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Variability and drivers of winter near-surface temperatures over boreal and tundra landscapes

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Abstract. Winter near-surface temperatures have important implications for ecosystem functioning such as vegetation dynamics and carbon cycling. In cold environments, seasonal snow cover can exert a strong control on the surface temperatures. However, the lack of in situ measurements of both snow cover and surface temperatures over high latitudes has made it difficult to estimate the spatio-temporal variability of this relationship. Here, we quantified the fine-scale variability of winter near-surface temperatures (+2 cm) and snow cover duration using a total of 441 microclimate loggers in seven study areas across boreal and tundra landscapes during 2019–2021. We further examined the drivers behind this variation and the extent to which surface temperatures are buffered from air temperatures during winter. Our results show that while average winter near-surface temperatures stay close to 0 °C across the study domain, there are large differences in their fine-scale variability among the study areas. Areas with large topographical variation, as well as areas with shallow snowpacks, showed the greatest variation in near-surface temperatures and in the insulating effect of snow cover. In the tundra, for example, differences in minimum near-surface temperatures were close to 30 °C. In contrast, flat topography and deep snow cover lead to little spatial variation and decoupling of the near-surface and air temperatures. Quantifying and understanding the landscape-wide variation in winter microclimates improves our ability to predict the local effects of climate change in the rapidly warming boreal and tundra regions.

1 Introduction

Boreal and tundra ecosystems are experiencing rapid climatic change, with average temperatures rising at 2–4 times the rate of global average temperatures in recent decades (Post et al., 2019; Rantanen et al., 2022). This macroclimatic trend (i.e., the overall trend in ambient air temperatures) is particularly pronounced during the winter months, and causes changes in the cryosphere that strongly feed back into the macroclimatic warming (Ruosteenoja et al., 2016; Bintanja and Andry, 2017;

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Bormann et al., 2018). Warmer winters have led to shorter snow cover duration and shallower snowpacks(Brown and Mote, 2009; Luomaranta et al., 2019), although increasing winter precipitation may have counteracting effects in some regions (Kellomäki et al., 2010). It is insufficiently investigated how these wintertime macroclimatic changes translate into microclimatic conditions, such as thermal conditions at and near ground surface. Near-surface temperatures have been shown to be essential for understanding for example species distributions and vegetation dynamics (Ashcroft and Gollan, 2012; Opedal et al., 2015; De Frenne et al., 2021). They also control largely ground temperatures which in turn influence the survival of wildlife (Kohler and Aanes, 2004) and ecosystem processes, such as greenhouse gas fluxes and seasonal frost (Semenchuk et al., 2016; Groffman et al., 2001; Larsen et al., 2007). However, it is not yet fully understood how near-surface temperatures vary over boreal and tundra regions as a function of air temperature and local environment, such as snow cover (De Frenne et al., 2021; Aalto et al., 2022).

Microclimates can differ significantly from the macroclimate due to local climatic processes (Aalto et al., 2017; De Frenne et al., 2021). Elevation influences microclimatic air temperatures through the atmospheric lapse rate, with temperatures typically decreasing at higher altitudes, although in landscapes with strong elevational gradients, cold-air pooling is also an important driver of winter air temperatures (Daly et al., 2010). At finer scales, topography influences both microclimatic temperatures and snow cover patterns for example, by controlling the spatial distribution of incoming solar radiation and wind drift (Barry and Blanken, 2016; Sanders-DeMott and Templer, 2017). Vegetation structure, such as canopy cover, controls radiation and heat fluxes within the canopy, and in turn, buffers the forest microclimate relative to ambient temperatures outside the forest (De Frenne et al., 2021). A dense forest reduces snow accumulation below the canopy by intercepting part of the snowfall, and is also likely to slow down snow melt during spring through energy balance controls (Koivusalo and Kokkonen, 2002; Ellis et al., 2011). These processes can lead to substantial fine-scale heterogeneity in microclimatic air temperatures and snow cover, and consequently in near-surface temperatures (Aalto et al., 2017; Sanders-DeMott and Templer, 2017). So far, the lack of empirical data has precluded quantitative assessments of these links across boreal and tundra landscapes.

In cold ecosystems, the thermal buffering between microclimate and macroclimate is most pronounced in winter, when seasonal snow cover acts as an insulator between the air and the ground and can sometimes completely separate (i.e. decouple) near-surface temperature variability from ambient air temperatures (Grundstein et al., 2005; Zhang, 2005; Aalto et al., 2018). A deep snowpack, particularly early in the winter, can decouple ground temperatures from the macroclimate as the ground temperatures remain close to 0 °C throughout the winter, whereas a shallow snowpack or absense of snow can expose ground surfaces to large variability and harsh temperatures (Grundstein et al., 2005; Pauli et al., 2013). A deep snowpack has been shown to increase soil respiration rates and shelter low-lying vegetation and roots from fluctuating air temperatures and erosive ice particles that affect vegetation growth in cold climates (Tierney et al., 2001; Nobrega and Grogan, 2007). On the other hand, a late-melting snowpack can keep near-surface temperatures colder than surrounding air temperatures during spring and early summer, limiting the onset of the growing season (Farbrot et al., 2011; Kankaanpää et al., 2018; Kelsey et al., 2021). However, the properties of a snowpack (e.g. depth, density, albedo) can vary considerably, both spatially and temporally, influencing the thermal conductivity of snow packs and thus its impact on ground thermal regime (Sturm et al., 1997; Domine et al., 2016). This variation is impractical to measure at fine spatial resolution over large spatial domains which complicates the assessments of fine-scale effects of snow cover on the near-surface temperatures. Furthermore, as boreal and tundra ecosystems cover a wide range of winter macroclimates, the impact and importance of snow cover on near-surface surface temperatures is expected to vary both regionally and from year to year.

The local-scale implications of rapidly changing winters at high latitudes are not yet fully understood. Furthermore, the importance of different landscape characteristics on microclimates may vary between regions and from one season and winter to the next, and it is important to understand this variability and its drivers (Barry and Blanken, 2016; Aalto et al., 2022). In this study, we 1) quantify the local variability of winter near-surface temperatures and snow cover in several boreal and tundra landscapes in northern Europe, 2) analyse the landscape-scale drivers of the variation, and 3) quantify the magnitude of the buffering of surface temperatures from air temperatures. Our study design consists of a large dataset of microclimatic stations (n=441) covering different boreal and tundra landscapes in Finland. We used structural equation modelling to investigate the hierarchical relationships among the predictors. Of the two study winters (2019–2020 and 2020–2021), the first one was unusually warm, and represents conditions that are likely to become more common under climate change while the second winter was closer to average winter conditions during the normal period 1991–2020.

2 Material and methods

2.1 Study area

The study domain consists of seven focal landscapes, covering large climatic and environmental gradients from hemiboreal forests in southern Finland to oroarctic tundra in the Scandean mountains in northern Finland (Aalto et al., 2022). The macroclimate is strongly influenced by the proximity to the Arctic Ocean in the north, the Baltic Sea in the south and west, and the Eurasian continent in the east (Tikkanen, 2005). Winter conditions vary considerably across the region: average temperatures in February vary from -5 °C in the southernmost study area to -12 °C in the north, while the length of the continuous snow cover period varies from three to seven months, respectively (normal period 1991–2020; Jokinen et al., 2021; Finnish Meteorological Insitute, 2022). The topographic relief in the study areas varies from nearly flat peatlands to areas with pronounced topographical variation, particularly in the north.

All seven study areas are situated in nature reserves and other protected areas in locations that represent different unmanaged environmental conditions of boreal and tundra regions (Fig. 1). Three of the study areas are located in northern Finland and have large elevational gradients extending below and above the tree line. Two of these, Mounts Malla (MAL) and Ailakkavaara (AIL) in Kilpisjärvi, are in the north-west, and one, Värriö Strict Nature Reserve (VAR), in the north-east. Two boreal study areas are dominated by peatlands and relatively flat topography: Tiilikkajärvi National Park (TII) in central Finland and the Hyytiälä region, including the Siikaneva National Park in southern Finland. Another boreal study area around the Pisa Nature Reserve in central Finland (PIS) is characterized by varied topography. The Karkali Nature Reserve (KAR) lies in the southern hemiboreal zone and is surrounded by Lake Lohjanjärvi.

