Supplementary Materials for

Microclimate temperature variations from boreal forests to the tundra

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Data availability

The raw microclimate data and code to preprocess these data are available in the study-area-specific Github repositories (https://github.com/poniitty?tab=repositories). The preprocessed data and code used in this study are available in a Github repository (https://github.com/poniitty/Boreal-Tundra_Microclimates) and a static version of this repository will be deposited and openly published in Zenodo upon acceptance for publishing.
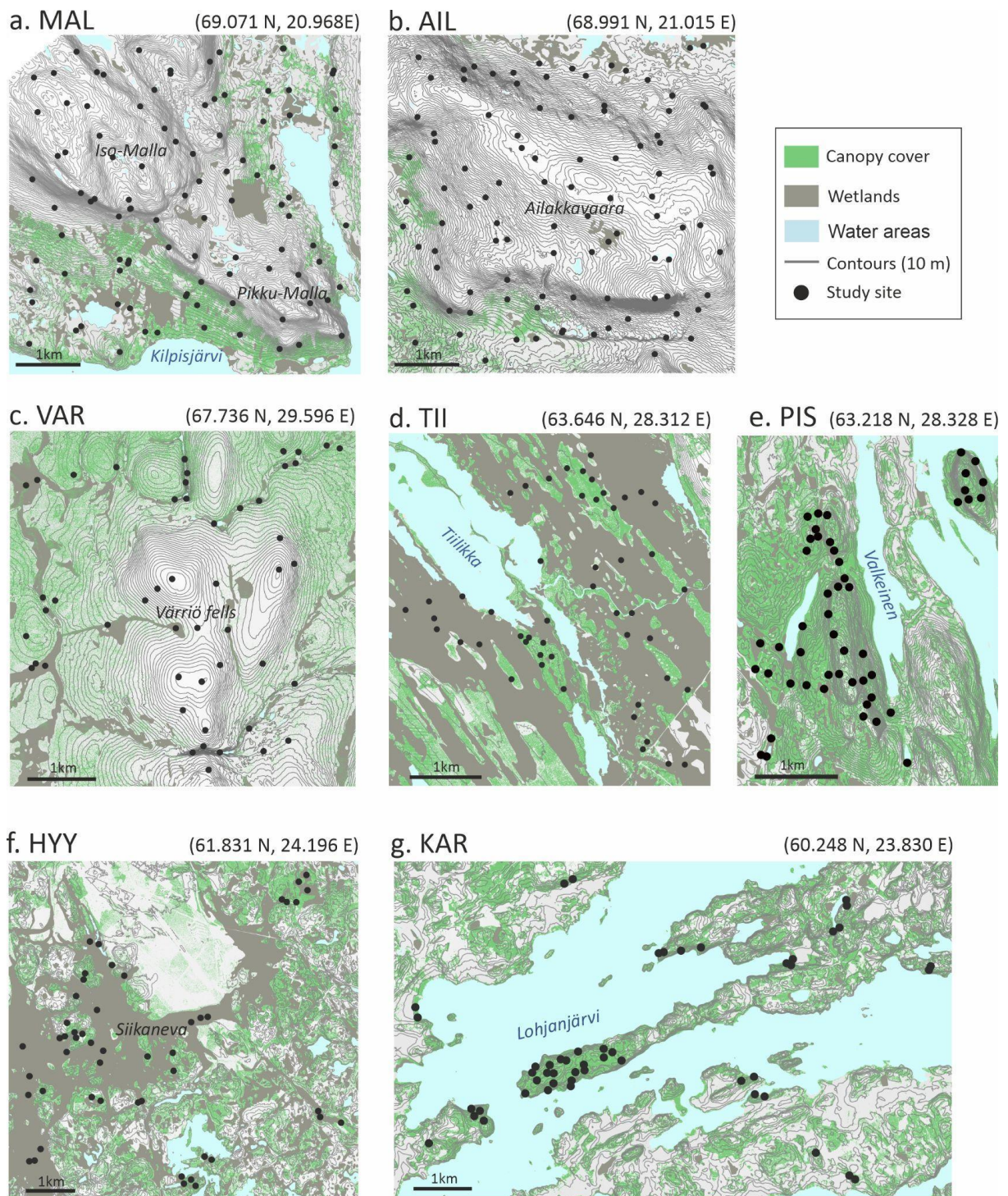
