific, and some minor editorial suggestions:

1) State the depth of the data loggers in the Abstract We added the information to the abstract (l. 6).

2) Line 28 Low Arctic is commonly capitalized, and change the “an” to “a” We removed the sentence in question for other reasons and corrected other occurrences of Low Arctic (l. 444, 449).

3) Line 37 You mention that tussock tundra is commonly found in depressions, which is not always my experience, and I’m not sure how widespread that it. Certainly not on the exposed hilltops, but more often I think that tussock tundra is found on mesic slopes, as opposed to more saturated lowland positions. We agree with the reviewer that tussock tundra can often be found on mesic slopes and added this information to the introduction (l. 48). At our site specifically, 95% of the tussock patches have a slope of less than 4°, which is by far the lowest value of all vegetation types (l. 116–117).

4) Line 40 should be “active layer thickness at the end of summer” Changed (l. 51)

5) **Line 88** “gasses” should be “grasses” Changed (l. 106)

6) **Lines 139-140** since you use “summer” here, I was wondering if you should define your seasons first. Also wondering if there is a better way of stating this – e.g. average topsoil temperature was more than 5 degrees C lower than air temperature. We changed the order of the paragraphs to first define the seasons before we use this definition. We also replaced the sentence as suggested (l. 159–165, 168).

7) **Lines 140-142** how were these values determined, i.e. the -5 and +7 degrees C differences? We decided to takes these thresholds based on the histogram in Figure A1. In case (b) (the average summer topsoil temperature was more than 5 °C colder than air temperature) the three excluded time series where really a lot different from all the others and all thresholds between -5 and –8 °C had the same effect. In case (c) (more than 5% of the single summer measurements were more than 7 °C above air temperature), the definition of the threshold was less clear and more subjective, also based on a close inspection of the time series. Other values would be possible but we think that we excluded the timeseries which were most prone to errors in this way.

8) **Line 148** Assuming that you smoothed the data prior to defining the seasons? Did smoothing remove all spikes in the data such that the winter and summer temperature thresholds yielded continuous seasons, i.e. were there any days within winter or summer that fell outside of the threshold temperatures? We did not do any additional smoothing despite the two steps mentioned: (1) average all (365) daily air temperatures for 20 years and (2) smooth using a 7-day moving window. As you can see in Figure A2, this removed most spikes and the resulting seasons were continuous. I suppose in many environments such a simple approach would not yield continuous seasons. In our case, the temperature rise between winter and summer and the temperature drop end of summer until winter are very steep. Therefore, the definition of the seasons is not very sensitive to the defined temperature thresholds. We found that seasons defined in this way suit the data and environment much more than the classical 3-month per season. Especially the winter is clearly longer than December to February.

9) **Lines 153-154** I understand how the slopes for fall and spring might work directionally as cooling and warming respectively, but I would imagine that the peak warm and cool days with fall somewhere in the middles of summer and winter respectively, and therefore the slopes would not be very informative for these seasons. Even if only a few cm below the soil surface, topsoil temperature generally lags behind air temperature, especially in winter under snow. Thus the coldest topsoil temperatures were observed in March, at the end of winter and the rate of cooling in winter is low but consistent and (we find) interesting. We agree that in summer (especially in the 2nd period), the warmest topsoil temperatures are not at the end of the season and the slope is less indicative and in some cases negative (when August is cold). We included the summer slope for consistency and prefer to keep it. However, we added an additional comment on negative summer slope values (l. 297–298).

10) **Lines 157-158** Would the day when temperatures first drop below 0.5 degrees C be the beginning of the freezing period in autumn? This should be the case. However, we did not observe a clear beginning of the freezing period as all timeseries

showed significant peaks (warm periods) after the first cold temperatures (Figure 5ab). The freezeback was not very clear for most sensors.

11) Line 168 remove the comma after “those” Done (l. 199)

12) Line 181 by “date of thawing” do you mean first date, end date, or both? The statement is true for both, start and end of thawing. We were mostly interested in the end of the thawing period (as in the sentence just before) and specified this now (l. 214).

13) Line 199 give the actual temperature ranges The actual mean October temperatures were -5.3°C and -1.0°C for the coldest and warmest location in the first period and -2.8°C and 0.2°C in the second period. We added these numbers to the manuscript (l. 234–236).

14) Lines 263-264 with regard to the relationship between October soil temperatures and active layer depth, I have a hard time believing that Oct. temperatures can influence active layer depth – more likely the other way around maybe? Absolutely, we agree. We replaced the misleading sentence (l. 325).

15) Figure 8 I’m not sure that this figure is very useful. If vegetation is influencing snow depth, than it’s very likely that snow depth in one year will be related to snow depth the next year. You might considering removing this. We agree that the former Figure 8 was not essential and moved it to the appendix (now Figure B2). We prefer to keep it in the manuscript because it supports our statement on wind redistribution in Section 3.2. Furthermore, the figure illustrates that the any model snow depth based on vegetation type will be limited by the substantial interannual variability.

16) Figure 7 you discuss these relationships a lot, but I don’t see any statistical analyses on them (with the exception of panels (a) and (f)). Are these significant relationships across and within vegetation types? Also, if these relationships are considered to be causal, then snow depth should be on the x-axis, as it is driving the other variables (again, except panels (a) and (f)). These relationships are all statistically significant ($p < 0.01$) and we added regression lines and correlation coefficients to Figure 7 for some (basic) statistical analysis. We also swapped the figure axis because we agree that snow depth is rather the driver than the response.

17) Figure 11 same as Figure 7 with regard to the statistical analyses (except panel (a)). Axes are fine in this figure as active layer depth is the assumed dependent variable. We added regression lines to Figure 10 (previously 11) in the case of significant ($p < 0.05$) relationships and correlation coefficients to the figure for some (basic) statistical analysis. As we discuss the differential relationships for different vegetation types in Section 4.4, we added additional panels with regression lines for lichen and dwarf shrubs and all other vegetation types combined.

18) Line 327 remove the word “temperature.” Done (l. -410)

19) Lines 332-334 examples of where relationships are being discussed with no statistical analyses The reviewer is right, we did not show statistical analysis within single vegetation types although we discuss them (in particular for winter

90 temperature – ALT, snow melt timing – ALT and positive degree days – ALT). We added the statistical analysis of these relationships for two groups of vegetation types: lichen and dwarf shrubs versus taller vegetation to the results Section 3.4 (l. 310–324) and Figure 10 (previously 11). We also expanded the discussion on this topic in Section 4.4 (l. 410–421).

95 **20)** Finally, with regard to the Discussion and Conclusions, the vegetation may indeed have an effect on active layer depth, through its effect on snowpack, as vegetation is effecting the snowpack, which is driving snowmelt and spring/summer temperature regimes. We agree that vegetation has an effect on active layer thickness or, at least, there is a correlation. As we describe in the results Section 3.4, vegetation explains 34% of the ALT variability (Table 2). We describe this effect as 'weak' even though it is statistically significant. We agree that this correlation is likely due to winter snow effects and added an additional comment to the discussion (l. 436).

Linking tundra vegetation, snow, soil temperature, and permafrost

Inge Grünberg¹, Evan J. Wilcox², Simon Zwieback³, Philip Marsh², and Julia Boike^{1,4}

¹Permafrost Research, Alfred-Wegener-Institut für Polar und Meeresforschung, Potsdam, Germany

²Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, ON, Canada

³Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, United States

⁴Humboldt-Universität zu Berlin, Berlin, Germany

Correspondence: I. Grünberg (inge.gruenberg@awi.de)

Abstract. Soil temperatures in permafrost regions are highly heterogeneous on small scales, in part due to variable snow and vegetation cover. Connections between vegetation and soil thermal dynamics are critical for estimating the vulnerability of permafrost to thaw with continued climate warming and vegetation changes. The interplay of complex biophysical processes results in a highly heterogeneous soil temperature distribution on small spatial scales. Moreover, the temperature distribution that results from the interplay of complex biophysical processes link between topsoil temperature and active layer thickness remains poorly constrained. Sixty-eight temperature loggers were installed at 1–3 cm depth to record the distribution of topsoil temperatures at the Trail Valley Creek study site in the Northwestern Canadian Arctic. The measurements were distributed across six different vegetation types characteristic for this landscape. Two years of topsoil temperature data were analysed statistically to identify temporal and spatial characteristics and their relationship to vegetation, snow cover, and active layer thickness. The mean annual topsoil temperature varied between -3.7°C and 0.1°C within a 1.2 km distance, with an approximate average across the landscape of -2.3°C in 2017 and -1.7°C in 2018. 0.5 km^2 . The observed variation can, to a large degree, be explained by variation in snow cover. Differences in height between vegetation types cause spatially variable snow depth during winter, leading to spatially variable snow melt timing in spring, causing pronounced differences in topsoil mean temperature and temperature variability during those time periods. Summer topsoil temperatures were quite similar below most vegetation types, and not consistently related to snow depth are strongly related with vegetation type and show complex associations with late-summer thaw depth. While cold winter soil temperature is associated with deep active layers in the following summer at lichen and dwarf shrub tundra, we observed the opposite beneath tall shrubs and tussocks. In contrast to winter observations, summer topsoil temperature is similar below all vegetation types with an average summer topsoil temperature difference of less than 1°C . Moreover, there is no significant relationship between summer soil temperature or cumulative positive degree days and active layer thickness at the end of August. The small-scale pattern of vegetation and its influence on snow cover height and snow melt governs the annual topsoil temperature in this permafrost-underlain landscape. Altogether, our results demonstrate the high spatial variability of topsoil temperature and the active layer thickness even within specific vegetation types. Given that vegetation type defines the direction of the relationship between topsoil temperature and active layer thickness in winter and summer, estimates of permafrost vulnerability based on remote sensing or model results will need to incorporate complex local feedback mechanisms of vegetation change and permafrost thaw.

25 1 Introduction

Arctic ecosystems are changing rapidly, with widespread reports of air temperature increase (IPCC, 2013), [shrinking snow cover](#) [\(?\)decreasing area and duration of snow cover \(AMAP, 2017\)](#), and warming and degrading permafrost (Biskaborn et al., 2019). Permafrost thaw [also](#) depends on local influences on the transfer of heat into the ground including [vegetation, hydrology, and soil physical properties](#). [Connections between vegetation and soil thermal dynamics are critical for estimating the vulnerability of permafrost to thaw with continued](#) [climate warming and vegetation changes, hydrology, and vegetation](#). Permafrost ecosystems are undergoing rapid vegetation change with increasing shrub abundance, cover, and biomass in many regions (Tape et al., 2006; Myers-Smith et al., 2011; Sturm et al., 2001b; McManus et al., 2012; Lantz et al., 2013; Frost and Epstein, 2014). Yet, permafrost models and remote-sensing-driven monitoring approaches are still limited in their representation of small-scale spatial variability of snow and vegetation (Langer et al., 2013; Zhang et al., 2014; Park et al., 2016).

35 The interaction of vegetation and active layer thickness is very complex if the energy balance and soil properties are considered simultaneously (Loranty et al., 2018). [Observational evidence indicates that increased shrub cover reduces summer soil temperatures and decreases seasonal permafrost thaw depths \(Anisimov et al., 2002; Walker et al., 2003, 2008; Blok et al., 2010\), but tall shrub expansion in the tundra warms soils on annual timescales \(Loranty and Goetz, 2012\).](#)

[? found the largest offset between air and soil temperature in the low Arctic at an mean annual air temperature of roughly \$-10^{\circ}\text{C}\$ due to snow cover and vegetation variability.](#)

40 In winter, snow insulates the soil from the cold air temperature. The resulting difference between the soil and air temperature is important for the ground thermal regime and thus permafrost temperatures (Zhang, 2005). [This temperature difference varies widely in space, and how faithfully this parameter is represented differs widely in different land surface models \(?\). The insulating effect of snow is driven by snow depth, texture, and density, which are affected by snow redistribution and the formation of depth hoar \(?Pomeroy et al., 1997\).](#) Vegetation affects snow depth and density because tall shrubs trap snow (Pomeroy et al., 2006; Sweet et al., 2014); also some vegetation types preferentially grow in locations with deeper

45 snow cover in order to be protected from cold air temperatures [\(Sturm et al., 2005b\)and profit from additional moisture in spring \(Grippa et al., 2005; Sturm et al., 2005b\)](#). This association leads to warm soil temperature in winter below tall shrubs (Lantz et al., 2009; Frost et al., 2018) and in tussock tundra [which is commonly found in depressions \(and experiences found in poorly drained areas in our study region \(with long freeze-back periods\), but also occurs on mesic slopes elsewhere;](#) in contrast, lichen tundra is usually associated with wind exposed hill tops and ridges which accumulate the least snow (Pomeroy et al., 1997; Burn and

50 Kokelj, 2009).

Snow melt timing is considered [to be](#) one of the most important drivers of active layer thickness [at the](#) end of summer (Chapin et al., 2005; Wilcox et al., 2019). However, in certain areas the strong association may also be an artefact of the confounding relationship with other variables which strongly affect the active layer thickness. For instance, wind-blown ridges with thin snow cover and hence early [snow melt snowmelt](#) also tend to store less organic matter, and are therefore less insulating

55 [.](#) (Michaelson et al., 1996) than more sheltered locations where more snow is deposited. Also, depressions and tall shrub sites that accumulate deep snow cover and exhibit late [snow melt snowmelt](#) are expected to be moister and to accumulate more peat and organic soil as compared to wind-exposed ridges [\(Walker et al., 2008\)\(Walker et al., 2008; Pajunen et al., 2011\)](#). Therefore, the thicker moss and organic layer at tussock and tall shrub sites may be the factor that helps to keep the active layer cooler and

shallower, rather than the late snow melt (Walker et al., 2008; Frost et al., 2013; Loranty et al., 2018). snowmelt (Walker et al., 2008; Frost et al., 2013; Loranty et al., 2018).

Observational evidence indicates that increased shrub cover reduces summer soil temperatures and decreases seasonal permafrost thaw depths (Anisimov et al., 2002; Walker et al., 2003, 2008; Blok et al., 2010), but tall shrub expansion in the tundra warms soils on annual timescales (Loranty and Goetz, 2012). Summer surface temperature is influenced by reduced by tall vegetation through radiation shading and rainfall interception and evaporation (Loranty and Goetz, 2012; Zwieback et al., 2019). Tall vegetation cover is more closely coupled to increased soil organic matter (Pajunen et al., 2011) and decreased soil moisture during summer. These factors generally lead to reduced evapotranspiration (Loranty and Goetz, 2012; Zwieback et al., 2019). Increased evapotranspiration may reduce summer soil warming below tall shrubs (Frost et al., 2018) as less energy is available below the canopy and the soil tends to be drier and is thus more insulating. as it is an energy sink and decreases soil moisture and thus soil thermal conductivity during summer (Fisher et al., 2016). While these factors lead to reduced summer warming underneath shrubs, the magnitude and even the sign of this association varies in space and time. To exploit vegetation cover as a proxy for permafrost soil temperatures in summer, detailed observations of soil temperature and vegetation cover are required. The influence of all these factors on active layer thickness is complex and spatially variable, highlighting the difficulty of attributing active layer thickness trends to any one particular variable.