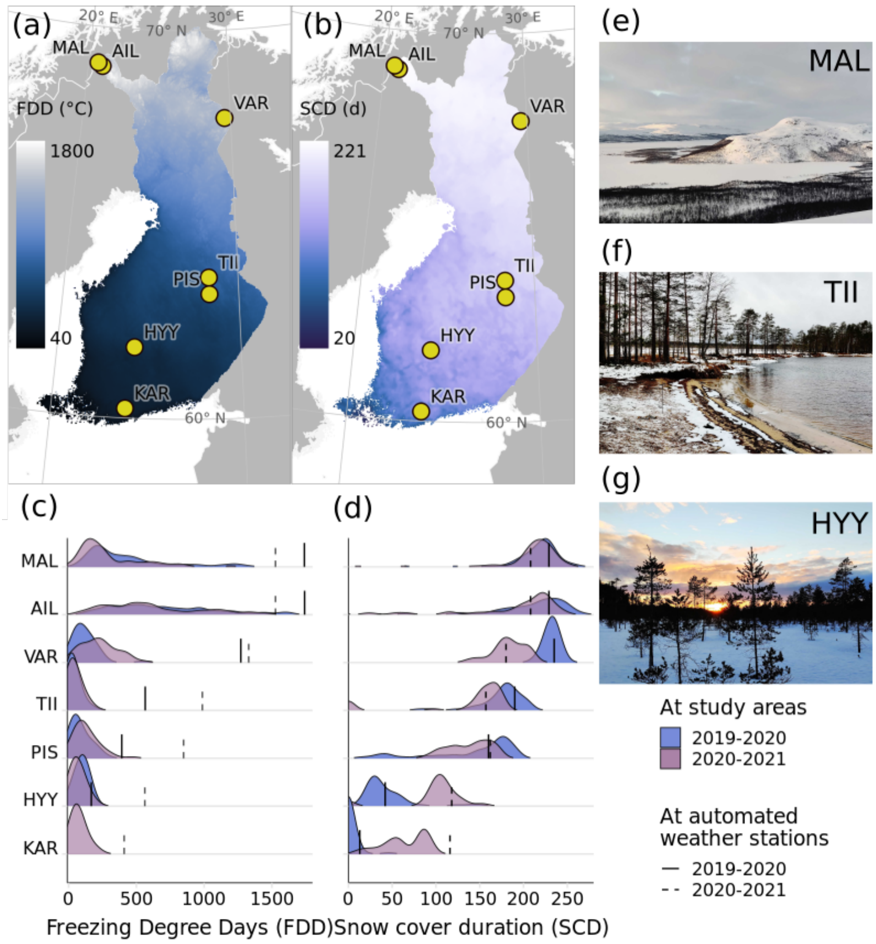

Figure 1. Study domain and winter temperature and snow conditions. Panels (a) and (b) represent the locations of the seven study areas in relation to (a) maximum winter freezing degree days (FDD) (1991–2020) and (b) average snow cover duration (SCD; 1991–2020) in Finland. Panel (c) shows variation in the near-surface FDD within each study area during the study winters (2019–2020 and 2020–2021). Panel (d) shows variation in snow cover duration during the study period. Field photos from MAL, TII and HYY are shown in panels (e), (f) and (g). Study area abbreviations are defined in the main text, section 2.1.

2.2 Microclimate temperature data

Each study area contains 50–100 study sites equipped with microclimate stations that continuously measure air and surface temperature throughout the year. The locations of the study sites were randomly chosen to characterize the main environmental gradients within each study area based on topographical variation, vegetation properties and land surface characteristics (Aalto et al., 2022). Each study site consists of one Tomst TMS-4 logger (Wild et al., 2019), which measures soil and near-surface temperature at three heights (-6 cm, 2 cm, and 15 cm) with a precision of 0.0625 °C and an accuracy of ±0.5 °C. In this study, we used the near-surface temperature at 2 cm height (ST) which allowed us to focus on the insulating effect of snow cover and to more reliably compare surface temperatures between areas with highly varying soil properties. Additionally, air temperature (AT) at 1.5 m height was measured using either a LogTag HAXO-8 (LogTag North America Inc.; precision of 0.1 °C; ±accuracy 0.3 °C for ambient temperatures from 0 °C to 50 °C and ±0.6 °C for ambient temperatures below 0 °C) or the Onset HOBO U23 Pro v2 logger (Onset Computer Corporation; precision 0.04 °C; accuracy ±0.2 °C from 0 to 70 °C and ±0.25 from -40 to 0 °C). These loggers were placed at all study sites except in MAL and AIL, which each had 100 TMS-4 loggers and 40 air temperature loggers. The AT loggers were placed under white, well-ventilated radiation shields on the north-facing side of a tree or a pole to mitigate exposure to solar radiation. Logging intervals were set to 15, 30 and 120 minutes for the TMS-4, HOBO and HAXO loggers, respectively. The study period covered two winters, 2019–2020 and 2020–2021. However, not all loggers remained functional throughout the study period and thus the data from winter 2020–2021 contain fewer loggers (Table A1). The data were also checked to correct errors such as systemically too high or low temperature measurements and erroneous peaks as well as errors arising from damaged or dislocated loggers (Aalto et al., 2022).

2.3 Macroclimate data

Hourly weather data, consisting of free-air temperatures measured at 2 m height and snow depth, for the study period of 01 Jan 2019 – 30 Jun 2021 and long-term averaged climate data for the most recent normal period, 1991–2020, were acquired from the nearest automated weather station (operated by the Finnish Meteorological Institute) to each study area. Gridded climate data (2 m air temperature and snow cover duration) were extracted from the Climgrid dataset (Aalto et al. (2016); available at https://en.ilmatieteenlaitos.fi/gridded-observations-on-aws-s3). The dataset represents daily weather station observations interpolated to a 1km*1km grid using statistical interpolation with guiding variables such as topography and land cover.

2.4 Snow cover duration

The snow cover duration and the first and last days of the snow season were calculated based on the variability of the near-surface temperature (+15 cm) as recorded by the TMS-4 loggers. The loggers were estimated to be under snow when the diurnal temperature range was less than 1 °C, the maximum surface temperature stayed below 1 °C within a centered 9-day moving window and the temperature range was below 2 °C calculated with the same 9-day moving window which was qualitatively considered as an optimal window size to minimize the risk of separating otherwise stable and cold conditions from snow covered periods. Lastly, because the moving window will slightly underestimate the snow cover duration, we tuned the snow calculations with a 5-day centered moving window where all days were deemed as snow-days if any day within the moving window was a snow-day. The deployed algorithm can be considered as conservative, and it represents the days when the snow cover is deep enough to buffer the near-surface temperatures effectively. In addition, the outcome was visually inspected for each logger (Fig. A1). While determining the snow cover duration with this method is challenging in situations where snow depth varies close to the height of the sensor, these situations were rare in our study domain, and the algorithm was considered to detect periods of snow cover reasonably well. On average the snow cover onset and offset dates are close to those measured at the nearby weather stations (Fig. A2). The code for calculating the snow cover duration is available in the study-area-specific Github repositories (https://github.com/poniitty?tab=repositories).