Figure S1. Maps of the focus areas. Canopy cover shows trees and shrubs with canopy height > 1 m (except for MAL and AIL canopy height > 0.5 m). Coordinates in parentheses mark the center coordinate of the focus area (EPSG:4326).
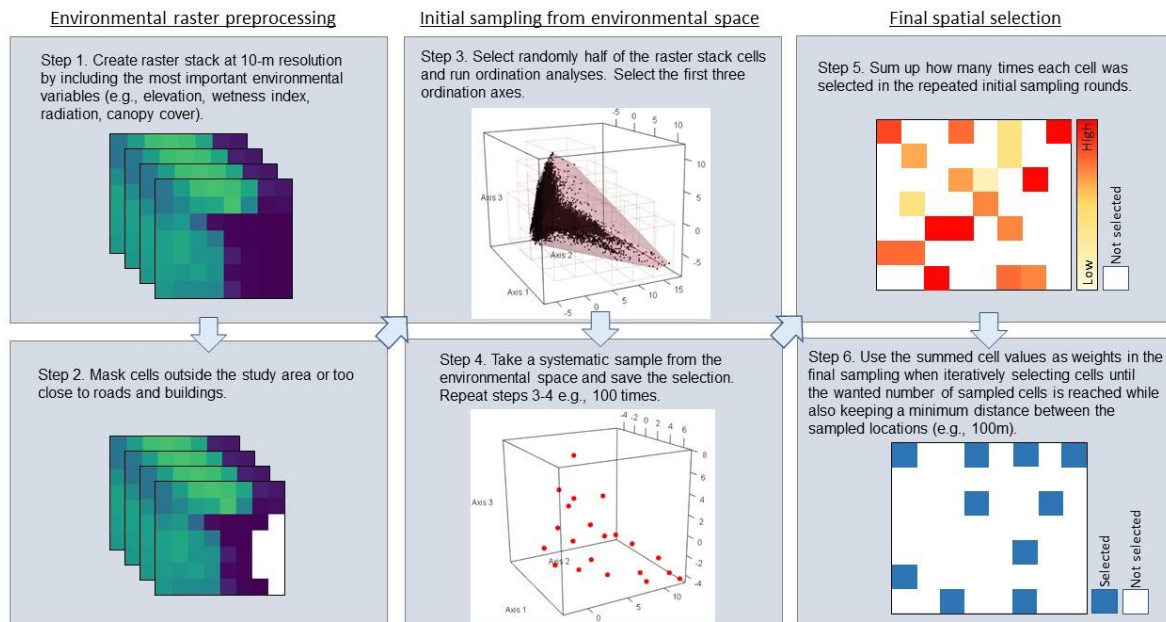
Figure S2. Workflow of the stratified sampling of the logger locations. In step 1 the most important environmental layers to be used in the sampling are predetermined (layers may vary from study area to area depending on the area characteristics). Step 2 forces the selection to overall suitable areas. Steps 3 & 4 ensure that the environmental gradients are sampled efficiently and thoroughly. Repeating the steps 3 & 4 provides enough initial samples that the spatially comprehensive final sample can be achieved (steps 5 & 6).