This study assesses This study quantifies the complex relationship between vegetation cover, snow, topsoil temperature and active layer thickness and explores the local seasonal variability of the three four components. We hypothesise that in winter the dependence of topsoil temperatures on vegetation is largely shaped by the association of vegetation with snow depth, owing to the strong insulating effect of snow. Moreover, we expect that in summer tall vegetation cools the soil through shading and evapotranspiration. We also hypothesise that the timing of snow melt and accumulation will be snowmelt is a dominant control on topsoil temperature during spring and autumn, with snow melt being largely affected by interactions between vegetation and snow depth.

active layer thickness. Moreover, we expect that active layer thickness is reduced by tall vegetation through shading in summer. In the current study, we aim to quantify the topsoil temperature variability and elucidate the correlation between such variability and vegetation cover, thus improving improve our understanding of the feedback mechanisms in the complex permafrost–vegetation–atmosphere system across the four seasons. The results provide a basis for upscaling and modelling attempts and assess for assessing the potential of vegetation remote sensing for permafrost applications.

2 Methods

2.1 Field site, soil, and vegetation

The Trail Valley Creek research site is located at the tree line in the tundra-taiga transition zone 45 km north of Inuvik, Northwest Territories, Canada, east of the Mackenzie Delta (133.499°E133.499°W, 68.742°N, Figure 1a). The mean annual air temperature in the 1999 – 2018 period was −7.9 °C (Environment and Climate Change Canada, 2019). During this 20-year period, it rose by 1.1 °C per decade and the strongest warming trend was observed in May with an increase of 2.8 °C per decade (Environment and Climate Change Canada, 2019). Although the site is only 70 km south of the Arctic Ocean, the climate is continental and summers can be quite warm (Figure B1). The study site is underlain by continuous permafrost

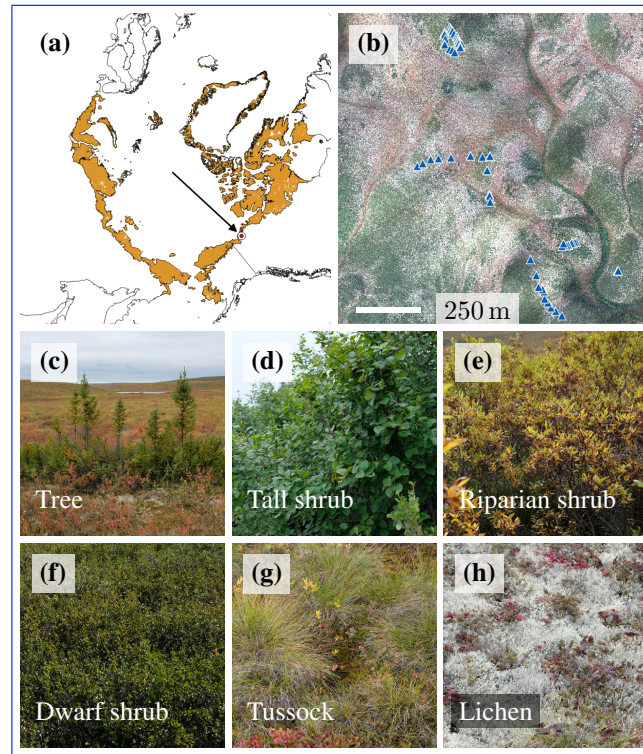


Figure 1. (a) Location of the Trail Valley Creek research station, Northwest Territories, Canada and Arctic tundra extent in orange colour (data from Walker et al., 2005), (b) airborne orthophoto (Polar 5 airplane, MACS camera, 08/2018) of the site including topsoil temperature measurement locations, (c–h) six vegetation types used in this study.

100–150 m thick (Marsh et al., 2008) and is characterised by an active layer 25–100 cm deep at the end of summer. The catchment is dominated by mineral-earth hummocks which have a 5 cm thick organic layer and are underlain by fine grained material composed of roughly one third sand, one third silt, and one third clay (Quinton et al., 2000). Between the hummocks is a several decimeters thick peat layer, known as the inter-hummock zone (Quinton et al., 2000). The permafrost is ice-rich and thus susceptible to warming and thawing (Burn and Kokelj, 2009).

Gently rolling hills structure the lowland landscape (Marsh et al., 2010) and provide habitats for different tundra vegetation types and, in favourable locations, forest patches. The vegetation can be divided into six main types (Figure 1c–h) based on the classification by Walker et al. (2005):

- 1) **Trees** can be found in river channels and on adjacent slopes as well as in isolated patches. While trees growing in the forest patches can reach 10 m height, trees in isolated patches are usually 0.5–2.5 m tall (Anders et al., 2018)(Anders et al., 2018; Antonova et al., 2019). The tree species are white and black spruce (*Picea glauca* and *Picea mariana*) (Palmer et al., 2012). Forest patches cover roughly 2% of the landscape (Grünberg and Boike, 2019).

- 2) **Tall shrub** tundra is characterised by sparse patches of green alder (*Alnus alnobetula*) (Street et al., 2018); tall shrubs on
105 hill slopes grow 3–5 m apart. While the alder shrubs are up to 2 m tall, the area between the shrubs is covered by shorter
shrub species such as dwarf birch (*Betula glandulosa*) and by ~~gasses~~ **grasses** and sedges. Tall shrubs (class S2 (low-shrub
tundra) in Walker et al. (2005)) cover at least 11% of the wider Trail Valley Creek area (Grünberg and Boike, 2019).
- 3) **Riparian shrub** tundra can be found next to streams and at water tracks. Willow (*Salix*) species dominate these areas and
grow up to 2.1 m tall. Additional shrub species include green alder and dwarf birch. Riparian shrubs (class S2 (low-shrub
110 tundra) in Walker et al. (2005)) cover about 14% of the landscape (Grünberg and Boike, 2019).
- 4) **Dwarf shrub** tundra is one of the most abundant vegetation types growing on hill tops and slopes. In general, dwarf birch
forms a dense canopy 20–50 cm high; in extreme cases it can reach 1 m. Dwarf birch is often complemented by shorter
dwarf shrubs such as Labrador tea (*Ledum palustre*) and mountain cranberry (*Vaccinium vitis-idaea*), forbs (e.g. sweet
coltsfoot, *Petasites frigidus*), graminoids, mosses, and lichen (Street et al., 2018). Dwarf shrubs (class S1 (erect dwarf-
115 shrub tundra) in Walker et al. (2005)) cover roughly 24% of the landscape (Grünberg and Boike, 2019).
- 5) **Tussock** tundra is mostly located in flat, poorly drained areas **in our study region. At our site specifically, 95% of the
tussock patches have a slope of less than 4°, which is by far the lowest value of all vegetation types.** Tussock-
forming sedges such as cotton grasses (*Eriophorum*) and *Carex* species dominate. However, a variety of dwarf shrubs
such as dwarf birch, willows, Labrador tea, mountain cranberry, bilberry (*Vaccinium uliginosum*), crowberry (*Empetrum*
120 *nigrum*), bearberry (*Arctostaphylos uva-ursi*), and cloudberry (*Rubus chamaemorus*) are also present and mosses can be
found between the tussocks. The vegetation height is 10–30 cm in general. Tussock tundra (class G4 (tussock-sedge,
dwarf-shrub, moss tundra) in Walker et al. (2005)) is the most abundant vegetation type in the study area with roughly
37% coverage (Grünberg and Boike, 2019).
- 6) **Lichen** tundra is dominated by lichen and dwarf shrubs 3–15 cm high, including mostly Labrador tea, mountain cranberry,
125 crowberry, bearberry, and cloudberry. Some graminoids may also be present. Lichen tundra (class S1 (erect dwarf-shrub
tundra) in Walker et al. (2005)) covers about 10% of the study area (Grünberg and Boike, 2019).

The approximate current spatial distribution of the six vegetation types and water is shown in Figure 2. The extent of tall shrub
cover has expanded in the past and is likely to increase in the future at the Trail Valley Creek study site (MacKay, 1995; Lantz
et al., 2010).

130 2.2 Field measurements

Topsoil temperature was measured for two years at 68 locations distributed below different vegetation types at a maximum
distance of 1200 m between the sensors in the study area (Figure 1b). We used iButton® temperature loggers (DS1922L) at
11 bit (0.0625 °C) resolution with an accuracy of 0.5 °C provided by the manufacturer. The sensors are 17 mm in diameter and
6 mm thick. Before deployment, we coated them with plastic to ensure water resistance. We tested all sensors in an ice bath

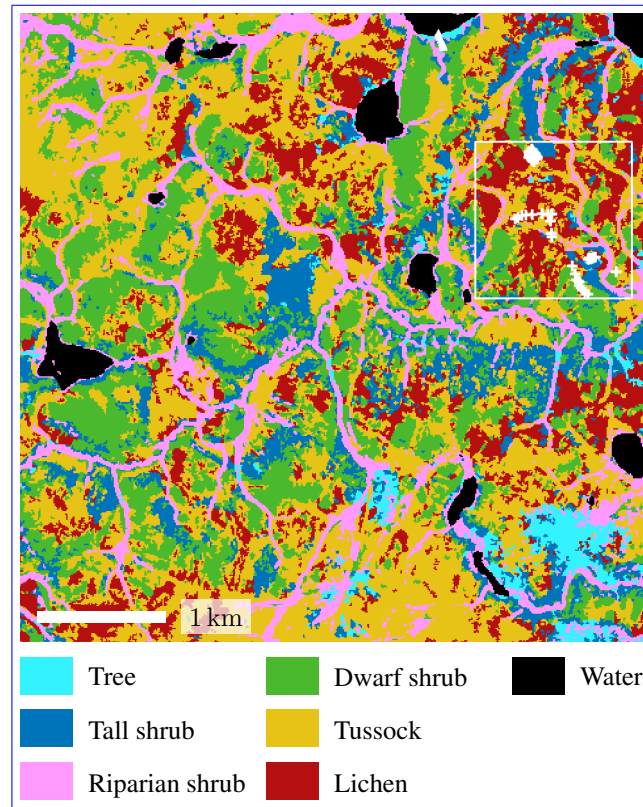


Figure 2. Vegetation map of the study region using the vegetation types as described above (Grünberg and Boike, 2019); the map is based on airborne orthophotos and vegetation height derived from airborne laser scanning (Anders et al., 2018); the white square indicates the study site extent including all sensor locations (white plus signs) as shown in Figure 1b.

135 and verified the temperatures measured at the zero curtain. As all sensors had zero-curtain temperatures between -0.12°C and 0.30°C , we assume that the accuracy provided by the manufacturer is realistic.

We installed all temperature loggers as close as possible to the surface (soil, moss, or lichen) but deep enough to be protected from solar radiation (typically 1–3 cm deep). The measurement interval was every three hours, the measurement periods were 27 August 2016, 17:00 (local time) to 03 September 2017, 08:00 and 04 September 2017, 05:00 to 22 August 2018, 14:00. In
 140 between the two measurement periods, the sensors had to be removed in order to obtain data records and were reinstalled at the same positions. We peeled off the coating, read out the data, and used tape as the new coating, as the plastic could not be reapplied in the field setting. This was done in the field to assure that each sensor was reinstalled as close as possible to the original location. However, the coating was different and possibly the micro-location and the contact to the surrounding moss, lichen or soil also differed slightly. Thus, we treated the two periods separately in our statistical analysis.

145 We classified the vegetation type into one of the six categories described above at each topsoil temperature location based on observations in the field and pictures taken while installing and removing the sensors. Maximum vegetation height was measured from 04–06 August 2019 within 30 cm around the sensor position.

Depth to the frozen soil was measured on 22 and 23 August 2018 three times around each topsoil temperature location within a 30 cm radius. We averaged the three values before continuing with the statistical analysis. Thawing of the soil potentially
150 continues until freeze-back starts in October; thus, maximum thaw depths were not recorded. Snow depth was measured on 30 April 2017 approximately at the topsoil temperature locations based on a hand-held GPS because the flags marking each location were buried below the snow. In 2018, snow depth was measured by calculating the difference between a digital elevation model (DEM) of the snow and a DEM of the bare ground. The snow DEM was created using structure from motion photogrammetry in the software Pix4Dmapper (Pix4D SA, 2019), using images taken by an eBee Plus RTK at 3.5 cm/pixel
155 resolution on 22 April 2018 (Mann, 2018). The 1 m resolution bare ground DEM was created using airborne LiDAR acquired in 2008 (Hopkinson et al., 2009). The resulting 1 m resolution snow depth raster was calibrated using 1370 Magnaprobe (Sturm and Holmgren, 2018) snow depth measurements taken between 19 and 25 April 2018.

2.3 Data analysis

We analysed the topsoil temperature data separately for the four seasons. The definition of seasons used in our statistical
160 analysis is based on mean daily air temperatures of the last 20 years (1999–2018) at Trail Valley Creek (Environment and Climate Change Canada, 2019). To obtain a complete 20-year record, we gapfilled the Trail Valley Creek data using a piecewise linear regression with data from the climate stations in Inuvik, 45 km further south. Furthermore, we smoothed the average annual cycle using a 7-day moving window (Figure A2). We defined winter as all days with average air temperature below -15°C (06 November - 10 April) while summer was defined as air temperature above 8°C on average
165 (10 June - 25 August). The periods in-between were defined as spring and autumn (Figure A2).

Before analysis, we checked the quality of all time series data during the two measurement periods and removed the series if (a) the data record had more than 10% data gaps (4 series), (b) the mean deviation of topsoil temperature minus air temperature in summer was less than -5°C average summer topsoil temperature was more than 5°C colder than air temperature indicating that the sensor was either buried too deep and affected by the permafrost or affected by running water (3 series), or (c) more than 5% of the
170 single summer measurements were more than 7°C above air temperature indicating additional sensor warming by direct solar radiation (8 series) (Figure A1). We used air temperature measurements by Environment and Climate Change Canada (2019) at Trail Valley Creek for this comparison. The number of remaining data series in each measurement period per vegetation type is listed in Table 1.