2.5 Geospatial datasets

We utilized several open geospatial datasets to understand how different landscape characteristics affect ground thermal conditions, snow cover duration and local air temperatures. For topographical variables, we used LiDAR (light detection and ranging) data provided by the National Land Survey of Finland (NLSF; https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/expert-users/product-descriptions/laser-scanning-data), collected in 2016–2019. From these data, we calculated a digital terrain model (DTM) with a resolution of 2 m for each study area using the lidR R library (Roussel et al., 2020). From the DTM, we calculated the annual sum of potential incoming solar radiation (PISR) using the Potential Incoming Solar Radiation tool in the SAGA-GIS software (version 7.6.2; http://www.saga-gis.org/saga_tool_doc/7.6.2/ta_lighting_2.html). We also calculated the Topographic Position Index (TPI) which describes the elevational difference between a point and its surroundings using a radius of 20 m and 500 m (hereafter, TPI20 and TPI500). It was calculated using the Topographic Position Index tool in SAGA-GIS (http://www.saga-gis.org/saga_tool_doc/7.6.2/ta_morphometry_18.html). A canopy height model (resolution 1 m) based on the same LiDAR data described above was provided by the Finnish Forest Center (https://www.metsakeskus.fi/fi/avoin-metsa-ja-luontotieto/aineistot-paikkatieto-ohjelmille/paikkatietoaineistot). This was used to calculate canopy cover, defined as the proportion of minimum 2 meters high vegetation within a 5 m radius.

2.6 Statistical analyses

We used a structural equation modelling framework (SEM) to study the direct and indirect links between the spatial variation in temperatures, snow cover, topography and canopy cover. SEM is a statistical method for combining pathways of multiple predictor and response variables into a single hierarchical network (Grace et al., 2010). We used the SEM implementation in the R package ‘piecewiseSEM’, version 2.1.0 (Lefcheck, 2016). In SEM, variables can appear as both predictors and responses (i.e. endogenous variables), thus allowing the investigation of indirect, mediating or cascading effects of a multivariate system (Lefcheck, 2016).

The air and near-surface temperature variables for the SEMs were calculated as two-week averages of the temperatures in the middle and end of the snow cover season for each study area. The end of the snow cover season was estimated to be when 90 % of the study sites within the study area were snow-free. Snow cover in the mid-season models describes the total number of days with snow cover and the end date of the snow cover season in the late-season models. We also expected that the strength of the links between variables may be different in the more southern and northern regions, and thus, fitted the SEMs separately for the four southernmost (KAR, HYY, PIS and TII) and three northernmost study areas (VAR, MAL and AIL). Additionally, our dataset includes data from two winters that had very different snow conditions for many of the study areas. Thus, we decided to fit the SEMs also separately for the two winters. Therefore, two study periods, two winters and two spatial study domains resulted in eight different models.

In addition to the temperature variables, we included four topographic variables (namely elevation, TPI500, TPI20 and PISR), and the snow cover duration and canopy cover. SEM is a hypothesis-driven method where a SEM network is first constructed based on prior knowledge on how the system functions. We expected solar radiation to have only a marginal effect in mid-winter and therefore only included PISR in the SEMs for late winter conditions. Otherwise the structure of the SEMs was similar in all eight models. Because the study sites are spatially aggregated within the seven landscapes we included the study area as a random intercept in all sub-models in each SEM. The structure of the fitted SEMs is presented alongside the numerical modelling results in Fig. 5.

To estimate the buffering of near-surface temperatures from local air temperatures, we calculated the slope of a linear regression model (beta) between near-surface and air temperatures using a 2-week moving window throughout both winters.

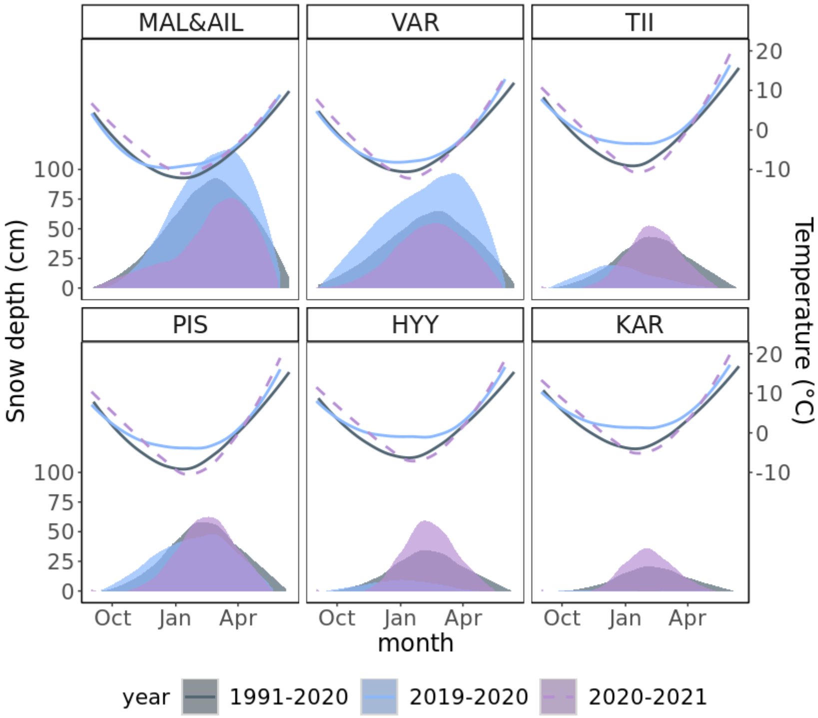

Figure 2. Mean monthly air temperature (lines) and snow depth (polygons) smoothed with local regression during winters 2019–2020 and 2020–2021, as well as during the normal period of 1991–2020, measured in the closest automated weather station to each study region. MAL and AIL are combined as they share the closest weather station.

3 Results

3.1 Macroclimatic variation

Macroclimate and snow conditions varied between the two winters (2019–2020 and 2020–2021) and between the seven study areas (Fig. 2). The winter of 2019–2020 was generally warmer, particularly in midwinter and in southern and central Finland where mean February temperatures were nearly 10 °C warmer than during the normal period 1991–2020 and during 2020–2021. In northern Finland, temperature differences between the two years were smaller. The winter of 2020–2021 was similar to the last normal period throughout Finland, although the autumn was generally a few degrees warmer. Snow depth in 2019–2020 varied from non-existing in southernmost parts of Finland to more than 100 cm in the northernmost part of Finland. In 2020–2021, snow depths varied less across Finland and each study area had several months of snow cover. While the maximum snow depth in 2020–2021 was slightly higher than average in the southern parts and slightly lower in the north, the length of the snow cover season was shorter, particularly in southern and central Finland.

3.2 Microclimatic variation

At the ground surface, mean winter temperatures varied little compared to air temperatures (Fig. 3 a-b). Mean February near-surface temperatures averaged over the study areas varied from 0 °C (KAR, Feb 2020) to -4 °C (AIL, Feb 2021), while local air temperatures varied from 1 °C (KAR, Feb 2020) to -14 °C (VAR, Feb 2021; Fig. 3 a-b). In February, which was in the middle of the snow cover period in all study areas, the within-area variation in mean near-surface temperatures was small, except in MAL and AIL where temperatures varied from 0 to -11 °C (Fig. 3 a). There was also more variation in winter minimum near-surface temperatures which varied on average by 10 degrees within the study areas and by 30 degrees in the northernmost study areas (Fig. 3 c). Variance in the minimum air temperatures within areas ranged from less than 10 degrees in the southern areas to 20 degrees in the northern areas, but in general the variation in air temperatures was smaller than in the near-surface temperatures (Fig. 3 c-d). Largest spatial variation of near-surface temperatures was observed in the northernmost (AIL and MAL) study areas (Fig. 1 c-d and 4). In TII, near-surface temperatures showed the least spatial variation, with nearly all microclimate loggers recording close to 0 °C during both winters (Fig. 4). There were large differences in February mean and overall minimum air temperatures between the two winters. In the southern areas, the air temperature difference was nearly 10 °C, whereas the pattern was not as clearly visible in near-surface temperatures, which varied on average by only a few degrees between years.

The duration and timing of the snow cover period also varied within and between the study areas (Fig. 1 c-d and 3 e-f). The average length of the snow cover period ranged from almost nine months in the north (AIL; 2019–2020) to zero days in the south (KAR; 2019–2020) (Fig. 3 e-f). Within the study areas, there was generally less variation at the beginning of the period than at the end of the period (Fig. 3 e-f). First snow reached most study sites within each area in less than a month but in MAL and AIL in 2019–2020, the date of first snow varied by two months among study sites (Fig. 3 e). The length of the snowmelt period was less than a month in VAR in 2019–2020 and one to five months in the other areas (Fig. 3 f).