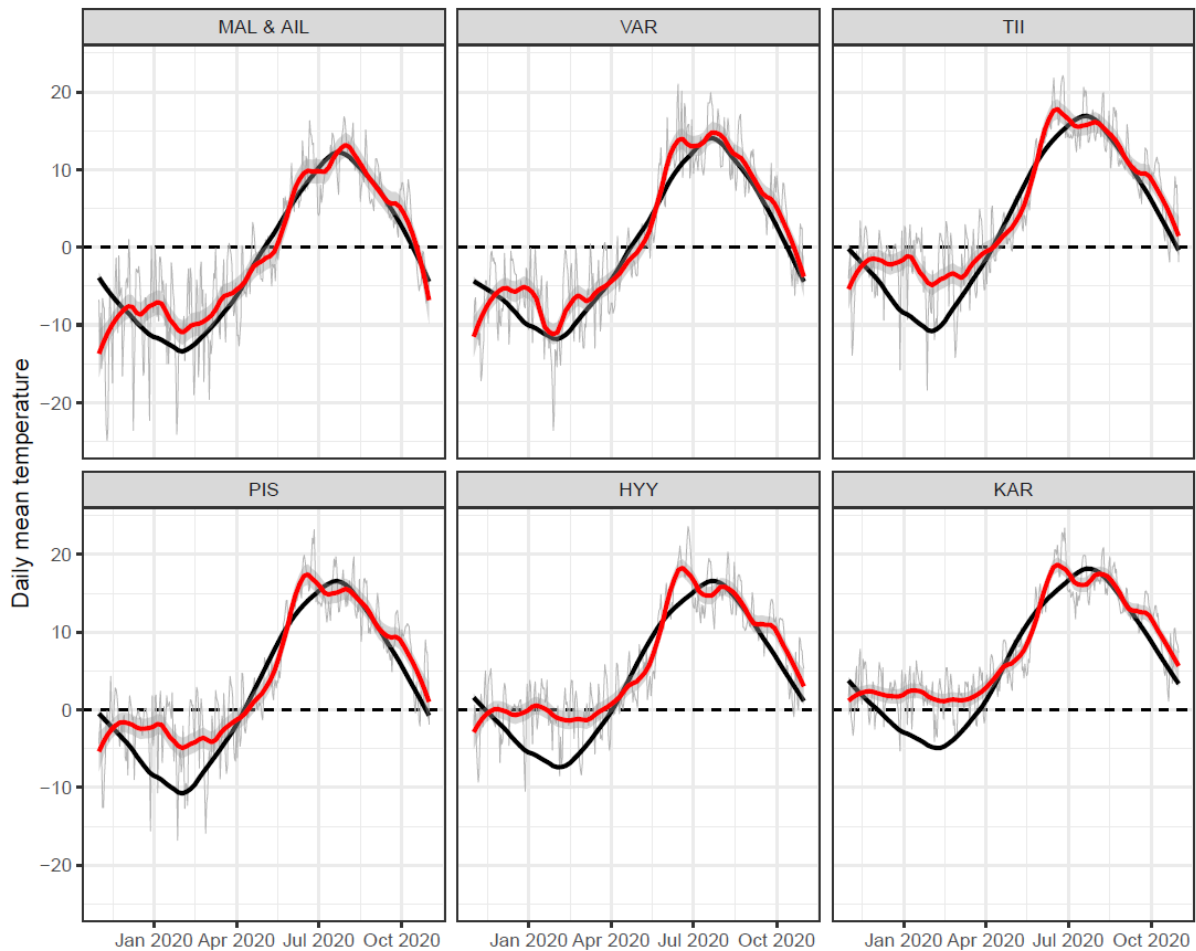
Figure S3. Macroclimatic air temperature variations at the focus areas. Daily mean air temperatures are derived from the nearest automated weather stations operated by the Finnish Meteorological Institute. Gray lines represent the daily mean temperatures of the study period. Red lines are smoothed loess lines of the study period temperatures. Black lines represent the 30-year (1991-2020) daily averages also slightly smoothed with loess.
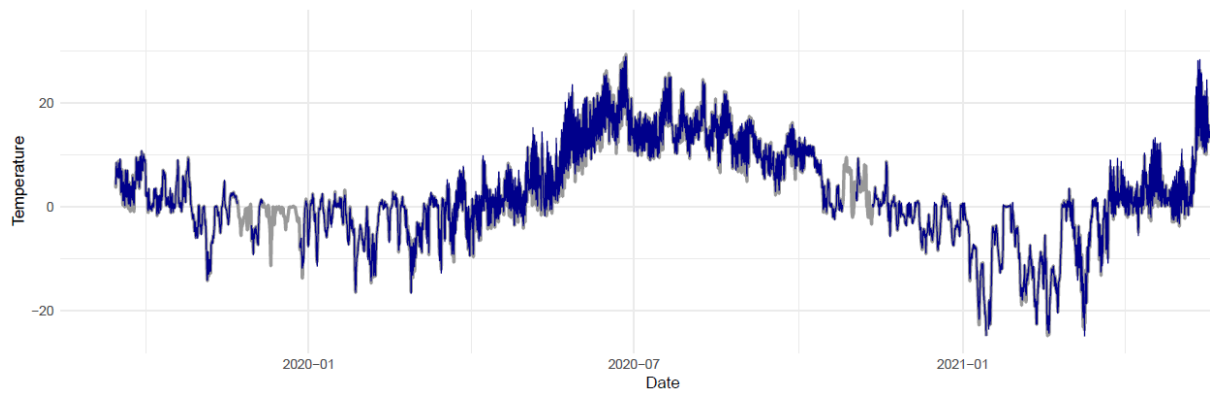
Figure S4. Example of a corrected air temperature (T4) time series. The data were corrected for non-matching time-stamps from a Haxo-8 logger in Pisa (PIS) study area. Blue line represents the