The definition of seasons used in our statistical analysis is based on mean daily air temperatures of the last 20 years (1999–2018) at Trail Valley Creek (Environment and Climate
175 Change Canada, 2019). To obtain a complete 20-year record, we gapfilled the Trail Valley Creek data using a piecewise linear regression with data from the climate stations in Inuvik, 45 km further south. Furthermore, we smoothed the average annual cycle using a 7-day moving window (Figure A2). We define winter as all days with average air temperature below -15°C (06 November - 10 April) while summer is defined as air temperature above 8°C on average (10 June - 25 August). The periods in-between are defined as spring and autumn (Figure A2).

Table 1. Number of data series per vegetation type in each measurement period; period 1: 27 August 2016, 17:00 (local time) to 03 September 2017, 08:00 and period 2: 04 September 2017, 05:00 to 22 August 2018, 14:00.

Vegetation type	Number of data series	
	Period 1	Period 2
Tree	3	3
Tall shrub	17	15
Riparian shrub	2	2
Dwarf shrub	15	17
Tussock	14	14
Lichen	10	9
Total	61	60

We calculated a variety of different characteristics for each topsoil temperature series, namely (I) the mean value for the whole year, each season, and each month, (II) the range of all three hourly values between the 10th and the 90th percentile for the whole year, each season, and each month, (III) the slope of a linear regression of all daily average values within each season, i.e. the rate of warming or cooling, (IV) the cumulative sum of positive degree days from the beginning of the melt season until the end of August, (V) the day of the year when the soil temperature first rose above -0.5°C which indicates the beginning of the thawing period, (VI) the day of the year when the soil temperature first rose above 0.5°C which indicates the end of the thawing period, and (VII) the day of the year when the soil temperature first drops below -0.5°C which indicates the end of the freezing period in autumn. We used -0.5°C and 0.5°C as thresholds instead of 0°C to account for sensor uncertainty. We used Python 3.6 to analyse the topsoil temperature series. In boxplots, we always show the absolute minimum and maximum as whiskers, the 25th and 75th percentile as the box, and the median as a line within the box.

In terms of statistical analysis, we [calculated used linear models \(lm in R\) to calculate](#) Pearson’s correlation coefficients [and linear regressions](#) for all numerical variables [and to determine whether the variables were significantly related at \$\alpha = 0.05\$. In a first step, we used data of all vegetation types. In the second step, we split the data into two subsets, one containing the upland vegetation types *Lichen tundra* and *Dwarf shrub tundra* and one containing all other vegetation types.](#) To assess the relationship of vegetation type to topsoil temperature characteristics, active layer thickness, and snow depth, we used a linear model (lm in R) to estimate the adjusted R^2 and the fraction of variance explained by vegetation type. Prior to the analysis, we excluded the vegetation types ‘tree’ and ‘riparian shrub’, as we do not have enough measurement series for these types. We assessed the impact of vegetation type on topsoil temperature characteristics based on all data series from both measurement periods. By analysing the two periods separately in the statistical model we accounted for the systematic differences between the years. For example, the summer of 2017 was warmer and started earlier than the summer of 2018. When we were interested in the impact of vegetation type on active layer thickness and snow depth, we used all sensor locations, even those , for which

200 we removed the temperature record, for example due to missing data. Results which were not significant at a level of 0.05 are shown in grey. We used R version 3.4 for all statistical analyses.

3 Results

We found a complex relationship complex spatial relationships between the different topsoil temperature characteristics, snow depth, active layer thickness, and vegetation in space. In general, the temperatures correlate well for all mean topsoil temperatures of the months
205 between December and April were strongly correlated (Figures 3 and 4). This implies that locations with relatively cold December topsoil temperatures were generally still colder than average in April. Locations which are were colder in winter correspond corresponded to warmer topsoil temperatures in May; however, the correlation of May temperatures with winter temperatures is was much stronger for the first period (September 2016 – August 2017) than for the second (September 2017 – August 2018). The summer temperatures between June and September are were also highly correlated. In the first period,
210 November topsoil temperature correlates correlated well with October values and thus belongs belonged to autumn, while November correlates correlated more strongly with the winter months in the second period. Due to the long winter, the mean annual topsoil temperature correlates correlated strongly with the topsoil temperature of the winter months, while it is was almost uncorrelated with the summer topsoil temperature. The end date of the spring thawing period is was strongly related to winter temperatures, snow depth and active layer thickness. Contrary to this, the date of thawing is not end of thawing was not significantly
215 related to summer topsoil temperature (Figures 3 and 4).

The annual mean topsoil temperature recorded by all single sensors varies varied between -3.7°C and -0.8°C in the first period and between -3.7°C and 0.1°C in the second period. In both periods, we find found both the warmest and the coldest values in tussock tundra. On average The substantial variability within single types contributed to the low fraction of variance explained by vegetation (Table 2). If all locations within each vegetation type were averaged, lichen tundra has had the
220 coldest topsoil temperature with -2.6°C and -2.3°C in the first and second period, respectively. The warmest average topsoil temperature of -2.0°C and -1.3°C in the first and second period were measured below tall shrubs. If we consider considered the approximate landscape fractions of each vegetation type (Section 2.1), we estimate estimated a mean annual topsoil temperature of -2.3°C and -1.7°C in the first and second period, respectively.

3.1 Soil temperature and vegetation in autumn

225 The two years 2016 and 2017 had different meteorological conditions in autumn. While air temperature dropped gradually to -7°C before the first snowfall in 2016 (Figure B1a), daily mean air temperature had only dropped to 0°C by the date of the start of the snow accumulation in autumn 2017. Thus, the topsoil was significantly cooler in October 2016 as compared to 2017 (Figure 5d).

Autumn topsoil temperatures and cooling rates are were not significantly related to vegetation type (Figure 5a–d, Table 2).
230 The same is was true for the start of the frozen period, which is was almost identical at most sensor locations independent of vegetation type (Figure 5e). However, we observed considerable variability in the mean temperature within each vegeta-

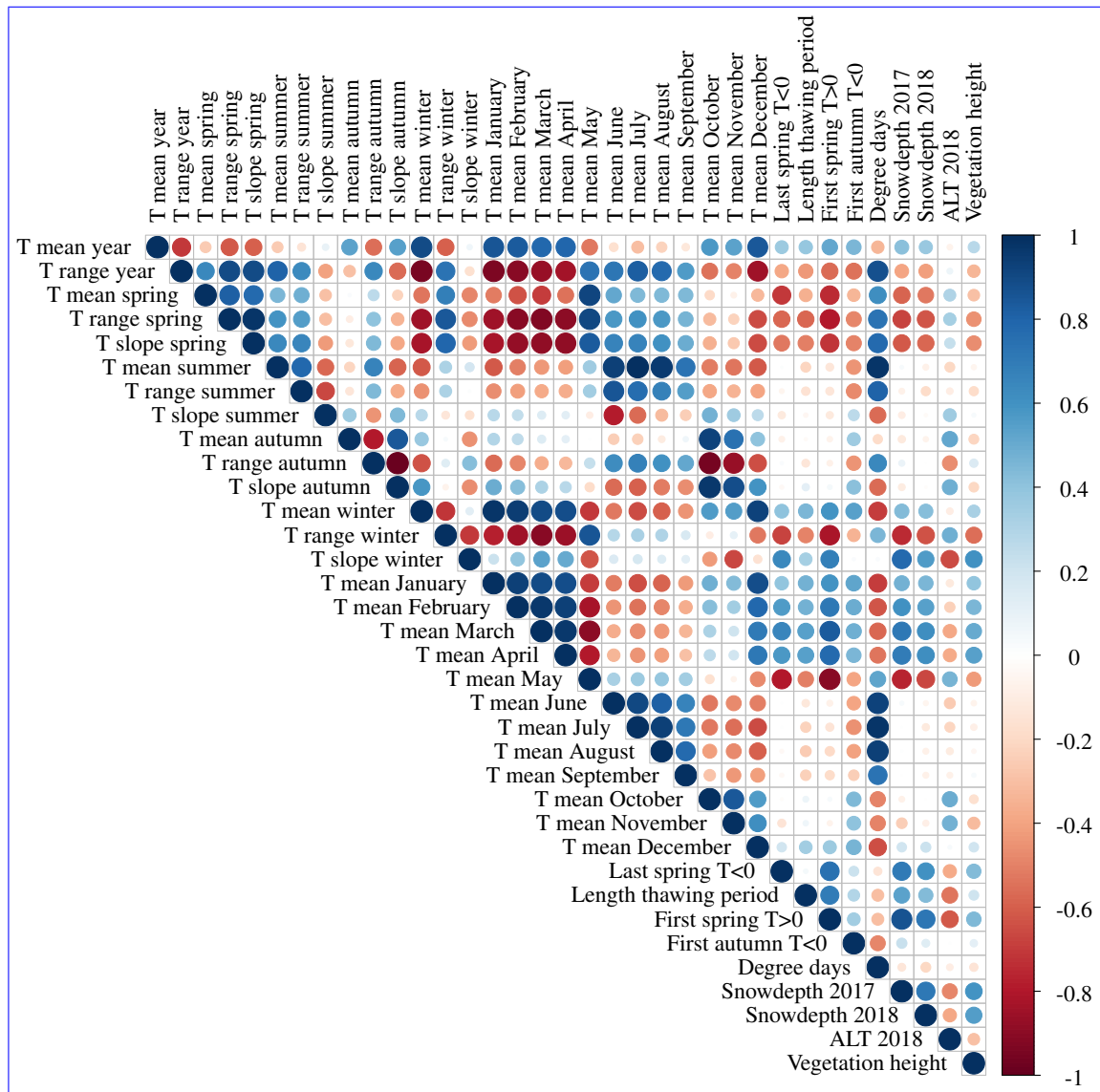


Figure 3. Pearson's correlation coefficients (R) of all topsoil temperature characteristics ($^{\circ}\text{C}$), active layer thickness (cm), and snow depth (cm) in the first period (September 2016 to August 2017).

tion type, at the landscape level, and between the different years. Considering the complete autumn season (26 August – 05 November), the mean autumn temperatures vary varied between -0.9°C and 1.2°C in 2016 and between 0.3°C and 1.7°C in 2017. For October only, the range of mean topsoil temperatures was even higher, with a difference of 4.3°C and 3.0°C between between -5.3°C and -1.0°C for the coldest and the warmest locations in 2016 and 2017, respectively the first period and between -2.8°C and 0.2°C in the second period (Figure 5d). Similar differences can be observed in the cooling rates, which varied most

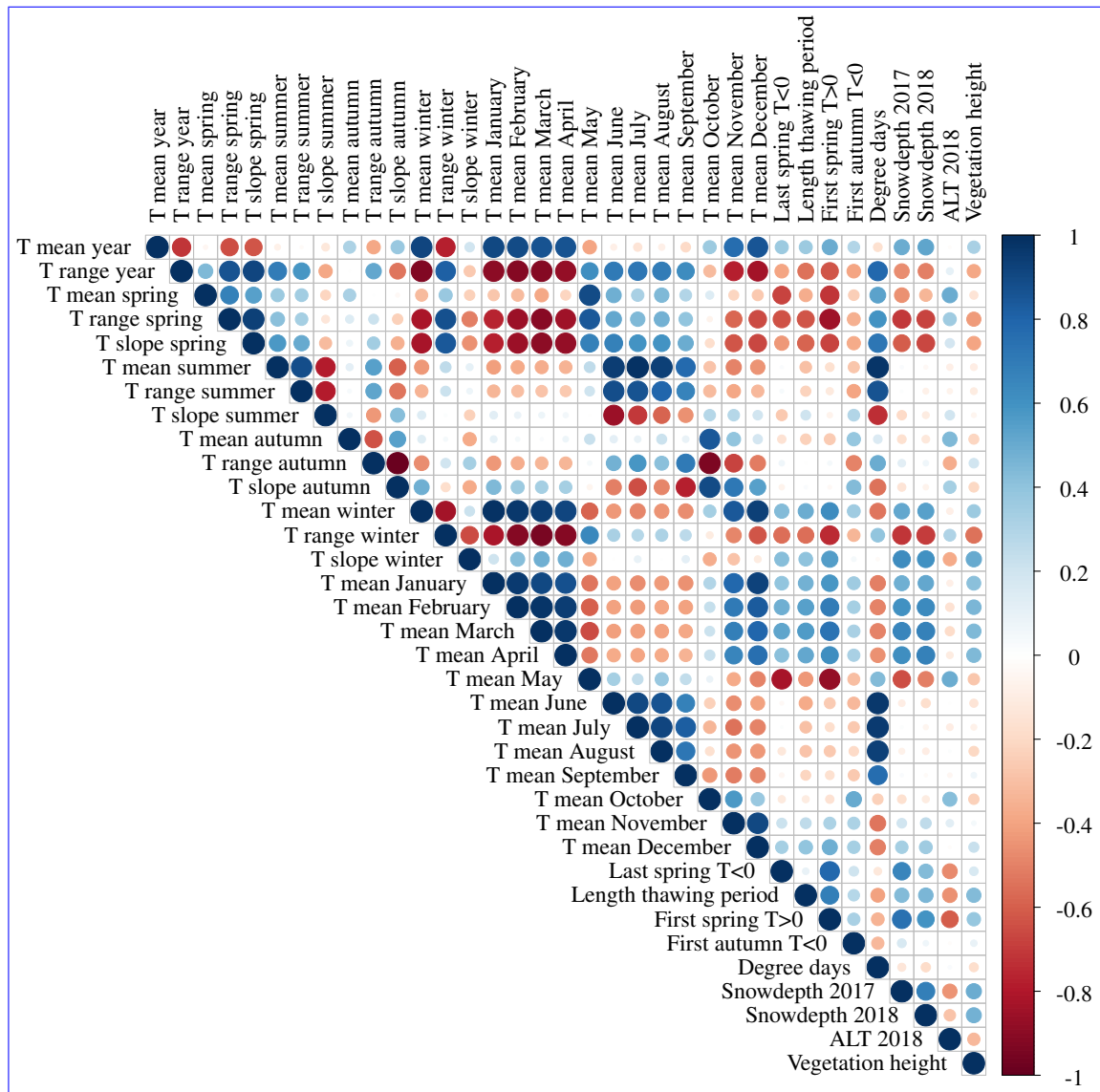


Figure 4. Pearson's correlation coefficients (R) of all topsoil temperature characteristics ($^{\circ}\text{C}$), active layer thickness (cm), and snow depth (cm) in the second period (September 2017 to August 2018).

strongly within tussock tundra and tall shrubs. Some locations within these two types cool cooled down more than twice as fast as other locations (Figure 5c).