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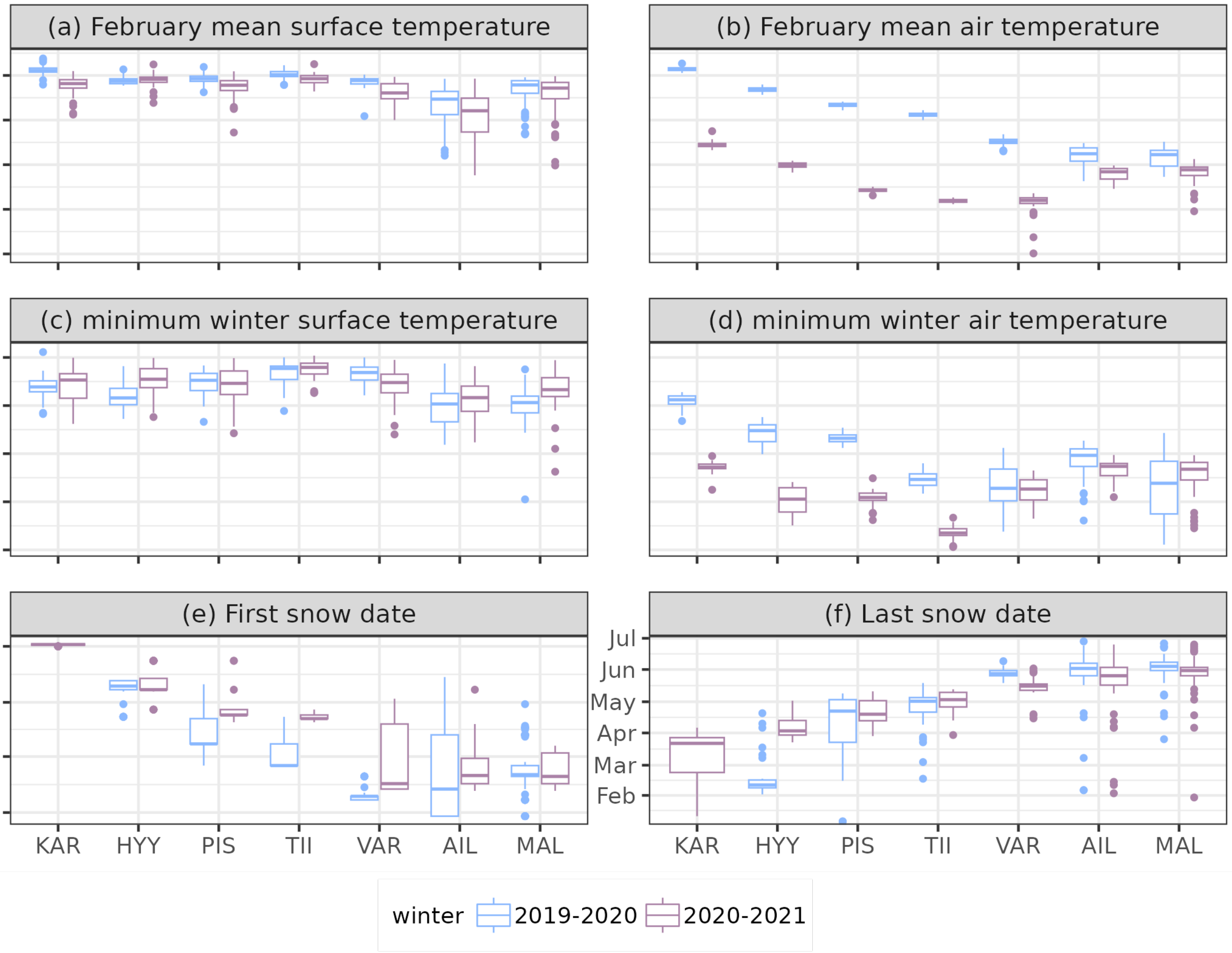

Figure 3. Variation in winter temperatures and snow cover in the seven study areas during two winters, 2019–2020 and 2020–2021. Figures (a) and (b) show average near-surface and air temperatures in February and figures (c) and (d) show minimum near-surface and air temperatures of the whole winter. Figures (e) and (f) show the onset and offset dates of snow cover.

3.3 Drivers of near-surface temperature variability

Structural equation models revealed season and area-specific controls for near-surface and air temperatures and snow cover duration (Fig. 5). According to Fisher's C statistics, all SEMs provided an adequate fit to the data with C ranging from 0.3 to 200 8.3 (p>0.05). In the northern areas, local air temperatures and snow cover duration were mostly controlled by elevation and local topography although the effects varied somewhat between seasons (Fig. 5 a-b). Elevation, for example, had a moderate positive effect (0.40, averaged over two winters) on mid-winter air temperatures but a moderate negative effect in late winter (-0.53) while fine-scale TPI had a weak negative effect on snow cover duration (-0.26). In the southern areas, canopy cover had

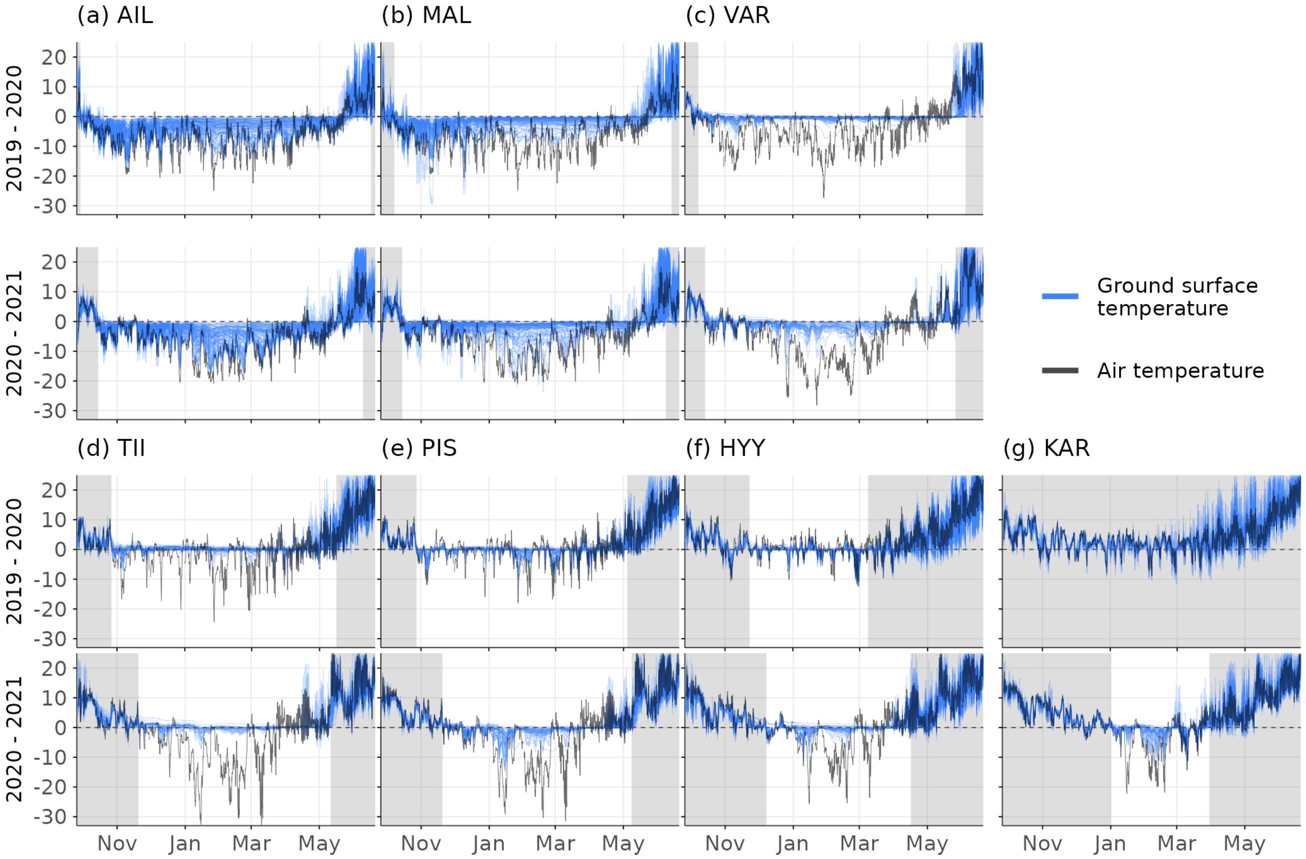

Figure 4. Variation of near-surface temperatures and snow cover timing during winters 2019–2020 and 2020–2021. Winter temperatures at each measurement site over the study areas are shown in the blue lines and nearest weather station temperature in the black line. The shaded areas delineate snow cover periods.

a weak negative effect on air temperature (-0.22) and a weak positive effect on SCD (0.11) (Fig. 5 c-d). In late winter, PISR had a weak negative effect (-0.26) on snow cover in both northern and southern areas (Fig. 5 b and d).