individual time series of which timestamps were splitted and shifted by matching it with the reference time series (gray line; median over all other T4 loggers within PIS study area).
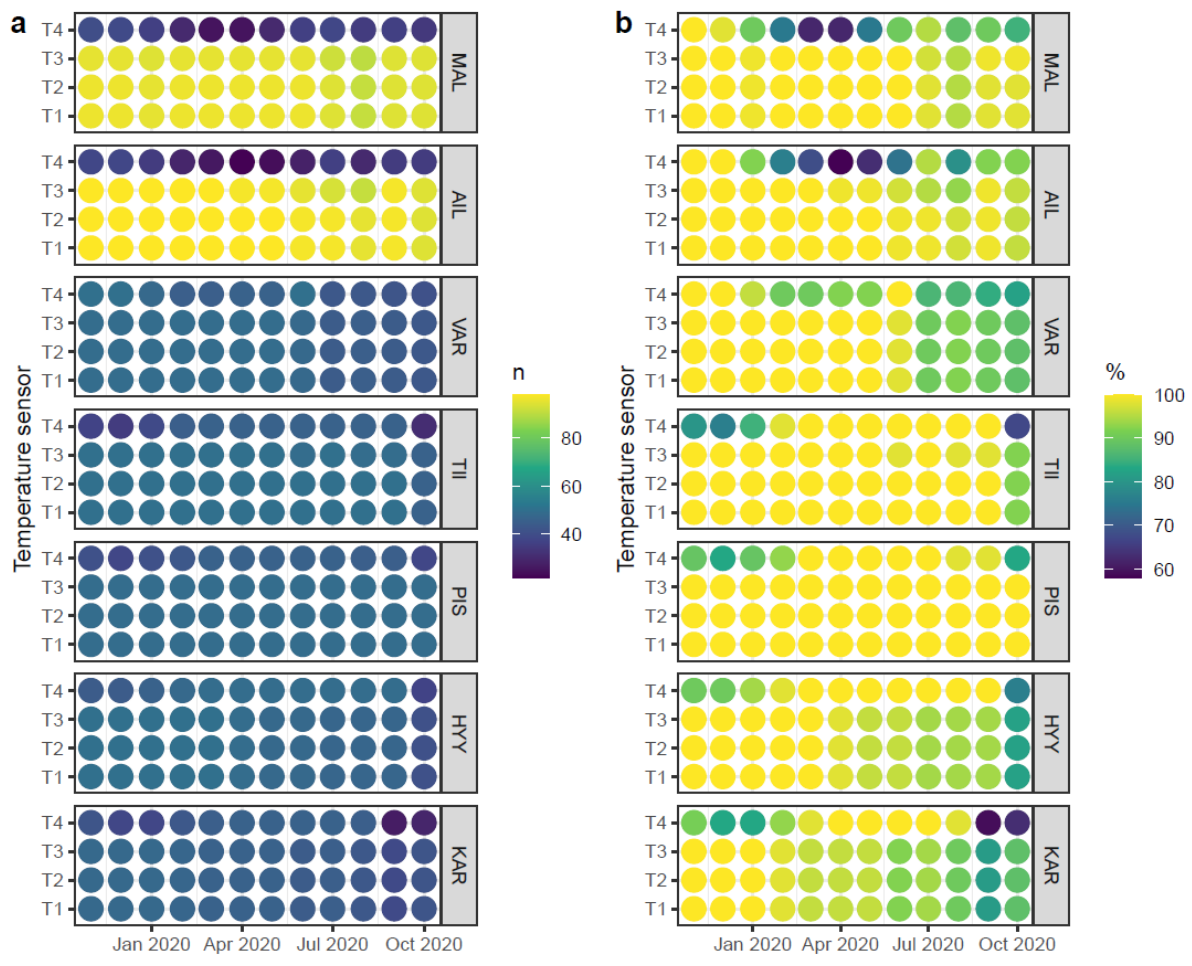
Figure S5. Data coverage. The absolute (a) and relative (b) number of functional temperature sensors per month per study area after data cleaning. T1=soil temperature, T2=surface temperature, T3=near surface temperature, T4=air temperature. The relative number is the percentage of functional sensors compared to the maximum number of sensors in each area.
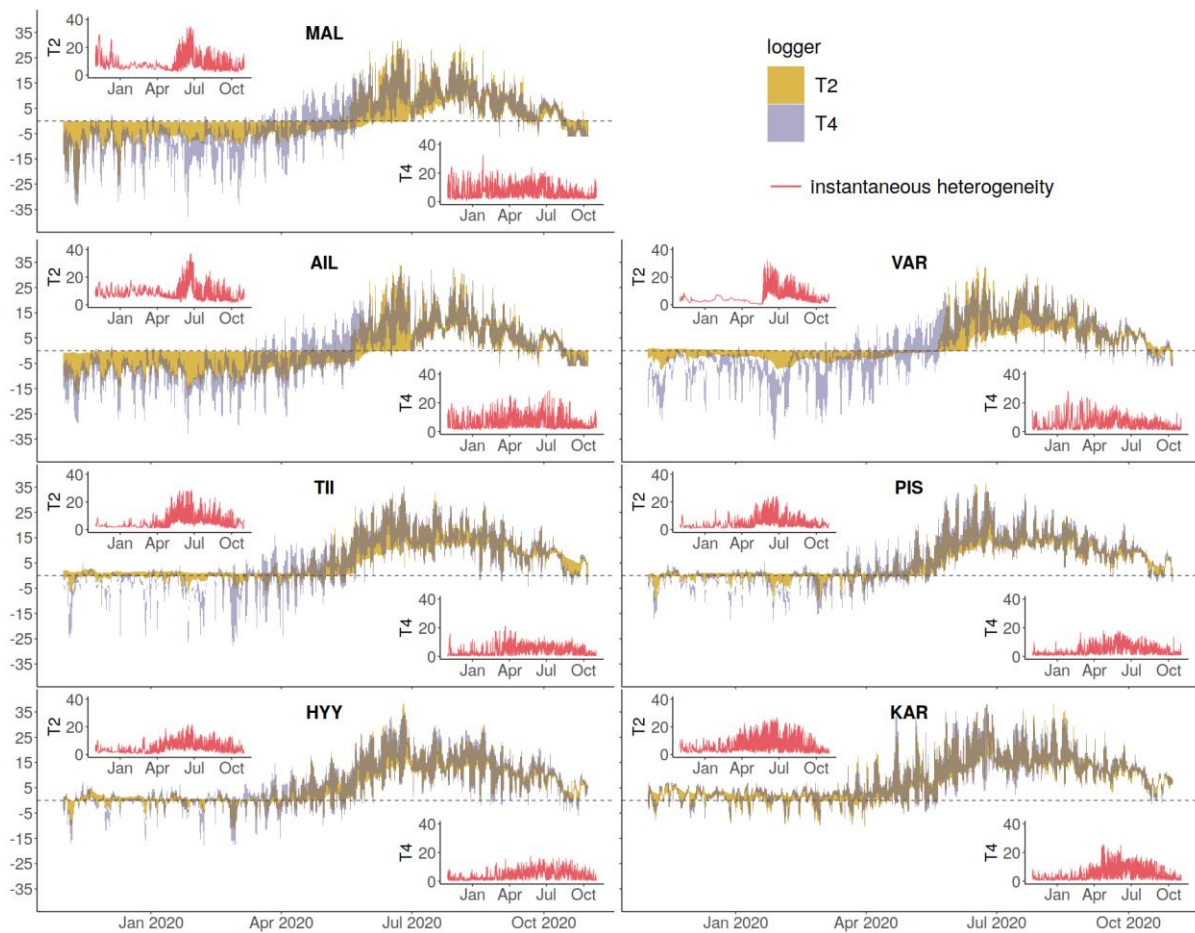