Relationship of vegetation and topsoil temperature characteristics, active layer thickness, snow depth, and vegetation height expressed by the fraction of variance explained by vegetation type in a statistical model ($\text{lm}(\text{response} \sim \text{period} + \text{vegetation type})$) and the adjusted R^2 ; complete data set accounting for the measurement period of topsoil temperature first; results which are not significant at a level of 0.05 are shown in grey.

Table 2. Relationship of vegetation and topsoil temperature (T) characteristics, active layer thickness, snow depth, and vegetation height expressed by the fraction of variance explained by vegetation type in a statistical model (lm(response ~ period + vegetation type)) and the adjusted R²; complete data set accounting for the measurement period of topsoil temperature first; results which are not significant at a level of 0.05 are shown in grey.

Response	Fraction of variance	Adjusted R ²
Mean annual T (°C)	0.125	0.25
Date of first T>0 °C	0.548	0.55
Cumulative degree days (°C)	0.071	0.56
Mean T May (°C)	0.543	0.53
Mean T July (°C)	0.118	0.10
Mean T October (°C)	0.035	0.51
Mean T March (°C)	0.355	0.56
T slope spring (°C/day)	0.327	0.40
T slope summer (°C/day)	0.058	0.51
T slope autumn (°C/day)	0.053	0.09
T slope winter (°C/day)	0.432	0.56
Active layer thickness 2018 (cm)	0.342	0.31
Snow depth 2017 (cm)	0.699	0.68
Snow depth 2018 (cm)	0.584	0.56
Vegetation height (cm)	0.427	0.40

Response Fraction of variance Adjusted R² Mean annual T (°C) 0.125 0.25 Date of first T>0 °C 0.548 0.55 Cumulative degree days (°C) 0.071 0.56 Mean T May (°C) 0.543 0.53 Mean T July (°C) 0.118 0.10 Mean T October (°C) 0.035 0.51 Mean T March (°C) 0.355 0.56 T slope spring (°C/day) 0.327 0.40 T slope summer (°C/day) 0.058 0.51 T slope autumn (°C/day) 0.053 0.09 T slope winter (°C/day) 0.432 0.56 Active layer thickness 2018 (cm) 0.342 0.31 Snow depth 2017 (cm) 0.699 0.68 Snow depth 2018 (cm) 0.584 0.56 Vegetation height (cm) 0.427 0.40

3.2 Soil temperature, snow, and vegetation in winter

There were significant differences in soil temperature between the two winter seasons (06 November - 10 April). Average topsoil temperatures were roughly 2 °C colder beneath all vegetation types in the winter 2016/2017 as compared to the following year. This observation agrees well with the difference in mean winter air temperature of −20.3 °C and −18.2 °C in the first and second period, respectively (Figure B1a). The extremely cold December of 2016 (6.5 °C colder than in the second period) led to a much faster soil cooling in the first winter as compared to the second (Figure B1a).

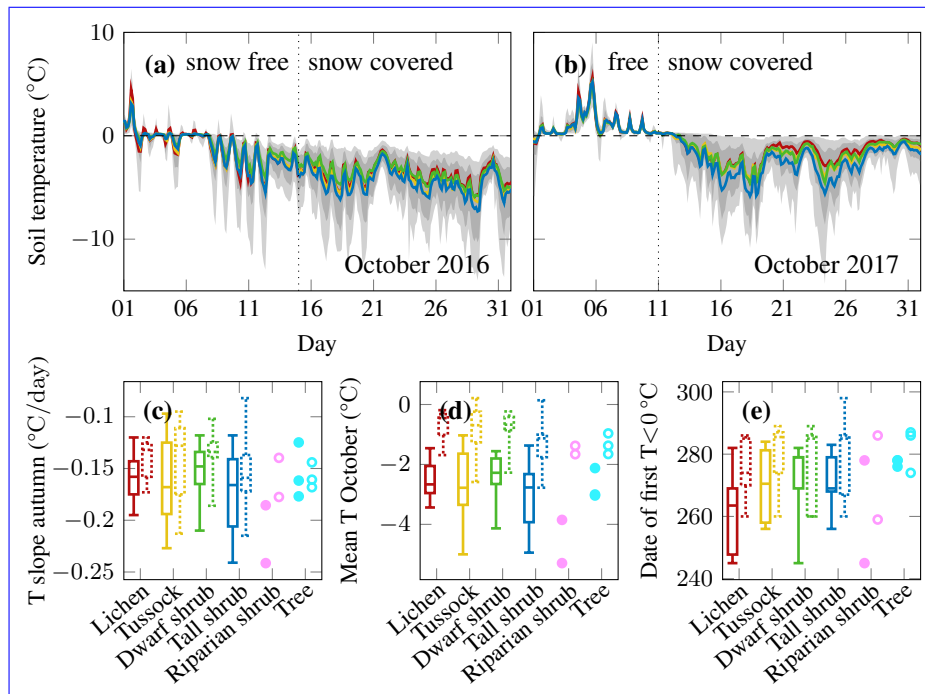


Figure 5. Topsoil temperature series of (a) October 2016 and (b) October 2017 representing autumn of the two different measurement periods; mean of all measurements below four different vegetation types in colour, the range of all single sensors in light grey and the range of all sensors between the 10th and 90th percentile in darker grey; the beginning of snow accumulation was derived from the Trail Valley Creek weather station albedo data; boxplots of all measurements per vegetation type with boxes of the first period left and the second period right and dotted; for riparian shrubs and trees all single observations are shown with filled symbols for the first period and open symbols for the second; (c) rate of cooling in autumn; (d) mean October topsoil temperature; (e) date when the freezing is completed.

There **is was** a strong relationship between vegetation type and topsoil temperature in winter. Topsoil under tall shrub tundra **stays stayed** warmest, followed by topsoil beneath tussock, dwarf shrub, and lichen tundra (Figure 6). Vegetation type **explains explained** 36% of the topsoil temperature variations in the coldest month (March) in a single year and 43% of the cooling rate during winter (Table 2). The coldest mean temperatures **are were** associated with the highest temperature variations below lichen tundra (Figure 6).

Snow depth strongly **mediates mediated** the association between vegetation type and winter soil temperatures. Different vegetation types **show showed** characteristic snow depth values (Figure 7a, f6e). The deepest snow cover **is was** associated with tall shrubs, followed by tussock tundra and dwarf shrubs while lichen tundra **is was** characterised by the shallowest snow cover. Vegetation **explains explained** 70% and 58% of the observed snow depth variability in 2017 and 2018, respectively (Table 2). The predictability of snow depth from vegetation type is limited by the differences in snow cover in different years. For example, the snow depth at the end of April 2017 reached higher maximum and lower minimum values as compared

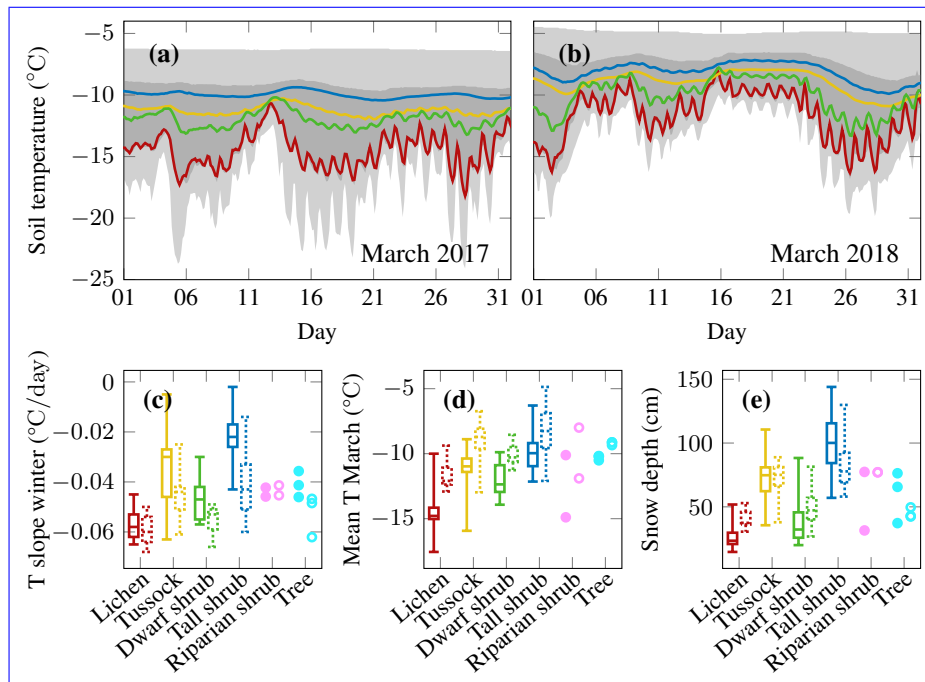


Figure 6. Topsoil temperature series of (a) March 2017 and (b) March 2018 representing the coldest topsoil temperatures in winter of the two different measurement periods; the mean of all measurements below four different vegetation types is shown in colour, the range of all single sensors is shown in light grey, and the range of all sensors between the 10th and 90th percentile is shown in darker grey; boxplots of all measurements per vegetation type are shown with boxes of the first period on the left and boxes representing the second period on the right and dotted; all single observations for riparian shrubs and trees are shown by filled symbols for the first period and open symbols for the second; (c) rate of cooling in winter; (d) mean March temperature; (e) range snow depth end of March temperature April.

to 2018 indicating a stronger snow redistribution. The correlation between snow depth values of the different years was $R^2 = 0.49$ (Figure B2).

265 Several winter and spring topsoil temperature characteristics are were also very strongly related to snow cover, in particular the day of the year when the topsoil warms warmed above 0°C , the topsoil temperature slope during winter cooling, and the mean temperature of the winter and spring months (Figure 7). In 2018, snow depth was less strongly related to vegetation or topsoil temperature characteristics than in 2017 (Figure 7, bottom row).

270 The predictability of snow depth from vegetation type is limited by the differences in snow cover in different years. For example, the snow depth at the end of April 2017 reached higher maximum and lower minimum values as compared to 2018 indicating a stronger snow redistribution. The correlation between snow depth values of the different years is $R^2 = 0.49$ (Figure B2).

Snow depth measured at the end of April in 2017 and 2018 at approximately the same locations. right column, Table 2).

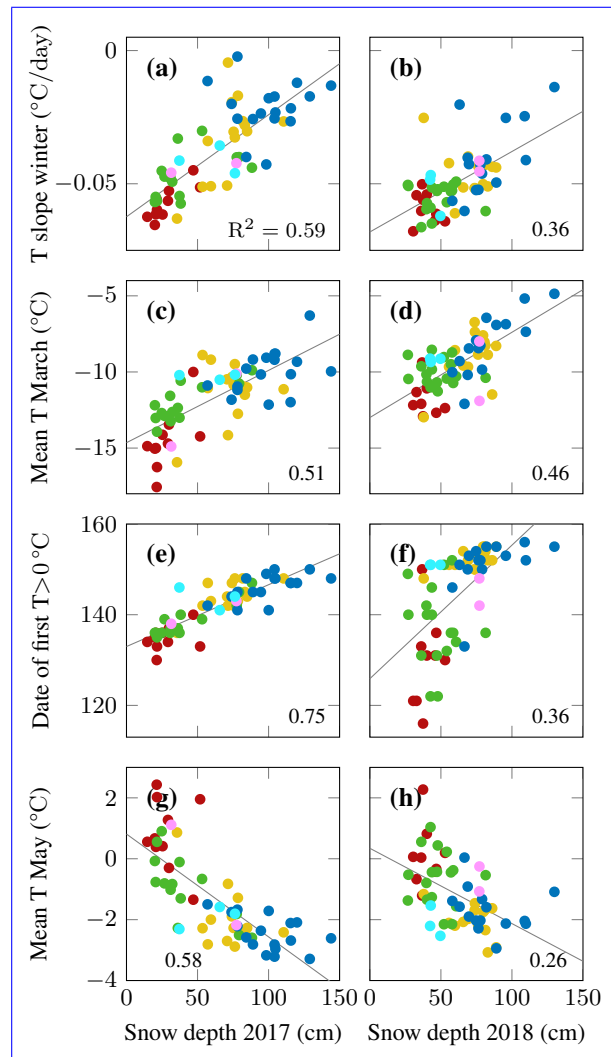


Figure 7. The relationship between snow depth end of April 2017 (top row left column) and 2018 (bottom row right column) and (a, f) vegetation type; (b, g) rate of cooling in winter; (c, h d) mean temperature in March; (d e, i f) day of year when the topsoil warms above 0 °C; (e g, j h) mean temperature in May; the symbol colours refer to different vegetation types (see e.g. Figure 6); the numbers indicate the Pearson's correlation coefficient R^2 ; the thin lines are regression lines of significant ($p < 0.05$) relationships.

3.3 Soil temperature, snow, and vegetation in spring

Starting from the beginning of May, the relationship between vegetation and topsoil temperature is was opposite to that found in winter (Figure 8a, b). In general, topsoil temperatures beneath all vegetation types are were very similar in the last few days of April. The soil below lichen tundra warms warmed up first and most strongly and shows showed the most pronounced diel variation. Dwarf shrub tundra is was still cooler in May and warms warmed up a bit more slowly than lichen tundra. Tussock

tundra topsoil temperatures **rise** **rose** above 0 °C even later; tall shrub temperatures were the last to reach positive temperatures in 2017 and were similar to tussock tundra in 2018. This order **becomes** **became** apparent in the slope of spring temperatures, in the mean May temperatures, and in the day of the year when the thawing period **ends** **ended** (Figure 8c–e). Using a statistical model, we **find** **found** that vegetation type **explains** **explained** 54% of the observed variability in the end of the thaw date and the mean May temperature and 33% of the variability in the spring warming rate (Table 2).