Both air temperatures and snow cover duration had a large effect in controlling near-surface temperatures. Snow cover duration had a strong positive effect (0.73) in mid-winter and a moderate negative effect (-0.49) in late winter, whereas air temperature mostly had a strong positive effect (0.81), except in mid-winter in northern areas where the effect was negative (-0.34). In mid-winter, canopy cover had a weak positive effect (0.23) on near-surface temperatures. Some effects in the models varied considerably between the two years. Most notably, local topography (both TPIs and PISR) had a significant effect on near-surface temperatures in the north only in winter 2020–2021. In southern areas, air temperatures in late winter had a positive effect (0.40) on snow cover duration in 2019–2020 but a negative effect (-0.19) in 2020–2021. The explained conditional variance, R^2, was generally higher in the two temperature models than in the snow cover model and in the southern areas than in the northern areas.

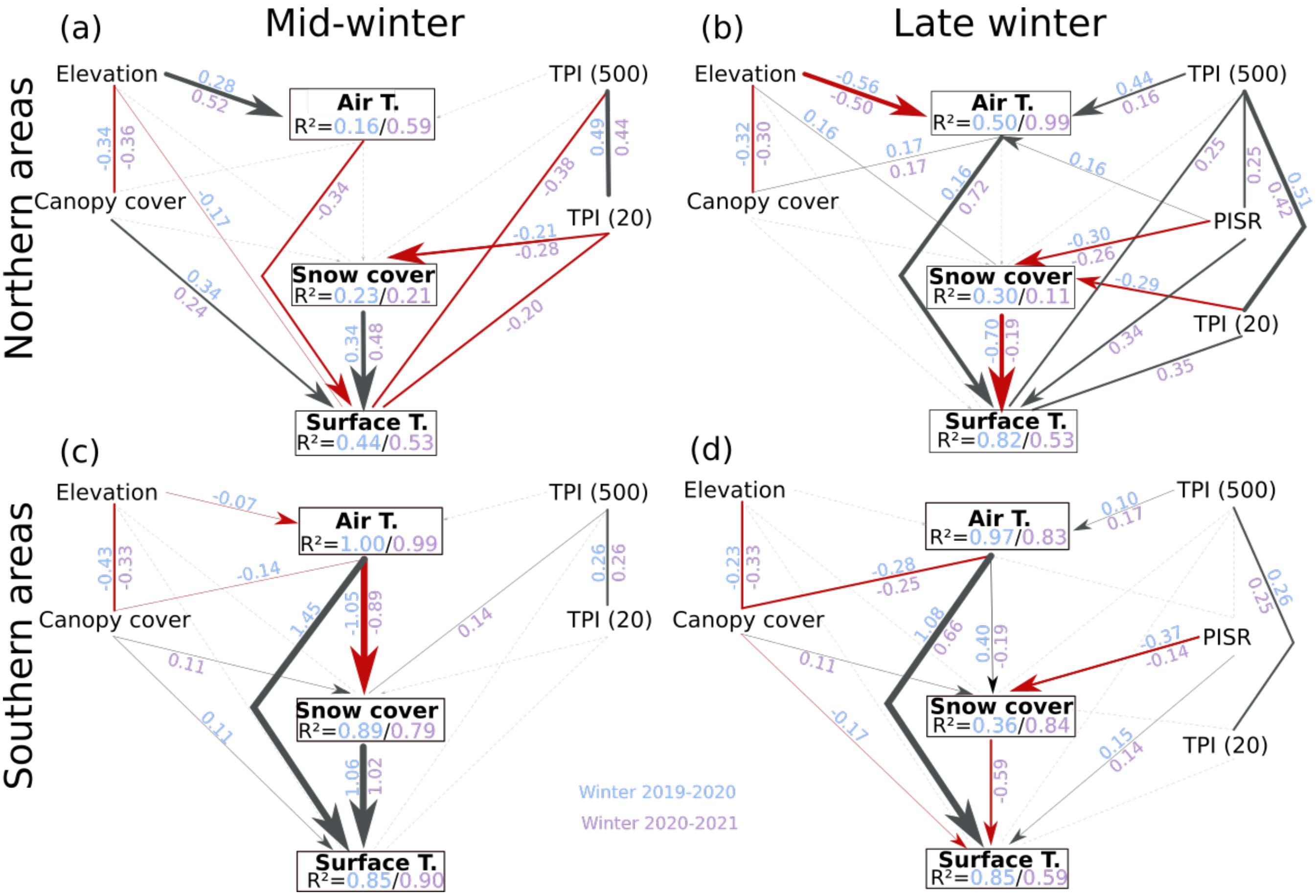

Figure 5. Environmental variables influencing air temperatures (shortened as Air T.) and near-surface temperatures (Surface T.) and snow cover duration (snow cover) in the middle of winter (a and c) and at the end of the snow cover period (b and d). Northern areas (a and b) include AIL, MAL and VAR, and southern areas (c and d) include TII, PIS, HYY and KAR. Statistically significant (P < 0.05) correlations are presented with their standardised regression slopes placed on the correlation lines. Black line indicates a positive correlation and red a negative one. Lines with no arrows indicate residual correlations. Correlations that were tested but were not found to be significant (P >0.05) are shown with light grey lines. The amount of explained variance is expressed as conditional R^2.

215 3.4 Magnitude of thermal insulation due to snow

Near-surface temperatures were largely buffered, and in many study sites decoupled (beta=0) from local air temperatures during snow cover periods in all study areas (Fig. 6). Insulation of near-surface temperatures from air temperature followed snow cover duration, increasing in early winter and decreasing again in late winter in all study areas. Insulation was greatest in

TII, VAR and MAL where beta was close to 0.0 in nearly all study sites (Fig. 6 d, c and b). In HYY, and PIS, temperatures were
220 more buffered during winter 2020–2021, when average values of beta were between 0.0-0.2 for most of the winter, whereas in 2019–2020 beta varied both temporally and spatially, ranging between 0.0-0.8 (Fig. 6 e and f). The differences between the two years were most pronounced in KAR where the complete lack of snow cover in 2019–2020 resulted in very little insulation of near-surface (Fig. 6 g). The spatial variation in the insulation of near-surface temperatures was largest in AIL where in some study sites beta remained above 0.5 throughout the winter, particularly in 2020–2021 (Fig. 6 a). In all study areas, the insulation
225 of near-surface temperatures correlated strongly with snow cover duration (Fig. 6 h).