Figure S6. Temporal variability in surface and air temperatures over the focus areas. The panels depict the recorded temperature variability at two heights: surface temperature (T2) and air temperature (T4) over the study period 2019/11/01–2020/10/31. The shaded areas depict the hourly range of variation over the loggers (number of loggers 50-100 per focus area, see Table 1 for T4). In the sub-panels, the red lines show the maximum difference between the temperatures at each time step (numerical results for T4 are shown in Table 2).
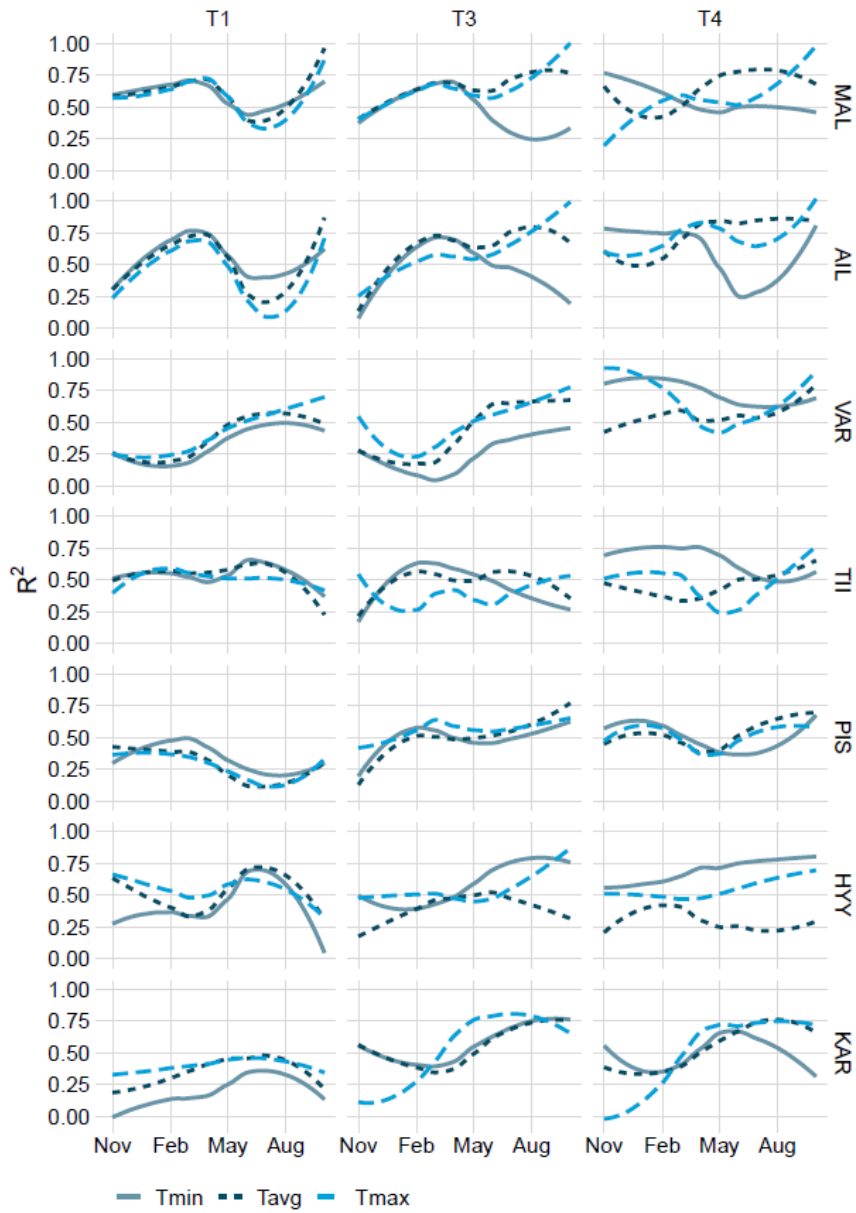
Figure S7. The performance of the monthly microclimate temperature models. The amount of variation explained by the models is indicated with the r-squared value (R^2). Lines are slightly smoothed (loess, span = 0.8) to facilitate readability.