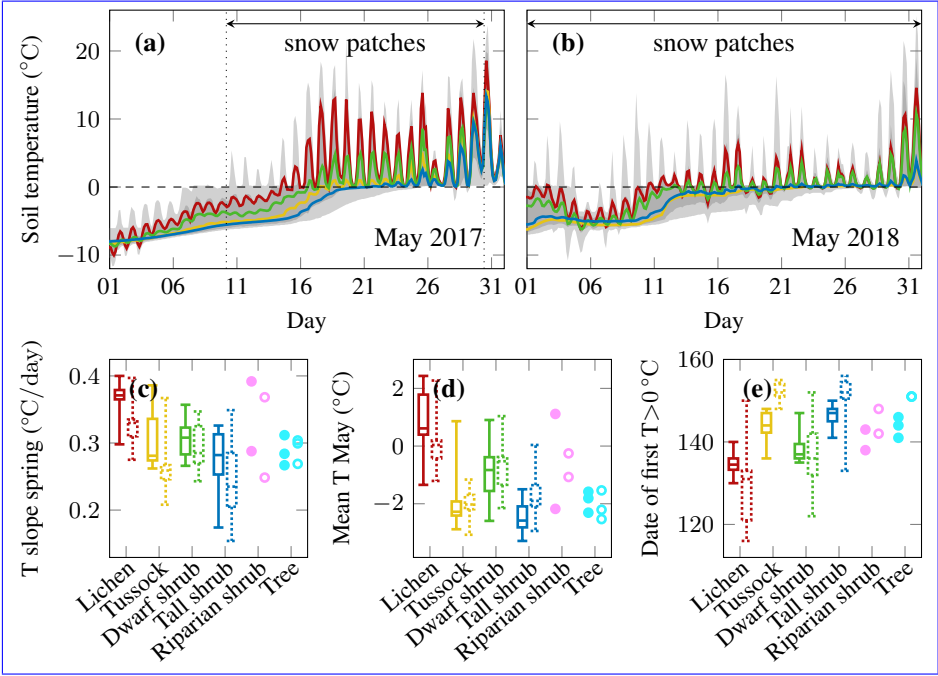


Figure 8. Topsoil temperature series of (a) May 2017 and (b) May 2018 representing spring of the two different measurement periods; mean of all measurements below four different vegetation types is shown in colour, the range of all single sensors is shown in light grey, and the range of all sensors between the 10th and 90th percentile is shown in darker grey; boxplots of all measurements per vegetation type are represented by boxes of the first period on the left and the second period on the right and dotted; for riparian shrubs and trees all single observations are shown with filled symbols for the first period and open symbols for the second; (c) rate of warming in spring; (d) mean May temperature; (e) date when thawing is complete.

Furthermore, **snow melt timing is** **snowmelt timing was** different between the years. Our observations of topsoil temperature **indicate that the snow melt** **indicated that the snowmelt** period of the entire landscape was 20 and 40 days long in 2017 and 2018, respectively (Figure 8e). This observation **is** **was** in contrast to the more spatially variable snow distribution observed in 2017 (Figure B2). The long melt period in 2018 **is** **was** associated with a 3.4 °C colder mean May air temperature and more cold spells as compared to May 2017 (Environment and Climate Change Canada, 2019) (Figure B1). However, due to the differences in **snow melt** **snowmelt** timing, the cold May air temperatures in 2018 did not necessarily translate into cold topsoil temperatures. While lichen tundra measurements indeed **reveal** **revealed** colder May topsoil temperatures in 2018, both years **are** **were** similar

for dwarf shrub soil and May 2018 is was associated with later warmer topsoil temperatures below tussock tundra and tall shrubs.

3.4 Soil temperature, active layer thickness, and vegetation in summer

Topsoil temperatures in summer are were more similar for all vegetation types than spring or winter temperatures (Figure 9a, b). In summer 2017, dwarf shrub tundra had the coolest summer temperatures. The other three vegetation types (excluding

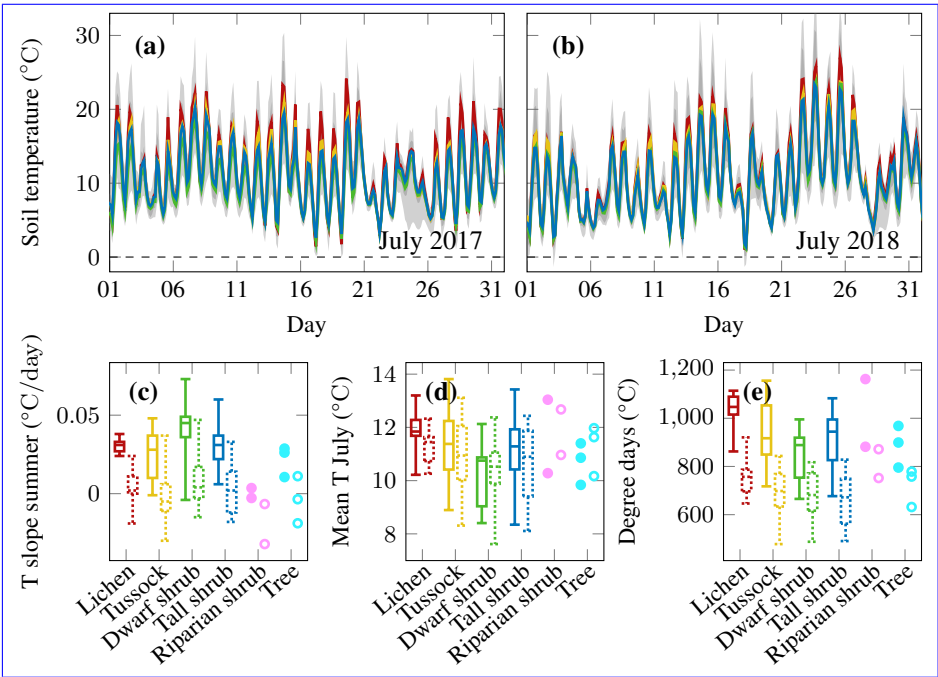


Figure 9. Topsoil temperature series of (a) July 2017 and (b) July 2018 representing summer of the two different measurement periods; mean of all measurements below the four different vegetation types is shown in colour, the range of all single sensors is shown in light grey, and the range of all sensors between the 10th and 90th percentile is shown in darker grey; boxplots show all measurements per vegetation type with boxes of the first period on the left and the second period on the right and dotted; for riparian shrubs and trees all single observations are shown with filled symbols for the first period and open symbols for the second; (c) rate of warming in summer; (d) mean July temperature; (e) cumulative sum of positive degree days until the end of August.

tree/riparian shrub) have had almost identical mean values and the distributions largely overlap overlapped (Figure 9c, d). In 2018, the difference between dwarf shrubs and the other vegetation types was much smaller and the mean summer slope is was almost equal for lichen, dwarf shrub, and tall shrub tundra, while tussock tundra warmed at a slightly lower rate. Some locations had negative summer slopes in 2018 as the end of summer was relatively cool. The temperature difference between the two years is was much larger than the variability between vegetation types. The 2018 mean summer air temperature was 2.7°C cooler than in 2017. This difference translates translated into topsoil temperatures which are were, on average per vegetation type,

1.3–2.2 °C colder in 2018, with the smallest difference for dwarf shrubs. The small difference between vegetation types **is was** also reflected in the low fraction of July mean temperature variance (12%) that **can could** be explained by the vegetation type (Table 2). Lichen tundra featured slightly higher cumulative degree days than the other three vegetation types, which all showed similar values on average (Figure 9e). Even though the influence of vegetation type on cumulative degree days **is was** statistically significant, vegetation only **explains explained** 7% of the observed variability (Table 2).

There **is was** a weak association between active layer thickness and vegetation type. On average, we found deeper active layers below lichen and dwarf shrub tundra as compared to tussock and tall shrub tundra (Figure 10a). The variability in active layer thickness within each vegetation type was substantial. Correspondingly, vegetation was only weakly related to active layer thickness at the end of summer as it **explains explained** only 34% of the variability between different locations (Table 2).

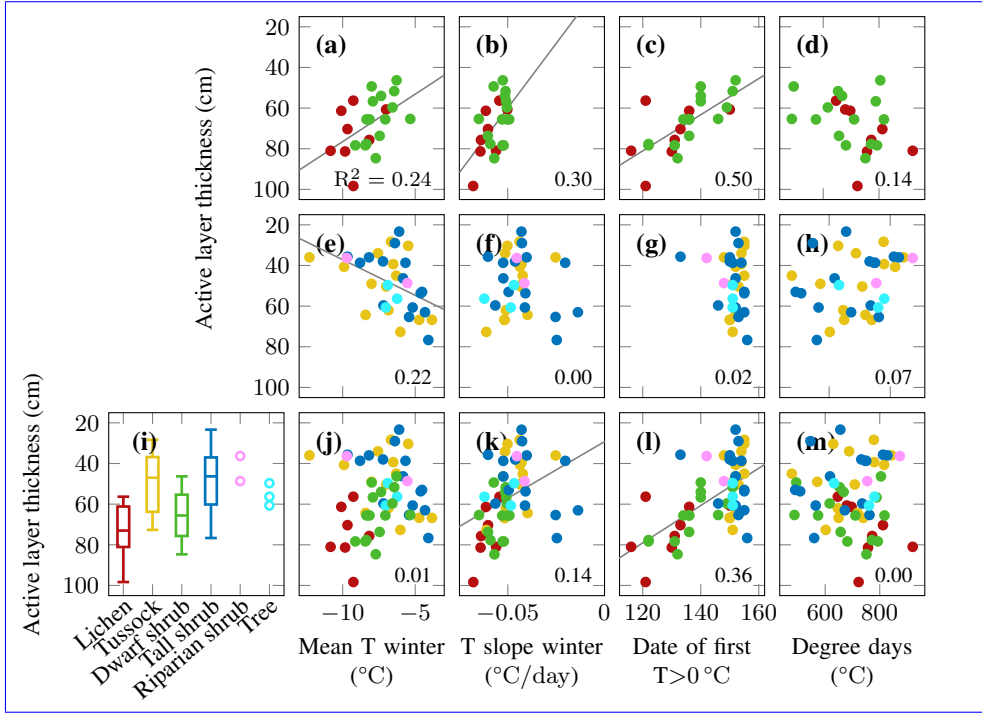


Figure 10. The relationship between active layer thickness at the end of August 2018 and (a) vegetation type; (b,a,e,j) mean topsoil winter temperature; (c,b,f,k) rate of topsoil cooling in winter; (d,c,g,l) day of the year when the topsoil warms above 0 °C; (e,d,h,m) cumulative sum of positive degree days until the end of August of the same year; top row: lichen and dwarf shrub tundra; middle row: tussock, tall shrub, riparian shrub and tree; bottom row: all vegetation types; the numbers indicate the Pearson's correlation coefficient R^2 ; the thin grey lines are regression lines of significant ($p < 0.05$) relationships.

In terms of The relationship between active layer thickness and topsoil temperature characteristics depended on vegetation type. If we considered all vegetation types jointly, active layer thickness **is was** most strongly related to the date when the topsoil temperature first **rises rose** above 0 °C in spring (Figure 10d). While a moderate association **exists existed** with other

spring, autumn, and winter characteristics, such as the cooling rate in winter (Figure 10k), summer characteristics show no did not show a significant correlation with active layer thickness when all measurements are vegetation types were considered (Figure 10e). However, when we consider only the dwarf shrub locations, sensors with higher degree days are m). If we split the data in two subsets, lichen and dwarf shrub tundra revealed very different winter characteristics as compared to the other vegetation types. While cold winter temperatures were associated with deeper active layers in the following summer for lichen and dwarf shrub tundra (Figure 10e). Deep active layers are also associated with higher topsoil temperatures in October a), tall shrub and tussock locations with cold winter temperatures developed shallow active layers (Figure 4). Within vegetation types, the thawing degree day correlation is very weak for tall shrubs (and other types), and so is the date of the first $T > 0$. 10e). The spring temperature characteristics were not significantly related to active layer thickness for tall shrub and tussock locations (Figure 10g). Conversely, the date of the first $T > 0$ also apparently explains explained a moderate fraction of the active layer thickness variance within lichen and dwarf shrub tundra . For tall shrubs, we can observe that warmer winter temperatures are (Figure 10c). Higher positive degree days were associated with deeper active layers below dwarf shrub and lichen tundra (Figure 10b). d), however, this relationship was not statistically significant ($p=0.08$). We observed significantly higher topsoil temperatures in October at locations with deep active layers (Figure 4).

4 Discussion

In this study, we analysed how local variability of vegetation cover relates to topsoil temperature, active layer thickness and snow depth at one site at the Arctic forest–tundra transition. Both the observed variability and the absolute values are site dependent. We found distinct vegetation effects in the four seasons, which were partly counteracting each other in terms of the overall topsoil temperature and active layer thickness variability. In particular, low vegetation lead to an inverse relationship between winter temperature and active layer thickness and summer topsoil temperature did not influence active layer thickness significantly.

In agreement with Kropp et al. (2020) we found that winter topsoil temperatures controlled annual mean temperatures, and that topsoil below tussocks and tall shrub tundra was generally warmer than topsoil below short-statured vegetation. Furthermore, we found that topsoil temperature was most variable in space under the snow cover in winter and during snow melt snowmelt in May, while the spatial variability was less pronounced in summer and autumn, which agrees well with Gislén et al. (2014).

4.1 Vegetation and soil temperature in relation to autumn processes

While vegetation Vegetation type did not play a significant part in the autumn topsoil temperature variation , we (Figure 5), which agrees well with Romanovsky and Osterkamp (1995) who observed very similar dates of the start of ground freezing across three sites up to 63 km apart. On the other hand, Frost et al. (2018) found that tall shrubs experienced a delayed start of freezing by almost one month as compared to other vegetation types. We found that at all locations the general pattern topsoil temperature signal was dominated by air temperature and snowfall timing. However The importance of snowcover onset for soil temperature was highlighted by many authors, including Ling and Zhang (2003); Zhang (2005).

345 While all vegetation types had similar average autumn temperatures and cooling rates, we observed considerable variability between different locations and years, within single types as well as between years. The temporal variability of the start of freezing was described by Romanovsky and Osterkamp (1995), who found up to 18 days difference in the start of freezing date at a single location between 1987 and 1992. In their study, the temporal variability was higher than the spatial variability although the stations were up to 63 km apart. On the other hand, we observed considerable local variability of up to 39 days difference in the timing of the first below zero topsoil temperatures in a single year (Figure 5e). This variability is potentially driven by the soil cover of mosses or lichen, soil moisture, and microtopography rather than vascular plants. The importance of soil moisture in the freezing period was highlighted by Morse et al. (2016). We observed the largest range of mean October topsoil temperatures in tussock tundra (Figure 5d) which may be caused by a large range of moisture conditions depending on the microtopography in this vegetation type. However, it should be noted that variations in the sensor depth will play a major role in autumn when steep temperature gradients can be expected.

4.2 Vegetation and soil temperature in relation to winter snow processes

In winter, warm soil temperatures can be expected at locations with more snow such as below tall shrubs and in poorly drained and somewhat sheltered tussock-dominated areas (Lantz et al., 2009; Frost et al., 2018). The snow observed at our measurement locations was indeed deepest in tall-shrub areas, where soils were also the warmest in winter (Figure 7a, f6e). Across all vegetation types, the differences in snow depth influenced the winter topsoil temperatures, temperature variability, and cooling rates. Winter temperatures were coldest and most variable at vegetation types associated with low snow, in particular below lichen tundra and, to a lesser extent, below dwarf shrubs (Figure 6c).