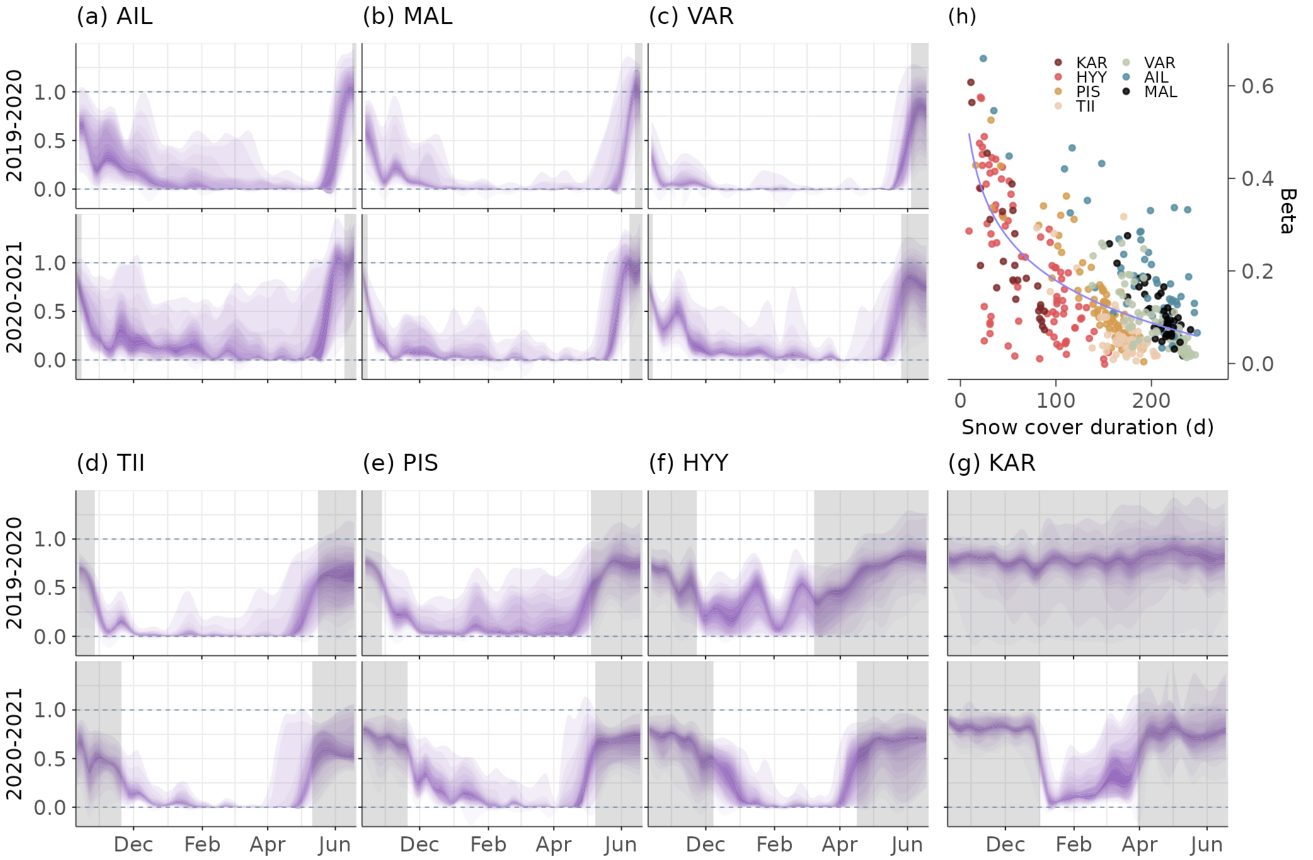

Figure 6. The relationship between in situ measured near-surface and air temperatures in the study areas during winters 2019–2020 and 2020–2021, indicated as the slope of a linear regression model calculated from a two-week moving window. Snow cover period for each study area are delineated with shaded areas. Panel (h) shows correlation and a fitted exponential function between the average length of the snow cover duration and average beta (correlation between near-surface and air temperatures) during the two winters.

4 Discussion

4.1 Winter-time heterogeneity in thermal conditions and snow cover

Our study design covered a wide gradient of winter climates and revealed considerable landscape-scale variability in microclimate temperatures and snow conditions. Air temperatures ranged from short and mild winters in the southern parts of Finland to long and severe winters in the northern tundra areas. There were notable differences between the two winters, as 2019–2020 was unusually warm and snow-free in the southern study areas. While average near-surface temperatures remained close to 0 °C in all study areas, the heterogeneity within the study areas varied considerably. The largest within-area variations (up to nearly 30 °C) in near-surface temperatures were found in the open tundra in northwestern Finland (MAL and AIL) where snow cover duration (and presumably snow depth) also varied the most. In these tundra landscapes, heterogeneous topography and low-lying vegetation strongly influence snow accumulation patterns, creating a mosaic of thermal conditions (Essery and Pomeroy, 2004; Sturm and Wagner, 2010; Gisnås et al., 2014). In contrast, in the flat, peatland-dominated TII, variation in near-surface temperatures was small, as nearly all study sites remained close to 0 °C throughout both winters. In the southern and central Finland study areas, variation in both snow cover duration and near-surface temperatures was greater in 2019–2020. This was likely influenced by the shallow snowpack, due to which some parts of the landscapes melt early that year. This was visible in the southernmost KAR during the winter of 2020–2021, when the area had a long-lasting but shallow snow cover.

4.2 Drivers of variability

The results show that microclimate temperatures and snow cover duration are influenced by topography and vegetation structure. In the northern study areas, elevation and coarse-scale topography (i.e. TPI500) strongly influenced air temperatures. While the relationship between elevation and temperature is typically negative due to the atmospheric lapse rate, our results showed a positive relationship (i.e. inversion) in mid-winter, due to the strong cold-air pooling into topographic depressions and lowlands. This is in line with previous studies that have shown cold-air pooling to be a strong driver of winter temperature variability in landscapes with strong elevational gradients (Nicholas C. et al., 2009; Daly et al., 2010). Fine-scale topography (i.e. TPI20), on the other hand, had a stronger influence on snow cover duration. TPI has been shown to correlate well with snow accumulation patterns in mountain and tundra landscapes although the relevant radius may vary between landscapes (López-Moreno et al., 2017; Bennett et al., 2022). In addition to TPI, incoming solar radiation influenced the distribution of snow cover in late winter. While its impact on melting rates has been shown in previous studies (e.g. Cartwright et al., 2020), some studies have found its relative importance on the distribution of snow to be small compared to other topographical parameters (Schmidt et al., 2009; Revuelto et al., 2014).

In the southern study areas, the influence of topography was largely replaced by canopy cover which influenced both air and near-surface temperatures, as well as snow cover duration. According to our results, there was a negative correlation between canopy cover and air temperatures in both mid and late winter. While forest canopy also tends to buffer minimum temperatures, De Frenne et al. (2019), for example, found the effect on average to be a cooling one. The effect of canopy cover on snow cover duration was positive, which was likely due to slower melting rates within the forests. Previous studies have shown that while snow accumulates more in open areas (Hedstrom and Pomeroy, 1998; Koivusalo and Kokkonen, 2002), the effect of canopy cover on melting rates is more complex, depending on the impacts on longwave and shortwave radiation (Ellis et al., 2011). The variations in canopy structure (for example stand age, tree species) has also been shown to influence snow cover in forests (Ellis et al., 2011; Winkler and Moore, 2006) and may have improved the results.

4.3 Impact of snow cover on winter near-surface temperatures

Our results show that snow cover has a consistent and strong impact on near-surface temperatures. During the winter months, the impact was positive, with longer snow cover periods leading to warmer near-surface temperatures. In nearly all study areas, near-surface temperatures were largely decoupled from air temperatures, and in most study areas, mean near-surface temperatures in February were over 10 °C higher than the corresponding air temperatures. During the late snow cover season, there was a clear negative correlation between snow cover duration and near-surface temperatures. This is in line with previous studies which show that a late-melting snowpack can keep near-surface temperatures considerably colder from late winter to early summer (Zhang, 2005; Farbrot et al., 2011). While this effect is typically shorter and less pronounced than the warming effect in winter, it can have important implications for the onset of the growing season (Kelsey et al., 2021).