Table S1. Locations of the automated weather stations (AWS) from which weather station data

was acquired for the focus areas (2019/11/01–2020/10/31).

Focus area	AWS	ID	Latitude	Longitude	Elevation (m a.s.l.)	Distance to focus area center coordinates (km)
MAL & AIL	Kilpisjärvi kyläkeskus[*]	102016	69.04948	20.79115	480	4.4 & 11.1
VAR	Salla Värriötunturi	102012	67.74858	29.61132	360	1.4
TII	Nurmes, Valtimo	101743	63.66730	28.82927	114	25.4
PIS	Rautavaara, Ylä-Luosta	101603	63.37806	28.66166	164	24.7
HYY	Juupajoki, Hyytiälä	101317	61.84591	24.28696	154	6.2
KAR	Lohja, Porla	100974	60.24446	24.04951	36	12.8

*Station relocated after 20.09.2021

Table S2. Summary statistics of the environmental variables by each focus area.

area	stat	Elevation (m)	Solar radiation, January (kWh / m²)	Solar radiation, July (kWh / m²)	Canopy cover (%)	Snow cover duration (days)	Topographic position index	Soil moisture (VWC%)	Wetland cover (%)	Water cover (%)
MAL	mean	617.2	0.00	6.49	41	238	0.4	29.5	6	6
MAL	median	565.9	0.00	6.58	27	239	-0.3	27.3	0	1
MAL	min	482.8	0.00	4.33	0	166	-10.0	14.5	0	0
MAL	max	934.2	0.00	7.53	100	260	22.7	57.1	82	38
MAL	range length	451.3	0.00	3.20	100	94	32.7	42.6	82	38
AIL	mean	747.2	0.00	6.56	9	243	0.7	30.9	4	1
AIL	median	744.9	0.00	6.76	0	244	0.0	29.0	0	0
AIL	min	509.3	0.00	4.17	0	149	-6.4	12.5	0	0
AIL	max	933.5	0.00	7.48	96	262	17.0	56.9	81	7
AIL	range length	424.2	0.00	3.31	96	113	23.4	44.4	81	7
VAR	mean	359.0	0.01	6.40	53	232	-3.3	30.4	14	0
VAR	median	338.9	0.01	6.62	66	233	-0.5	25.4	0	0
VAR	min	261.8	0.01	4.22	0	210	-26.2	12.8	0	0
VAR	max	475.0	0.01	7.40	95	245	7.6	58.8	100	2
VAR	range length	213.2	0.00	3.17	95	35	33.8	46.0	100	2
TII	mean	194.6	0.13	6.89	73	176	0.3	39.8	54	6
TII	median	193.8	0.13	6.90	98	179	0.0	41.0	50	2
TII	min	187.4	0.12	6.65	0	139	-0.9	10.9	0	0
TII	max	205.8	0.13	7.01	100	202	3.8	58.9	100	46
TII	range length	18.3	0.01	0.37	100	63	4.7	48.0	100	46
PIS	mean	162.1	0.14	6.44	94	170	0.2	25.8	5	12
PIS	median	150.1	0.13	6.56	97	173	-1.0	26.5	0	7
PIS	min	103.4	0.12	4.40	60	132	-8.3	1.8	0	0
PIS	max	261.8	0.17	7.53	100	186	11.3	52.2	50	65
PIS	range length	158.4	0.05	3.13	40	54	19.6	50.4	50	65
HYY	mean	172.1	0.20	6.96	74	100	0.2	32.3	51	5
HYY	median	171.4	0.20	7.00	94	99	0.0	26.6	35	0
HYY	min	152.2	0.17	6.23	0	55	-4.0	13.6	0	0
HYY	max	203.0	0.25	7.32	100	140	6.6	57.8	100	54
HYY	range length	50.8	0.08	1.09	100	85	10.6	44.2	100	54
KAR	mean	53.4	0.27	6.71	89	1	0.5	28.6	2	34
KAR	median	54.5	0.26	6.83	100	1	-1.1	26.6	0	35
KAR	min	32.2	0.21	5.61	6	1	-7.7	9.5	0	0
KAR	max	99.2	0.41	7.54	100	2	13.5	52.6	31	74
KAR	range length	66.9	0.20	1.93	94	1	21.2	43.1	31	74

Table S3. Monthly R^2 values of the linear models averaged over focus areas.