The variability of snow depth within vegetation types (Figure 7a, f6e) is likely due to (I) topography and microtopography influencing the deposition of blowing snow (Essery and Pomeroy, 2004; Morse et al., 2012), (II) vegetation height and density differences within one vegetation type (Sturm et al., 2001a; Essery and Pomeroy, 2004; Sturm et al., 2005a) and (III) factors other than snow limiting shrub growth such as poor soil, too much or too little soil moisture, disturbances, and slow colonisation (Swanson, 2015).

We also observed variability in the relationship between snow depth and winter topsoil temperature characteristics such as the soil cooling rate and the mean and range of temperature values in the winter months (Figure 7b, c, g, ha–d). The topography of the site is gentle and cannot account for major differences in cold-season insolation; therefore, the variability is likely largely due to differences in snow density and texture, autumn soil moisture, snow density, and snow texture. Differences in snow density and texture across the landscape can be caused by snow compaction at wind exposed sites, by loose snow accumulating within shrub canopies, and by the formation of depth hoar. We do not have detailed snow observations at our measurement locations to analyse such differences in detail. However, our results suggest that, for the same snow depth, topsoil temperatures in March are colder at lichen sites as compared to dwarf shrub sites (Figure 7c, hd). This agrees very well with the observation that lichen tundra can be found at the most wind-exposed ridges. While historical surveys of snow density did not find differences between lichen and dwarf shrub tundra at the site (0.22 g cm^{-3} , Wilcox et al. (2019)), snow texture and depth hoar formation

likely differed between shrub and shrub-free areas (Belke-Brea et al., 2020), leading to differences in the heat conductivity of each snowpack.

380 4.3 Vegetation and soil temperature in relation to spring processes

In spring, a thick snow cover delays soil warming and thus results in a reversal of the topsoil temperature – vegetation type relationship. We observed similar topsoil temperatures beneath all vegetation types in the last few days of April. The soil below tall shrubs was coldest in May, followed by the temperatures below tussocks and dwarf shrubs, while lichen tundra topsoil was already the warmest (Figure 8d).

385 We found that the date when the topsoil warmed above 0 °C was strongly related to vegetation type in 2017, and less so in 2018 (Figure 8e). A strong relationship can be expected due to the influence of vegetation on snow depth, snow density, and snow melt snowmelt energetics (Pomeroy et al., 2006; Wilcox et al., 2019). The weaker relationship in 2018 is likely due to the more complex spring weather patterns including multiple periods of warming and subsequent freezing periods. The colder May air temperature in 2018 was associated with colder topsoil temperatures below lichen tundra and warmer topsoil temperatures below tall shrubs, where the snow melted later as compared to May 2017 (Figure 8d). This indicates a first-order control of snow depth as a buffer between air and topsoil temperature.

In general the presence of shrubs enhances snow melt snowmelt as soon as branches stick out of the snow, thus reducing surface albedo and increasing long-wave emissions (Pomeroy et al., 2006; Marsh et al., 2010). Wilcox et al. (2019) made extensive measurements of snow-free date with a drone at the same study site in 2016 and showed that dwarf shrub areas become snow free earlier than non-shrub areas, regardless of snow depth and hillslope aspect. However, we did not observe this relationship at our locations, likely due to the small number of points we measured at compared to Wilcox et al. (2019). Instead, we found the topsoil warmed above 0 °C first slightly earlier at the lichen tundra locations, even though they were similar in snow depth to the dwarf shrub locations (Figure 7d, i, e, f).

4.4 Vegetation and soil temperature in relation to summer processes and active layer thickness

400 Although shrubs may reduce summer soil warming through shading and evapotranspiration (Frost et al., 2018)(Pearson et al., 2013; Frost et al., 2018), in our study, the summer difference between all vegetation types is very small, and shrub tundra is comparable to tussock tundra in terms of topsoil temperature (Figure 9 and B3). Lichen tundra topsoil warms up slightly more, in particular during mid-day, but the average difference is less than 1 °C.

These generally small differences in topsoil temperature likely contribute to the weak relation between vegetation type and summer temperature characteristics (Figure 10a, e, i, m, Table 2).

On the other hand, winter and spring temperature characteristics such as the date when the topsoil warmed above 0 °C, are strongly related to active layer thickness (Figure 10). At first glance, our data suggest that the snow-free date and thus the length of the summer period is the most important driver for active layer thickness (Figure 10l). The strong influence of snow-free date on active layer thickness has been highlighted in several other studies (Chapin et al., 2005; Wilcox et al., 2019). temperature At first glance, our data suggest that the However, if we consider single vegetation types, the importance of snowmelt timing

is strongly reduced. In particular, for tall vegetation (tall shrubs, riparian shrubs, trees) and tussock tundra we did not observe any correlation between snow-free date and thus the length of the summer period is the most important driver for active layer thickness at the end of summer (Figure 10g).

While mean winter temperature is not significantly related to active layer thickness, while warm at the landscape scale, we found opposite effects for upland vegetation (lichen and dwarf shrubs) as compared to tall vegetation and tussocks (Figure 10a, e, j). Warm winter temperature is unexpectedly associated with a shallow active layer in upland areas, while warm winter temperature is related to deep active layers below tall vegetation and tussocks (Figure 10b, d). However, this agrees well with results by Morse et al. (2012) from the outer Mackenzie Delta. They found that deep snow was associated with thick active layers in alluvial sites whereas it was associated with thin active layers in upland terrain. The opposite response of active layer thickness to mean winter temperature (and other winter and spring characteristics) below different vegetation types may be an artefact of the spatial correlation between snow depth and soil properties (Lorant et al., 2018). For instance, both snow depth and organic layer thickness tend to be shallow on exposed lichen-covered ridges, and the latter favours deeper active layers. If we consider single vegetation types with presumably more uniform soil conditions, the importance of snow melt timing is strongly reduced. In particular, for tall shrubs and tussocks warm winter temperatures are related to deep active layers (Figure 10b) while the relationship with snow melt timing is weak for these two types (Figure 10d). As organic and moss layer thickness are important controls of active layer thickness (Fisher et al., 2016), the positive relationship between organic layer thickness and snow depth masks the actual effects of snow on the active layer thickness. Similarly, correlations between soil moisture, ice content, and snow depth may be different across the landscape, with variable effects on active layer development (Guan et al., 2010). It should also be noted that it was not recorded whether active layer thickness measurements were taken in a hummock or inter-hummock zone, which due to their vastly different soil properties, have a stronger effect on active layer thickness than any other variable (Wilcox et al., 2019). This reduces our ability to draw inferences from our active layer thickness measurements.

Vegetation type is thus a useful proxy for predicting topsoil temperatures in winter, through its modification of snowpack height, density, and texture. Conversely, its predictive value in summer is poor. The generally weak relationship between vegetation type and Summer topsoil temperature is only weakly related with vegetation type, which agrees well with Paradis et al. (2016). Vegetation type explains 12% of the variability of the summer topsoil temperature and 34% of the variability of active layer thickness we found in our study hinders upscaling approaches (Table 2), likely through its effects on snow depth. The generally weak relationships hinder upscaling approaches based on vegetation such as in Nelson et al. (1997); Widhalm et al. (2017). This is likely related to variable soil thermal properties, as one would expect a strong relation between We found that thawing degree days and are not correlated with active layer thickness for uniform soil properties. This is not the case at our site across vegetation types (Figure 10m) at the landscape scale, echoing previous findings by (Nelson et al., 1997) Nelson et al. (1997). This is likely related to variable soil thermal properties and soil moisture. Within dwarf shrubs shrub and lichen tundra, where more uniform soil properties conditions may be expected, larger cumulative positive degree days are indeed associated with deeper active layers. Again, as we did not record whether active layer thickness measurements were made in hummocks or inter-hummock zones, a large portion of the variance remains unexplained. In summary, our observations suggest that vegetation type is a better predictor of the near-surface thermal regime in winter than in summer in the low Arctic Low Arctic. Furthermore, the soil temperature – active layer thickness relationship differs between dwarf shrubs and tall shrubs. Both vegetation types are currently expanding in the

Arctic (Ropars and Boudreau, 2012; Tape et al., 2012) and our results indicate that their future distribution will govern the importance of summer versus winter processes for active layer thickness.

5 Conclusions

Based on topsoil temperature data from 68 sensors at a **low Low** Arctic tundra site, we found large small-scale variability within and between vegetation types as well as between years and seasons. **The spatial variation of the mean annual soil temperature was dominated by the winter signal.** Autumn topsoil temperatures were dominated by atmospheric forcing and only weakly related to vegetation type. Conversely, vegetation type explained approximately one half of the variability in winter and spring soil temperature. An even stronger relation was observed between vegetation type and end-of-winter snow depth. Snow depth and, most likely, snow structural differences in space lead to pronounced differences in topsoil mean temperature and temperature variability in the winter and spring months and in **snow melt snowmelt** timing, all of which were strongly related to vegetation type. **Summer topsoil temperatures were less variable in space, similar below most vegetation types, and not significantly related to active layer thickness at the end of August.** At the landscape scale, we found that active layer thickness was most strongly related to **snow melt snowmelt** timing. However, if we considered only specific vegetation types with presumably more similar soil conditions, mean winter temperature and summer thawing degree days played a more important part. **The spatial variation of the mean annual soil temperature was dominated by the winter signal** Unexpectedly, warm winter topsoil temperature was associated with shallow active layers below lichen and dwarf shrub tundra, whereas we found the opposite beneath other vegetation types. Summer topsoil temperatures were similar below all vegetation types and not significantly related to active layer thickness at the end of August. To conclude, vegetation can, with limitations, be used as a proxy for snow depth variability at the local scale, but it is a poor proxy for summer and autumn topsoil temperature or active layer thickness.

Data availability. **The topsoil temperature data used in this study is published in Pangaea** (doi:10.1594/PANGAEA.918615).

Appendix A: Methods

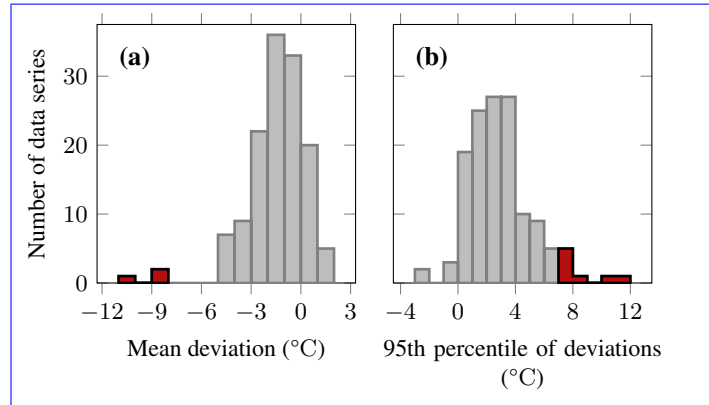


Figure A1. Histograms of the deviation of topsoil temperature minus air temperature in summer; (a) mean and (b) 95th percentile of the deviations for each sensor in each measurement period; data series coloured in red were removed from the analysis because (a) the average deviation was less than -5°C indicating that the sensor was either buried too deep and affected by the permafrost or affected by running water (3 series) or (b) more than 5% of the single summer measurements were more than 7°C above air temperature indicating additional sensor warming by direct solar radiation (8 series); air temperature data by Environment and Climate Change Canada (2019).

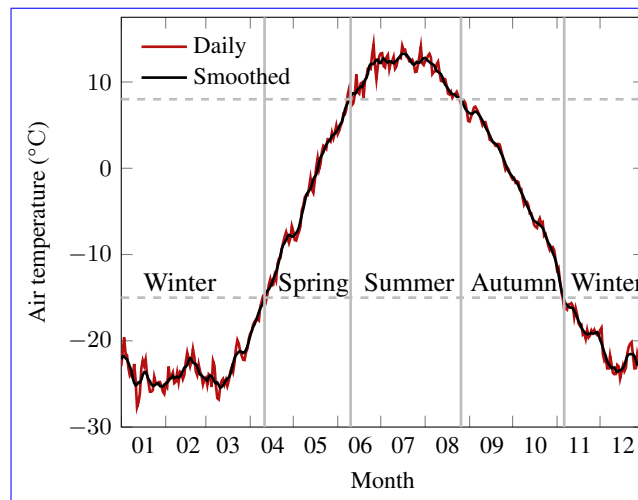


Figure A2. Mean annual cycle of air temperature at Trail Valley Creek for 1999–2018, gap-filled data series; daily values and values smoothed with a seven-day moving window as used for definition of the seasons; data by Environment and Climate Change Canada (2019).

Appendix B: Results

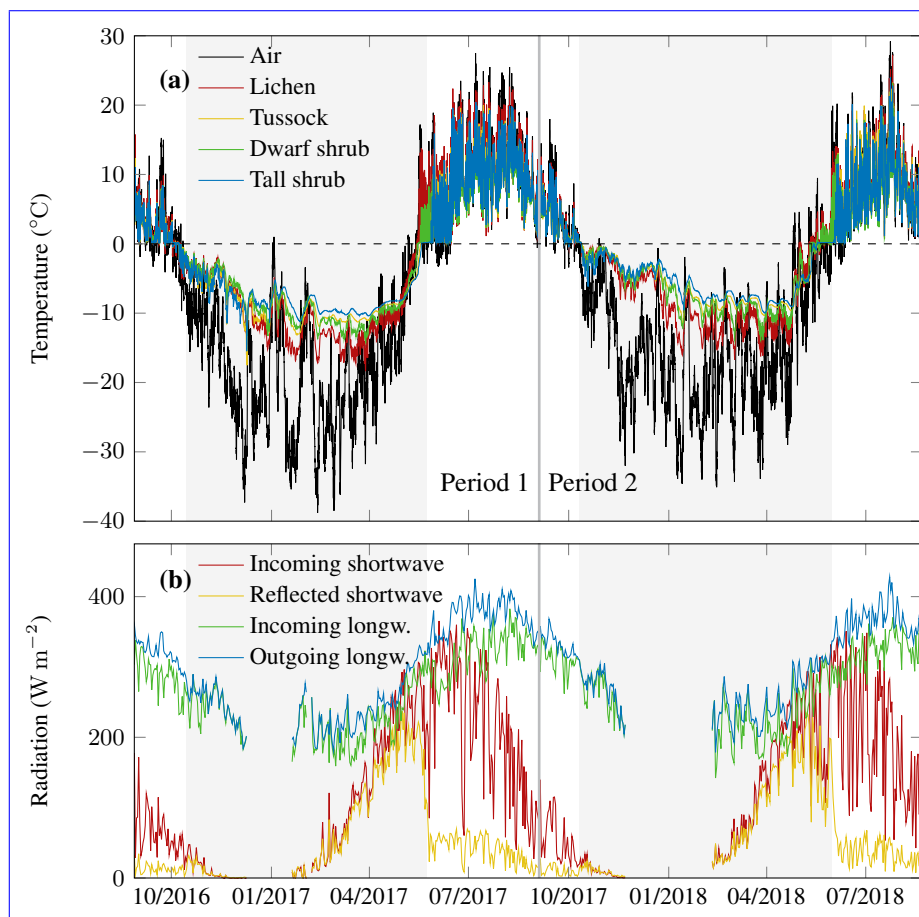


Figure B1. Meteorological conditions at the Trail Valley Creek weather station during the two study periods including snow cover estimated from daily albedo > 0.4 indicated as shaded area. (a) Air temperature by Environment and Climate Change Canada (2019) and median topsoil temperature of each vegetation type; (b) daily mean values of four component radiation.