The insulating effect of a snow cover is mostly related to its depth and other properties, such as density, rather than to its duration (Zhang, 2005; Farbrot et al., 2011). Nonetheless, our results indicate that snow cover duration is often also related to the insulation of near-surface temperatures. In the study areas where average maximum snow depths were close to or over 1 m and which had long snow cover periods, such as MAL and VAR, the insulating effect was strong throughout both winters. In southern and central Finland, where average maximum snow depths ranged from 0 to 70 cm and where the snow cover period was shorter, the effect was much more spatially and temporally variable. Previous studies have shown that the variability in the insulating effect of snow cover is largest with snow depths below 100 cm (Zhang, 2005; Gisnås et al., 2014), leading to pronounced spatial variations in the near-surface temperatures. However, even deep average snow depths do not necessarily lead to decoupling of near-surface temperatures in all parts of a landscape due to uneven snow accumulation and melting patterns driven by heterogeneous topography, as is seen in AIL as well as in previous studies in tundra regions (Farbrot et al., 2011; Gisnås et al., 2014).

4.4 Winter microclimates in the future

The temperature increase caused by climate change is projected to be particularly strong in the winter months in Finland and other high-latitude regions (Ruosteenoja et al., 2016). In addition to increases in the average and extreme temperatures, the length of the thermal winter is expected to become shorter (Ruosteenoja et al., 2020). These and the projected changes in precipitation also affect snow conditions, although the changes in precipitation are more complex and vary regionally (Luomaranta et al., 2019). However, while both ambient air temperatures and snow cover are important in determining ground thermal conditions, temperatures at the ground surface might not directly follow their changes. Previous studies have shown that in places with seasonal snow cover, despite rising air temperatures in winter, soil and near-surface temperatures might become colder due to reduced snow cover and depth (Brown and DeGaetano, 2011). This cooling depends largely on the magnitude of changes in both air temperatures and snow cover and can therefore vary considerably regionally (Kellomäki et al., 2010). For example, minimum temperatures in southern Finland were on average higher in 2020–2021 despite considerably colder air temperatures due to snow cover. At the local scale, static and more stable landscape characteristics such as topography will continue create fine-scale variation in near-surface temperatures and snow cover (Aalto et al., 2018). However, generally diminishing snowpacks might mean that in some parts of a landscape, snow depths are so shallow that near-surface temperatures stay coupled with air temperatures for most of the winter while in other parts of the landscape, temperatures stay decoupled. This could increase the fine-scale heterogeneity in winters in snow-covered areas. On the other hand, when snow cover is completely absent, which is likely to become more common during future winters in the southern parts of Finland, temperature decoupling decreases drastically, as can be seen for example in KAR in the winter of 2019–2020.

5 Conclusions

Our results highlight the notable variation in local winter near-surface temperatures across boreal and tundra landscapes. The results show pronounced spatial heterogeneity in snow cover duration and its control on winter near-surface temperatures. In general, the greatest variation in both snow cover duration and near-surface temperatures was found in the northern study areas in the tundra where pronounced topographical variability had a strong influence on the near-surface microclimate. Landscape-level microclimate variation was lowest in the flat peatland-dominated areas. The data, consisting of two contrasting winters, also revealed considerable variation in the insulation of near-surface from air temperatures depending on snow conditions. As ground thermal conditions in winter are key drivers of various ecosystem processes, these results provide important new insights into the spatio-temporal variability of winter surface microclimate across boreal and tundra ecosystems, and how these conditions may change in the future.

Code availability. The code to calculate the snow cover duration are available at the study-area-specific Github repositories (https://github.com/poniitty?tab=repositories).

Appendix A

A1

Table A1. Functioning loggers of near-surface temperature (ST) and air temperature (AT) per study area during the two study winters (2019–2020 and 2020–2021).

	ST			AT		
	Total (n)	19-20 (%)	20-21 (%)	Total (n)	19-20 (%)	20-21 (%)
AIL	100	98	92	40	75	70
MAL	100	99	98	40	88	83
VAR	50	98	86	50	96	84
TII	50	100	64	50	92	58
PIS	50	98	98	50	92	90
HYY	50	100	86	50	98	84
KAR	50	92	84	50	92	66

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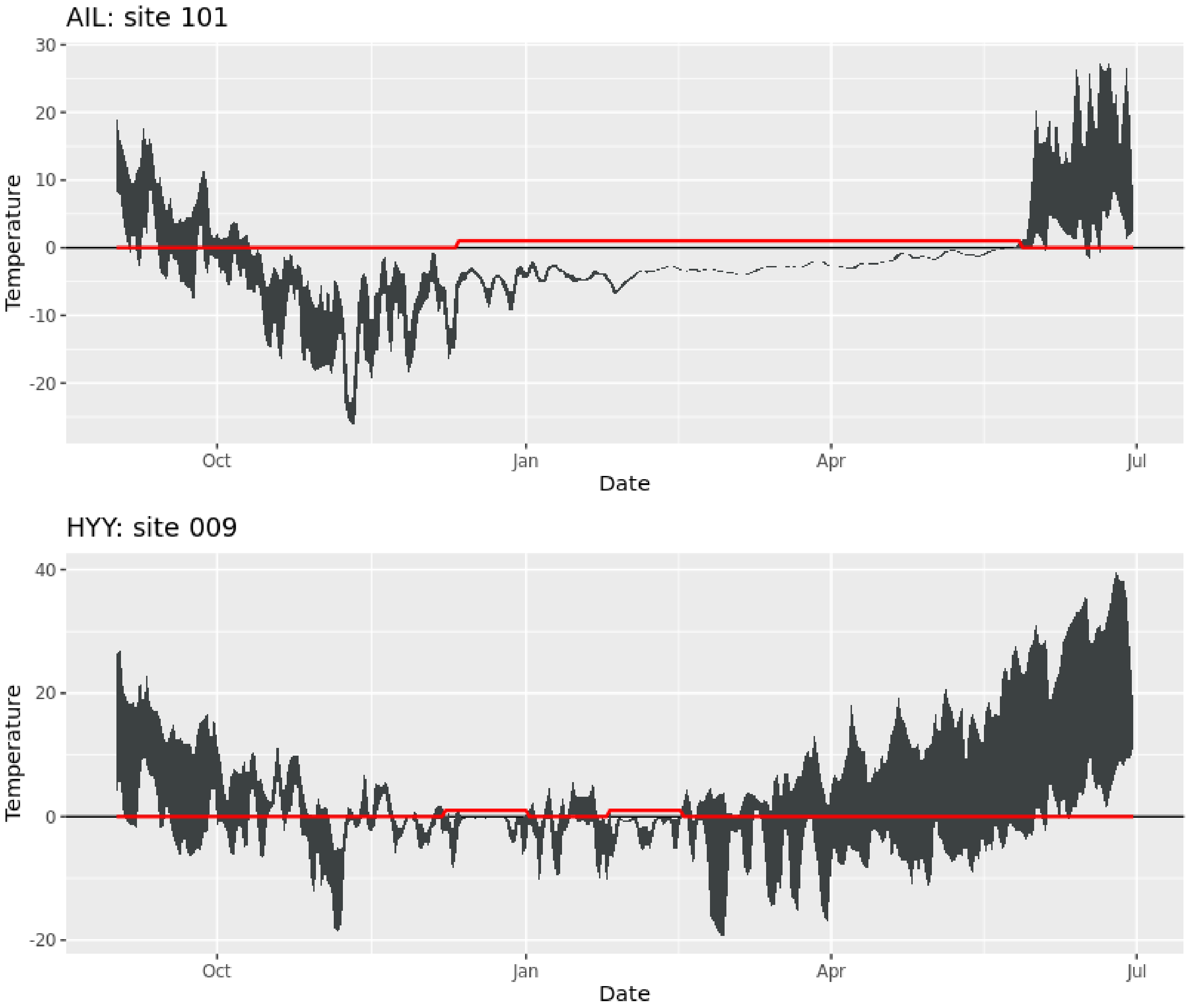

Figure A1. Examples of detecting snow cover duration from the temperature time series. The dark grey color shows daily maximum and minimum values of near-surface temperatures and the red line indicates when the algorithm detects snow cover (0 = no snow cover, 1 = snow cover).