T variable	T height	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Tmin	T1	0.33	0.35	0.42	0.42	0.47	0.42	0.47	0.39	0.54	0.46	0.36	0.39
Tmin	T3	0.30	0.39	0.47	0.46	0.48	0.53	0.48	0.50	0.50	0.51	0.48	0.49
Tmin	T4	0.65	0.73	0.60	0.67	0.62	0.63	0.62	0.52	0.47	0.59	0.55	0.61
Tavg	T1	0.41	0.42	0.46	0.43	0.45	0.49	0.55	0.40	0.41	0.46	0.54	0.44
Tavg	T3	0.25	0.40	0.44	0.46	0.51	0.51	0.52	0.56	0.70	0.64	0.62	0.62
Tavg	T4	0.48	0.42	0.44	0.43	0.53	0.49	0.51	0.59	0.67	0.59	0.61	0.69
Tmax	T1	0.40	0.43	0.49	0.46	0.46	0.52	0.53	0.35	0.37	0.38	0.46	0.53
Tmax	T3	0.45	0.30	0.35	0.37	0.55	0.60	0.46	0.54	0.65	0.67	0.74	0.77
Tmax	T4	0.50	0.43	0.52	0.51	0.66	0.50	0.46	0.56	0.62	0.60	0.75	0.80

Table S4. Variable importance scores of soil temperature (T1) models averaged over study areas. Signs of the values are determined by the sign of the corresponding t-statistic value in the model and depict the direction of the effect.

Predictor	T_var	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Elevation	Tmin	-0.09	-0.10	-0.10	-0.09	-0.11	-0.11	-0.14	-0.02	-0.15	-0.12	-0.13	-0.16
Elevation	Tavg	-0.10	-0.08	-0.09	-0.10	-0.13	-0.12	-0.10	0.00	-0.02	-0.05	-0.21	-0.24
Elevation	Tmax	-0.09	-0.10	-0.10	-0.10	-0.13	-0.12	0.03	0.00	0.00	0.01	-0.08	-0.25
Solar radiation	Tmin	0.00	0.00	0.00	0.00	0.05	0.05	0.17	0.07	0.02	0.10	0.09	0.06
Solar radiation	Tavg	0.00	0.00	0.00	0.00	0.09	0.16	0.21	0.09	0.06	0.15	0.23	0.10
Solar radiation	Tmax	0.00	0.00	0.00	0.00	0.09	0.20	0.11	0.07	0.07	0.11	0.20	0.15
Snow cover	Tmin	0.04	0.08	0.13	0.13	0.17	0.13	0.01	-0.05	0.00	0.00	0.01	0.04
Snow cover	Tavg	0.01	0.04	0.08	0.09	0.10	0.04	-0.11	-0.04	0.00	0.00	0.00	0.00
Snow cover	Tmax	-0.03	0.02	0.00	0.03	0.01	-0.03	-0.24	-0.03	0.00	0.00	-0.01	-0.03
Canopy cover	Tmin	0.09	0.17	0.14	0.07	0.06	0.06	0.01	-0.22	-0.23	-0.11	0.14	0.12
Canopy cover	Tavg	0.16	0.19	0.22	0.15	0.09	0.03	-0.17	-0.24	-0.26	-0.23	-0.10	0.12
Canopy cover	Tmax	0.16	0.18	0.20	0.18	0.09	-0.03	-0.20	-0.24	-0.26	-0.22	-0.16	-0.09
TPI	Tmin	0.07	0.06	0.03	0.01	0.00	-0.01	-0.01	0.02	0.06	0.07	0.03	0.01
TPI	Tavg	0.11	0.08	0.06	0.03	0.00	-0.01	-0.04	0.07	0.05	0.07	0.09	0.10
TPI	Tmax	0.08	0.06	0.05	0.00	-0.02	-0.03	0.00	0.05	0.05	0.07	0.06	0.09
Soil moisture	Tmin	0.14	0.09	0.08	0.14	0.16	0.08	0.09	0.06	0.11	0.17	0.04	0.10
Soil moisture	Tavg	0.10	0.06	0.03	0.08	0.07	0.09	0.02	-0.04	0.00	0.00	0.00	0.03
Soil moisture	Tmax	0.05	0.01	0.02	0.05	0.07	0.08	-0.02	-0.04	-0.05	-0.05	-0.06	-0.12
Wetland cover	Tmin	-0.05	-0.02	-0.01	-0.07	-0.05	-0.05	-0.05	-0.01	0.01	-0.03	0.04	0.02
Wetland cover	Tavg	0.00	-0.01	-0.01	-0.06	-0.05	-0.09	-0.01	0.00	-0.01	0.00	-0.01	0.04
Wetland cover	Tmax	-0.01	-0.01	-0.03	-0.05	-0.09	-0.09	-0.02	0.00	0.01	-0.01	0.00	0.00
Water cover	Tmin	-0.07	-0.04	-0.02	-0.04	-0.04	-0.03	-0.02	0.00	0.02	0.06	0.03	-0.03
Water cover	Tavg	-0.02	-0.01	0.01	-0.01	-0.03	-0.04	0.00	0.00	0.01	0.02	0.03	0.00
Water cover	Tmax	0.01	-0.01	-0.01	-0.02	-0.03	-0.03	-0.01	0.01	0.02	0.01	0.02	0.03