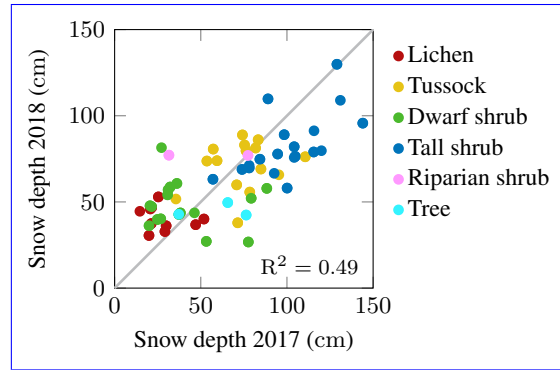


Figure B2. Snow depth measured at the end of April in 2017 and 2018 at approximately the same locations; the number indicates the Pearson's correlation coefficient R^2 .

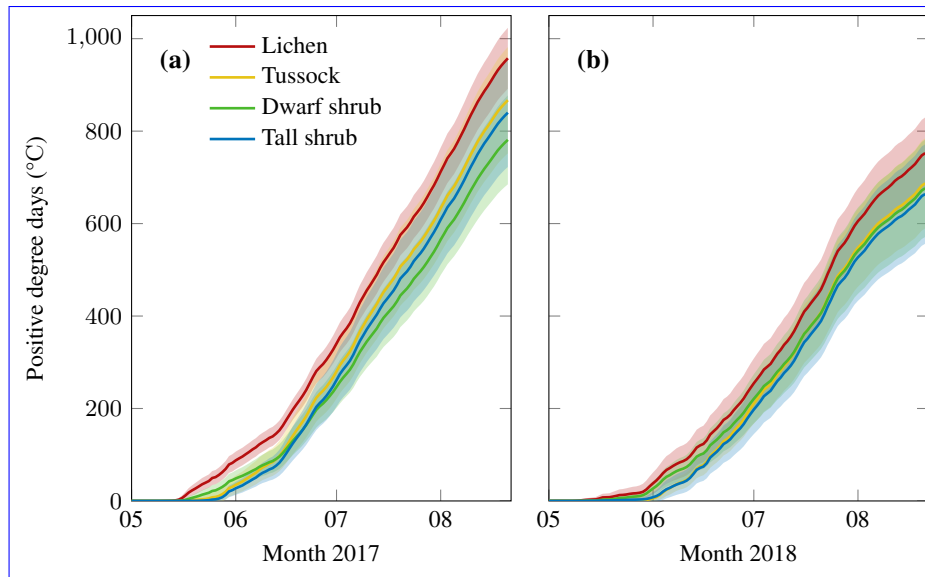


Figure B3. Cumulative positive degree days of topsoil temperature below different vegetation types; the lines indicate the mean of all series per type, the shaded areas represent the mean plus/minus the standard deviation; (a) 2017, (b) 2018.

Author contributions. J. Boike and I. Grünberg conceived the study. J. Boike, S. Zwieback, E. Wilcox, I. Grünberg, and several helpers carried out the field measurements. I. Grünberg analysed the data with input from J. Boike, E. Wilcox, and S. Zwieback. I. Grünberg prepared the manuscript with contributions from all co-authors.

Competing interests. We declare that no competing interests are present.

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- AMAP: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) , *Tech. rep.*, AMAP2017, , 2011. <https://www.amap.no/documents/download/2987/inline>, 2017.
- Anders, K., Antonova, S., Boike, J., Gehrmann, M., Hartmann, J., Helm, V., Höfle, B., Marsh, P., Marx, S., and Sachs, T.: Airborne Laser Scanning (ALS) Point Clouds of Trail Valley Creek, NWT, Canada (2016), <https://doi.org/10.1594/PANGAEA.894884>, 2018.
- 480 Anisimov, O. A., Shiklomanov, N. I., and Nelson, F. E.: Variability of seasonal thaw depth in permafrost regions: a stochastic modeling approach, *Ecological Modelling*, 153, 217–227, [https://doi.org/10.1016/S0304-3800\(02\)00016-9](https://doi.org/10.1016/S0304-3800(02)00016-9), 2002.
- Antonova, S., Thiel, C., Höfle, B., Anders, K., Helm, V., Zwieback, S., Marx, S., and Boike, J.: Estimating tree height from TanDEM-X data at the northwestern Canadian treeline, *Remote Sensing of Environment*, 231, 111251, <https://doi.org/https://doi.org/10.1016/j.rse.2019.111251>, <http://www.sciencedirect.com/science/article/pii/S0034425719302706>, 2019.
- 485 Belke-Brea, M., Domine, F., Barrere, M., Picard, G., and Arnaud, L.: Impact of Shrubs on Winter Surface Albedo and Snow Specific Surface Area at a Low Arctic Site: In Situ Measurements and Simulations, *Journal of Climate*, 33, 597–609, <https://doi.org/10.1175/JCLI-D-19-0318.1>, 2020.
- Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Eitzelmüller, B., Grosse,
- 490 G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johannsson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckman, J.-P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, A. B. K., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M., and Lantuit, H.: Permafrost is warming at a global scale, *Nature Communications*, 10, 2041–1723, <https://doi.org/10.1038/s41467-018-08240-4>, 2019.
- Blok, D., Heijmans, M. M. P. D., Schaepman-Strub, G., Kononov, A. V., Maximov, T. C., and Berendse, F.: Shrub expansion may reduce
- 495 summer permafrost thaw in Siberian tundra, *Global Change Biology*, 16, 1296–1305, <https://doi.org/10.1111/j.1365-2486.2009.02110.x>, 2010.
- Burn, C. R. and Kokelj, S. V.: The environment and permafrost of the Mackenzie Delta area, *Permafrost and Periglacial Processes*, 20, 83–105, <https://doi.org/10.1002/ppp.655>, 2009.
- Chapin, III, F. S., Sturm, M., Serreze, M. C., McFadden, J. P., Key, J. R., Lloyd, A. H., McGuire, A. D., Rupp, T. S., Lynch, A. H.,
- 500 Schimel, J. P., Beringer, J., Chapman, W. L., Epstein, H. E., Euskirchen, E. S., Hinzman, L. D., Jia, G., Ping, C.-L., Tape, K. D., Thompson, C. D. C., Walker, D. A., and Welker, J. M.: Role of land-surface changes in Arctic summer warming, *Science*, 310, 657–660, <https://doi.org/10.1126/science.1117368>, 2005.
- Environment and Climate Change Canada: Historical data Trail Valley, Northwest Territories, http://climate.weather.gc.ca/historical_data/search_historic_data_e.html, accessed 2019/01/10, 10, 2019.
- 505 Essery, R. and Pomeroy, J.: Vegetation and Topographic Control of Wind-Blown Snow Distributions in Distributed and Aggregated Simulations for an Arctic Tundra Basin, *Journal of Hydrometeorology*, 5, 735–744, [https://doi.org/10.1175/1525-7541\(2004\)005<0735:VATCOW>2.0.CO;2](https://doi.org/10.1175/1525-7541(2004)005<0735:VATCOW>2.0.CO;2), 2004.
- Fisher, J. P., Estop-Aragonés, C., Thierry, A., Charman, D. J., Wolfe, S. A., Hartley, I. P., Murton, J. B., Williams, M., and Phoenix, G. K.: The influence of vegetation and soil characteristics on active-layer thickness of permafrost soils in boreal forest, *Global Change*
- 510 *Biology*, 22, 3127–3140, <https://doi.org/10.1111/gcb.13248>, 2016.

- Frost, G. V. and Epstein, H. E.: Tall shrub and tree expansion in Siberian tundra ecotones since the 1960s, *Global Change Biology*, 20, 1264–1277, <https://doi.org/10.1111/gcb.12406>, 2014.
- Frost, G. V., Epstein, H. E., Walker, D. A., Matyshak, G., and Ermokhina, K.: Patterned-ground facilitates shrub expansion in Low Arctic tundra, *Environmental Research Letters*, 8, 015 035, <https://doi.org/10.1088/1748-9326/8/1/015035>, 2013.
- 515 Frost, G. V., Epstein, H. E., Walker, D. A., Matyshak, G., and Ermokhina, K.: Seasonal and Long-Term Changes to Active-Layer Temperatures after Tall Shrubland Expansion and Succession in Arctic Tundra, *Ecosystems*, 21, 507–520, <https://doi.org/10.1007/s10021-017-0165-5>, 2018.
- Gisnås, K., Westermann, S., Schuler, T. V., Litherland, T., Isaksen, K., Boike, J., and Etzelmüller, B.: A statistical approach to represent small-scale variability of permafrost temperatures due to snow cover, *The Cryosphere*, 8, 2063–2074, <https://doi.org/10.5194/tc-8-2063-2014>,
520 2014.
- Grippa, M., Kergoat, L., Le Toan, T., Mognard, N. M., Delbart, N., L’Hermite, J., and Vicente-Serrano, S. M.: The impact of snow depth and snowmelt on the vegetation variability over central Siberia, *Geophysical Research Letters*, 32, <https://doi.org/10.1029/2005GL024286>, 2005.
- Grünberg, I. and Boike, J.: Vegetation map of Trail Valley Creek, Northwest Territories, Canada, <https://doi.org/10.1594/PANGAEA.904270>,
525 2019.
- Guan, X. J., Westbrook, C. J., and Spence, C.: Shallow soil moisture – ground thaw interactions and controls – Part 1: Spatiotemporal patterns and correlations over a subarctic landscape, *Hydrology and Earth System Sciences*, 14, 1375–1386, <https://doi.org/10.5194/hess-14-1375-2010>, 2010.
- Hopkinson, C., Fox, A., Monette, S., Churchill, J., Crasto, N., and Chasmer, L.: Mackenzie Delta LiDAR collaborative research data report.,
530 revised , *Applied Geomatics Research Group, Dartmouth, Nova Scotia, Canada, Revised 03/2011*, 2009.
- IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, <https://doi.org/10.1017/CBO9781107415324>, 2013.
- Kropp, H., Loranty, M. M., Natali, S. M., Kholodov, A. L., , Rocha, A., Myers-Smith, I., Abermann, J., , Blanc-Betes, E., Blok, D., Blume-
535 Werry, G., Boike, J., , Breen, A. L., Cahoon, S. M., Christiansen, C. T., Douglas, T. A., Epstein, H. E., Frost, G. V., Goeckede, M., Høye, T. T., Mamet, S. D., O’Donnell, J. A., Olefeldt, D., Phoenix, G. K., Salmon, V. G., Sannel, B., Smith, S. L., Sonnentag, O., Vaughn, L. S., Williams, M., Elberling, B., Gough, L., Hjort, J., Lafleur, P. M., Euskirchen, E. S., Heijmans, M. M. P. D., Humphreys, E. R., Iwata, H., Jones, B. M., Jorgenson, M. T., Grünberg, I., Kim, Y., Laundre, J., Mauritz, M., Michelsen, A., Schaepman-Strub, G., Tape, K. D., Ueyama, M., Lee, B.-Y., and Langley, K.: Vegetation stature controls air–soil temperature coupling across pan-, and Lund, M.: Shallow soils are warmer
540 under trees and tall shrubs across Arctic ecosystems and Boreal ecosystems, submitted, 2020.
- Langer, M., Westermann, S., Heikenfeld, M., Dorn, W., and Boike, J.: Satellite-based modeling of permafrost temperatures in a tundra lowland landscape, *Remote Sensing of Environment*, 135, 12–24, <https://doi.org/10.1016/j.rse.2013.03.011>, 2013.
- Lantz, T. C., Kokelj, S. V., Gergel, S. E., and Henry, G. H. R.: Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps, *Global Change Biology*, 15, 1664–1675, <https://doi.org/10.1111/j.1365-2486.2009.01917.x>, 2009.
545
- Lantz, T. C., Gergel, S. E., and Henry, G. H. R.: Response of green alder (*Alnus viridis* subsp. *fruticosa*) patch dynamics and plant community composition to fire and regional temperature in north-western Canada, *Journal of Biogeography*, 37, 1597–1610, <https://doi.org/10.1111/j.1365-2699.2010.02317.x>, 2010.