A3

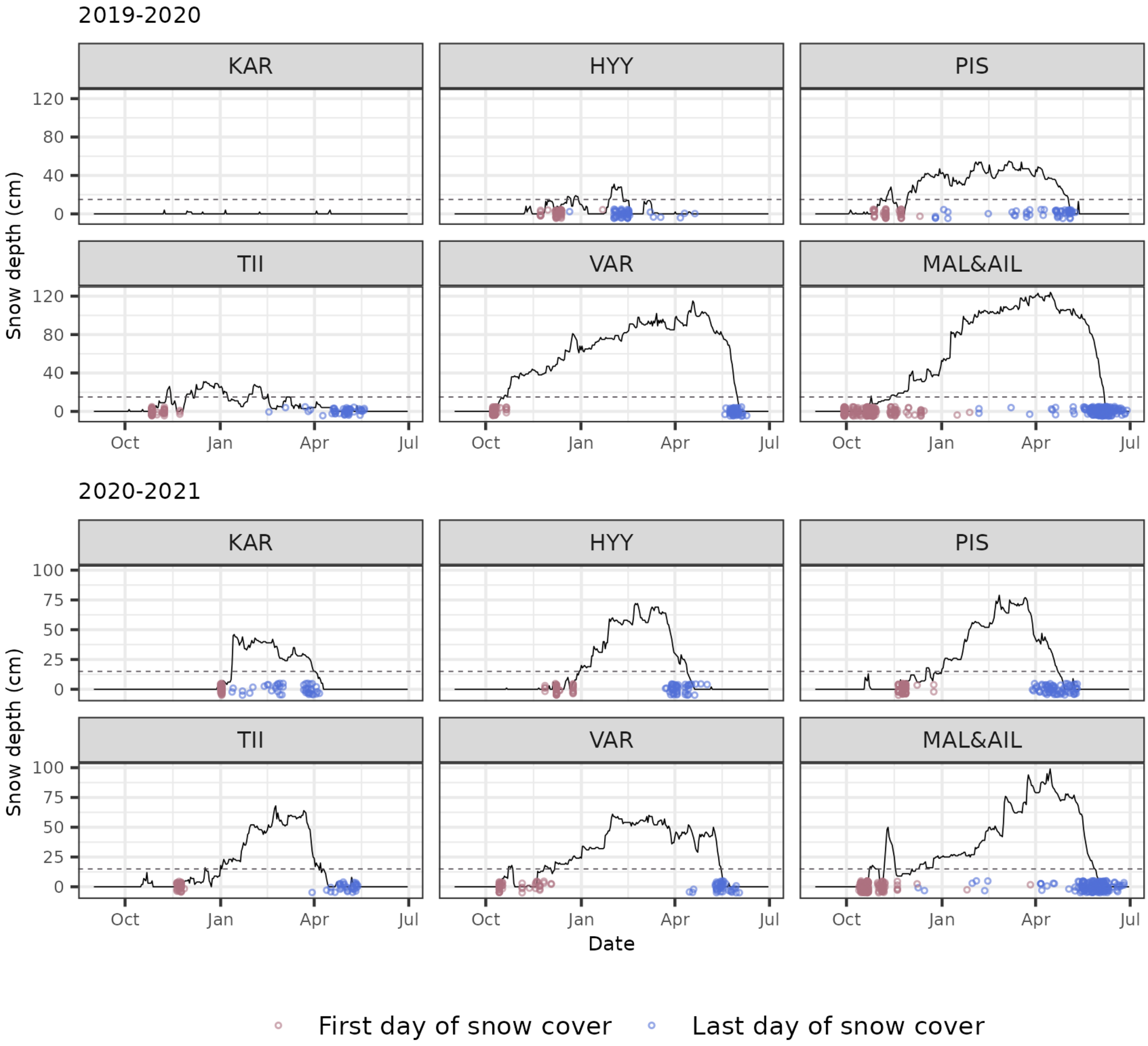

Figure A2. Predicted snow cover arrival and melting dates within the study areas and measured snow depth at the nearest weather station of each study area.

A4

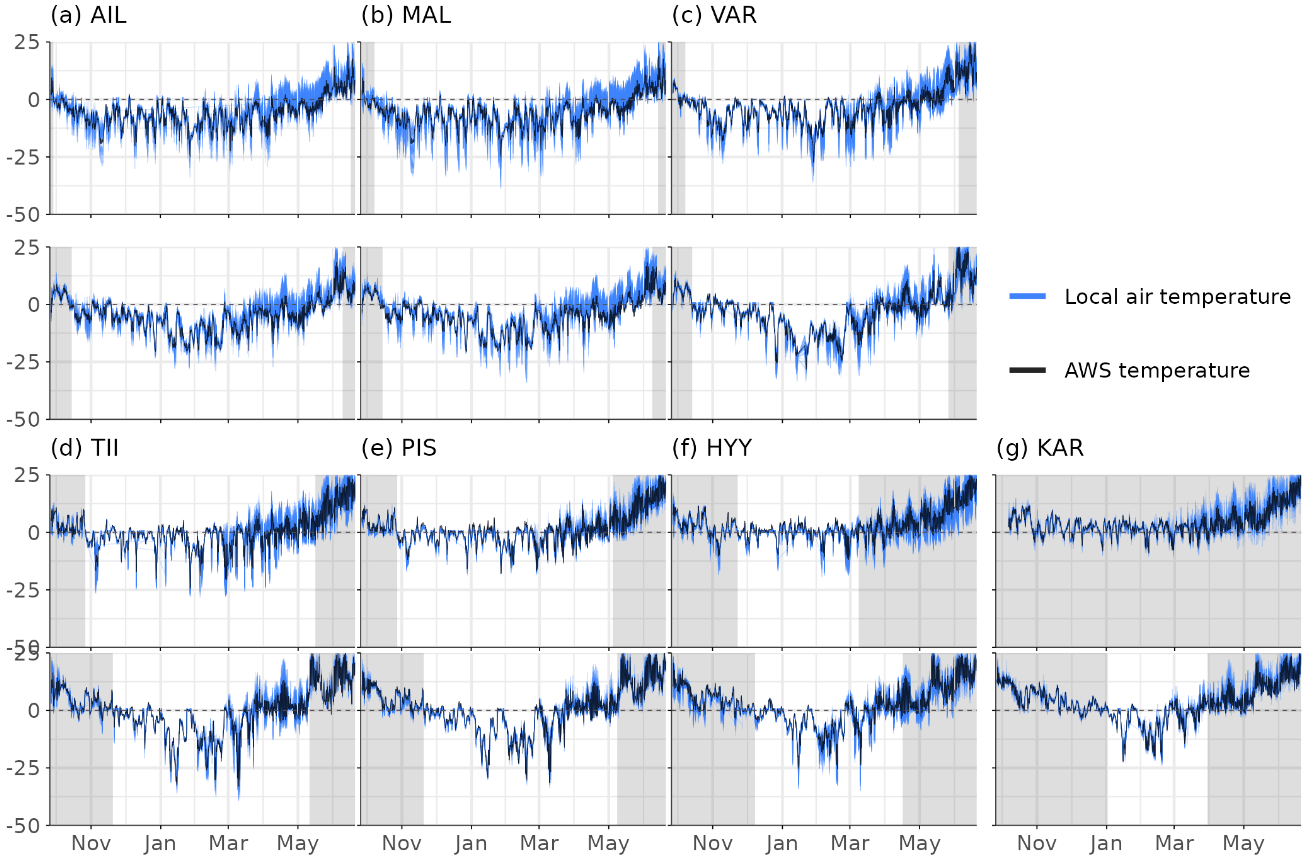

Figure A3. Variation of air temperatures and snow cover timing during the study winters 2019-2020 and 2020-2021. Winter temperatures at each study site are shown in the blue lines and nearest weather station temperature in the black line.

Author contributions. VT designed this study and analyzed the data; PN, VT and JA designed the SEM; PN wrote the code for calculating snow cover duration and the code for the SEM; ML, JA, PN and JK designed the study setting; All authors contributed to the data collection; VT prepared the MS with contributions from all co-authors. 320

Competing interests. The authors declare that they have no conflict of interest.

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