- Lantz, T. C., Marsh, P., and Kokelj, S. V.: Recent shrub proliferation in the Mackenzie Delta uplands and microclimatic implications, *Ecosystems*, 16, 47–59, <https://doi.org/10.1007/s10021-012-9595-2>, 2013.
- Ling, F. and Zhang, T.: Impact of the timing and duration of seasonal snow cover on the active layer and permafrost in the Alaskan Arctic, *Permafrost and Periglacial Processes*, 14, 141–150, <https://doi.org/10.1002/ppp.445>, 2003.
- Loranty, M. M. and Goetz, S. J.: Shrub expansion and climate feedbacks in Arctic tundra, *Environmental Research Letters*, 7, 011005, <https://doi.org/10.1088/1748-9326/7/1/011005>, 2012.
- Loranty, M. M., Abbott, B. W., Blok, D., Douglas, T. A., Epstein, H. E., Forbes, B. C., Jones, B. M., Kholodov, A. L., Kropp, H., Malhotra, A., Mamet, S. D., Myers-Smith, I. H., Natali, S. M., O'Donnell, J. A., Phoenix, G. K., Rocha, A. V., Sonnentag, O., Tape, K. D., and Walker, D. A.: Reviews and syntheses: Changing ecosystem influences on soil thermal regimes in northern high-latitude permafrost regions, *Biogeosciences*, 15, 5287–5313, <https://doi.org/10.5194/bg-15-5287-2018>, 2018.
- MacKay, J. R.: Active Layer Changes (1968 to 1993) following the Forest-Tundra Fire near Inuvik, N.W.T., Canada, *Arctic and Alpine Research*, 27, 323–336, <https://doi.org/10.1080/00040851.1995.12003129>, 1995.
- Mann, P. C.: Spatial and temporal variability of the snow environment in the Western Canadian Arctic, Master's thesis, [Wilfrid Laurier University](https://scholars.wlu.ca/etd/2011/), <https://scholars.wlu.ca/etd/2011/>, 2018.
- Marsh, P., Pomeroy, J., Pohl, S., Quinton, W., Onclin, C., Russell, M., Neumann, N., Pietroniro, A., Davison, B., and McCartney, S.: Snowmelt Processes and Runoff at the Arctic Treeline: Ten Years of MAGS Research, pp. 97–123, Springer Berlin Heidelberg, Berlin, Heidelberg, https://doi.org/10.1007/978-3-540-75136-6_6, 2008.
- Marsh, P., Bartlett, P., MacKay, M., Pohl, S., and Lantz, T.: Snowmelt energetics at a shrub tundra site in the western Canadian Arctic, *Hydrological Processes*, 24, 3603–3620, <https://doi.org/10.1002/hyp.7786>, 2010.
- McManus, K. M., Morton, D. C., Masek, J. G., Wang, D., Sexton, J. O., Nagol, J. R., Ropars, P., and Boudreau, S.: Satellite-based evidence for shrub and graminoid tundra expansion in northern Quebec from 1986 to 2010, *Global Change Biology*, 18, 2313–2323, <https://doi.org/10.1111/j.1365-2486.2012.02708.x>, 2012.
- Michaelson, G. J., Ping, C. L., and Kimble, J. M.: Carbon Storage and Distribution in Tundra Soils of Arctic Alaska, U.S.A., *Arctic and Alpine Research*, 28, 414–424, <https://doi.org/10.1080/00040851.1996.12003194>, 1996.
- Morse, P., Burn, C., and Kokelj, S.: Influence of snow on near-surface ground temperatures in upland and alluvial environments of the outer Mackenzie Delta, Northwest Territories, Canada, *Canadian Journal of Earth Sciences*, 49, 895–913, <https://doi.org/10.1139/e2012-012>, 2012.
- Morse, P. D., Wolfe, S. A., Kokelj, S. V., and Gaanderse, A. J. R.: The Occurrence and Thermal Disequilibrium State of Permafrost in Forest Ecotopes of the Great Slave Region, Northwest Territories, Canada, *Permafrost and Periglacial Processes*, 27, 145–162, <https://doi.org/10.1002/ppp.1858>, 2016.
- Myers-Smith, I. H., Forbes, B. C., Wilkening, M., Hallinger, M., Lantz, T., Blok, D., Tape, K. D., Macias-Fauria, M., Sass-Klaassen, U., Lévesque, E., Boudreau, S., Ropars, P., Hermanutz, L., Trant, A., Collier, L. S., Weijers, S., Rozema, J., Rayback, S. A., Schmidt, N. M., Schaepman-Strub, G., Wipf, S., Rixen, C., Ménard, C. B., Venn, S., Goetz, S., Andreu-Hayles, L., Elmendorf, S., Ravolainen, V., Welker, J., Grogan, P., Epstein, H. E., and Hik, D. S.: Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities, *Environmental Research Letters*, 6, 045509, <https://doi.org/10.1088/1748-9326/6/4/045509>, 2011.
- Nelson, F. E., Shiklomanov, N. I., Mueller, G. R., Hinkel, K. M., Walker, D. A., and Bockheim, J. G.: Estimating Active-Layer Thickness over a Large Region: Kuparuk River Basin, Alaska, U.S.A., *Arctic and Alpine Research*, 29, 367–378, <https://doi.org/10.2307/1551985>, 1997.

- Pajunen, A. M., Oksanen, J., and Virtanen, R.: Impact of shrub canopies on understorey vegetation in western Eurasian tundra, *Journal of Vegetation Science*, 22, 837–846, <https://doi.org/10.1111/j.1654-1103.2011.01285.x>, 2011.
- Palmer, M. J., Burn, C. R., and Kokelj, S. V.: Factors influencing permafrost temperatures across tree line in the uplands east of the Mackenzie Delta, 2004–2010, *Canadian Journal of Earth Sciences*, 49, 877–894, <https://doi.org/10.1139/e2012-002>, 2012.
- Paradis, M., Lévesque, E., and Boudreau, S.: Greater effect of increasing shrub height on winter versus summer soil temperature, *Environmental Research Letters*, 11, 085005, <https://doi.org/10.1088/1748-9326/11/8/085005>, 2016.
- Park, H., Kim, Y., and Kimball, J. S.: Widespread permafrost vulnerability and soil active layer increases over the high northern latitudes inferred from satellite remote sensing and process model assessments, *Remote Sensing of Environment*, 175, 349–358, <https://doi.org/10.1016/j.rse.2015.12.046>, 2016.
- Pearson, R. G., Phillips, S. J., Loranty, M. M., Beck, P. S. A., Damoulas, T., Knight, S. J., and Goetz, S. J.: Shifts in Arctic vegetation and associated feedbacks under climate change, *Nature Climate Change*, 3, 673–677, <https://doi.org/10.1038/nclimate1858>, 2013.
- Pix4D SA: Pix4Dmapper, 2019.
- Pomeroy, J. W., Marsh, P., and Gray, D. M.: Application of a distributed blowing snow model to the Arctic, *Hydrological Processes*, 11, 1451–1464, [https://doi.org/10.1002/\(SICI\)1099-1085\(199709\)11:11<1451::AID-HYP449>3.0.CO;2-Q](https://doi.org/10.1002/(SICI)1099-1085(199709)11:11<1451::AID-HYP449>3.0.CO;2-Q), 1997.
- Pomeroy, J. W., Bewley, D. S., Essery, R. L. H., Hedstrom, N. R., Link, T., Granger, R. J., Sicart, J. E., Ellis, C. R., and Janowicz, J. R.: Shrub tundra snowmelt, *Hydrological Processes*, 20, 923–941, <https://doi.org/10.1002/hyp.6124>, 2006.
- Quinton, W., Gray, D., and Marsh, P.: Subsurface drainage from hummock-covered hillslopes in the Arctic tundra, *Journal of Hydrology*, 237, 113–125, [https://doi.org/10.1016/S0022-1694\(00\)00304-8](https://doi.org/10.1016/S0022-1694(00)00304-8), 2000.
- Stocker, Romanovsky, V. E. and Osterkamp, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley E.: Interannual variations of the thermal regime of the active layer and near-surface permafrost in northern Alaska, *Permafrost and Periglacial Processes*, 6, 313–335, <https://doi.org/10.1002/ppp.3430060404>, 1995.
- Ropars, P. M., eds.: *Climate Change 2013: The Physical Science Basis*, Cambridge University Press, , IPCC, 2013, 2013. and Boudreau, S.: Shrub expansion at the forest–tundra ecotone: spatial heterogeneity linked to local topography, *Environmental Research Letters*, 7, 015501, <https://doi.org/10.1088/1748-9326/7/1/015501>, 2012.
- Street, L. E., Subke, J.-A., Baxter, R., Dinsmore, K. J., Knoblauch, C., and Wookey, P. A.: Ecosystem carbon dynamics differ between tundra shrub types in the western Canadian Arctic, *Environmental Research Letters*, 13, 084014, <https://doi.org/10.1088/1748-9326/aad363>, 2018.
- Sturm, M. and Holmgren, J.: An Automatic Snow Depth Probe for Field Validation Campaigns, *Water Resources Research*, 54, 9695–9701, <https://doi.org/10.1029/2018WR023559>, 2018.
- Sturm, M., McFadden, J. P., Liston, G. E., Chapin, III, F. S., Racine, C. H., and Holmgren, J.: Snow-Shrub Interactions in Arctic Tundra: A Hypothesis with Climatic Implications, *Journal of Climate*, 14, 336–344, [https://doi.org/10.1175/1520-0442\(2001\)014<0336:SSIIAT>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<0336:SSIIAT>2.0.CO;2), 2001a.
- Sturm, M., Racine, C., and Tape, K.: Increasing shrub abundance in the Arctic, *Nature*, 411, 546–547, <https://doi.org/10.1038/35079180>, 2001. 2001b.
- Sturm, M., Douglas, T., Racine, C., and Liston, G. E.: Changing snow and shrub conditions affect albedo with global implications, *Journal of Geophysical Research: Biogeosciences*, 110, G01004, <https://doi.org/10.1029/2005JG000013>, 2005a.

- Sturm, M., Schimel, J., Michaelson, G., Welker, J., Oberbauer, S., Liston, G., Fahnestock, J., and Romanovsky, V.: Winter Biological Processes Could Help Convert Arctic Tundra to Shrubland, *BioScience*, 55, 17–26, [https://doi.org/10.1641/0006-3568\(2005\)055\[0017:WBPCHC\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2005)055[0017:WBPCHC]2.0.CO;2), 2005. 2005b.
- Swanson, D. K.: Environmental Limits of Tall Shrubs in Alaska's Arctic National Parks, *PLOS ONE*, 10, 1–34, <https://doi.org/10.1371/journal.pone.0138387>, 2015.
- Sweet, S. K., Gough, L., Griffin, K. L., and Boelman, N. T.: Tall Deciduous Shrubs Offset Delayed Start of Growing Season Through Rapid Leaf Development in the Alaskan Arctic Tundra, *Arctic, Antarctic, and Alpine Research*, 46, 682–697, <https://doi.org/10.1657/1938-4246-46.3.682>, 2014.
- Tape, K., Sturm, M., and Racine, C.: The evidence for shrub expansion in Northern Alaska and the Pan-Arctic, *Global Change Biology*, 12, 686–702, <https://doi.org/10.1111/j.1365-2486.2006.01128.x>, 2006.
- Tape, K. D., Hallinger, M., Welker, J. M., and Ruess, R. W.: Landscape Heterogeneity of Shrub Expansion in Arctic Alaska, *Ecosystems*, 15, 711–724, <https://doi.org/10.1007/s10021-012-9540-4>, 2012.
- Walker, D. A., Jia, G. J., Epstein, H. E., Raynolds, M. K., Chapin, III, F. S., Copass, C., Hinzman, L. D., Knudson, J. A., Maier, H. A., Michaelson, G. J., Nelson, F., Ping, C. L., Romanovsky, V. E., and Shiklomanov, N.: Vegetation – soil-thaw-depth relationships along a low-arctic bioclimate gradient, Alaska: synthesis of information from the ATLAS studies, *Permafrost and Periglacial Processes*, 14, 103–123, <https://doi.org/10.1002/ppp.452>, 2003.
- Walker, D. A., Raynolds, M. K., Daniëls, F. J. A., Einarsson, E., Elvebakk, A., Gould, W. A., Katenin, A. E., Kholod, S. S., Markon, C. J., Melnikov, E. S., Moskalenko, N. G., Talbot, S. S., Yurtsev, B. A., and The other members of the CAVM Team: The Circumpolar Arctic vegetation map, *Journal of Vegetation Science*, 16, 267–282, <https://doi.org/10.1111/j.1654-1103.2005.tb02365.x>, 2005.
- Walker, D. A., Epstein, H. E., Romanovsky, V. E., Ping, C. L., Michaelson, G. J., Daanen, R. P., Shur, Y., Peterson, R. A., Krantz, W. B., Raynolds, M. K., Gould, W. A., Gonzalez, G., Nicolsky, D. J., Vonlanthen, C. M., Kade, A. N., Kuss, P., Kelley, A. M., Munger, C. A., Tarnocai, C. T., Matveyeva, N. V., and Daniëls, F. J. A.: Arctic patterned-ground ecosystems: A synthesis of field studies and models along a North American Arctic Transect, *Journal of Geophysical Research: Biogeosciences*, 113, G03S01, <https://doi.org/10.1029/2007JG000504>, 2008.
- Wang, W., Rinke, A., Moore, J. C., Ji, D., Cui, X., Peng, S., Lawrence, D. M., McGuire, A. D., Burke, E. J., Chen, X., Decharme, B., Koven, C., MacDougall, A., Saito, K., Zhang, W., Alkama, R., Bohn, T. J., Ciais, P., Delire, C., Gouttevin, I., Hajima, T., Krinner, G., Lettenmaier, D. P., Miller, P. A., Smith, B., Sueyoshi, T., and Sherstiukov, A. B.: Evaluation of air–soil temperature relationships simulated by land surface models during winter across the permafrost region, *The Cryosphere*, 10, 1721–1737, , 2016.
- Widhalm, B., Bartsch, A., Leibman, M., and Khomutov, A.: Active-layer thickness estimation from X-band SAR backscatter intensity, *The Cryosphere*, 11, 483–496, <https://doi.org/10.5194/tc-11-483-2017>, 2017.
- Wilcox, E. J., Keim, D., de Jong, T., Walker, B., Sonnentag, O., Sniderhan, A. E., Mann, P., and Marsh, P.: Tundra shrub expansion may amplify permafrost thaw by advancing snowmelt timing, *Arctic Science*, , accepted5, 202–217, <https://doi.org/10.1139/as-2018-0028>, 2019.
- Zhang, T.: Influence of the seasonal snow cover on the ground thermal regime: An overview, *Reviews of Geophysics*, 43, RG4002, <https://doi.org/10.1029/2004RG000157>, 2005.
- Zhang, T., Osterkamp, T. E., and Stamnes, K.: Influence of the Depth Hoar Layer of the Seasonal Snow Cover on the Ground Thermal Regime, *Water Resources Research*, 32, 2075–2086, , 1996.
- Zhang, Y., Olthof, I., Fraser, R., and Wolfe, S. A.: A new approach to mapping permafrost and change incorporating uncertainties in ground conditions and climate projections, *The Cryosphere*, 8, 2177–2194, <https://doi.org/10.5194/tc-8-2177-2014>, 2014.

Zhang, Y., Sherstiukov, A. B., Qian, B., Kokelj, S. V., and Lantz, T. C.: Impacts of snow on soil temperature observed across the circumpolar north, *Environmental Research Letters*, 13, 044 012, , 2018.

Zwieback, S., Chang, Q., Marsh, P., and Berg, A.: Shrub tundra ecohydrology: rainfall interception is a major component of the water balance, *Environmental Research Letters*, <https://doi.org/10.1088/1748-9326/ab1049>, 2019.