Table S5. Variable importance scores of the near surface temperature (T3) models averaged over the focus areas. Signs of the values are determined by the sign of the corresponding t-statistic value in the model and depict the direction of the effect.

Predictor	T_var	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Elevation	Tmin	0.03	-0.03	-0.06	-0.05	-0.09	-0.09	-0.09	0.10	0.00	0.11	0.06	0.02
Elevation	Tavg	-0.01	-0.05	-0.05	-0.07	-0.10	-0.16	-0.10	-0.10	-0.25	-0.23	-0.26	-0.34
Elevation	Tmax	-0.11	-0.06	-0.11	-0.11	-0.16	-0.15	0.01	-0.11	-0.21	-0.19	-0.27	-0.46
Solar radiation	Tmin	0.00	0.00	0.00	0.00	0.01	0.00	0.00	-0.09	-0.08	-0.05	-0.05	0.00
Solar radiation	Tavg	0.00	0.00	0.00	0.00	0.13	0.15	0.18	0.06	0.03	0.14	0.19	0.11
Solar radiation	Tmax	0.00	0.00	0.00	0.00	0.14	0.17	0.06	0.16	0.10	0.21	0.28	0.14
Snow cover	Tmin	0.03	0.15	0.20	0.20	0.24	0.24	0.20	-0.04	0.00	0.00	-0.01	-0.02
Snow cover	Tavg	0.00	0.08	0.10	0.14	0.09	0.01	-0.16	-0.02	0.00	0.00	0.00	-0.05
Snow cover	Tmax	-0.13	-0.09	-0.15	-0.14	-0.16	-0.20	-0.21	0.00	0.00	0.00	0.00	-0.02
Canopy cover	Tmin	0.09	0.12	0.10	0.08	0.04	0.04	0.05	0.13	0.21	0.18	0.20	0.19
Canopy cover	Tavg	0.08	0.16	0.09	0.04	0.00	-0.03	-0.09	-0.14	-0.22	-0.10	0.02	0.09
Canopy cover	Tmax	-0.01	0.06	0.03	0.01	0.01	-0.07	-0.12	-0.14	-0.21	-0.23	-0.23	-0.15
TPI	Tmin	-0.01	-0.03	-0.04	-0.03	-0.04	-0.04	-0.02	0.02	0.03	0.02	0.00	-0.04
TPI	Tavg	-0.03	-0.03	-0.06	-0.05	-0.07	0.00	0.03	0.25	0.14	0.13	0.06	0.01
TPI	Tmax	0.02	-0.02	-0.03	-0.03	-0.01	0.03	0.04	0.08	0.11	0.10	0.07	0.05
Soil moisture	Tmin	0.03	0.15	0.15	0.19	0.16	0.11	0.03	-0.04	0.01	0.03	0.03	0.03
Soil moisture	Tavg	0.07	0.18	0.12	0.19	0.14	0.02	-0.09	-0.21	-0.13	-0.19	-0.15	0.04
Soil moisture	Tmax	-0.04	0.06	-0.02	0.00	-0.09	-0.11	-0.03	-0.11	-0.13	-0.14	-0.16	-0.10
Wetland cover	Tmin	-0.07	-0.05	-0.09	-0.08	-0.09	-0.14	-0.17	-0.20	-0.22	-0.26	-0.20	-0.17
Wetland cover	Tavg	-0.02	0.02	-0.02	-0.05	-0.03	-0.01	0.05	0.05	0.08	0.01	-0.03	-0.04
Wetland cover	Tmax	0.14	0.03	0.05	0.03	0.10	0.07	0.05	0.09	0.13	0.12	0.17	0.10
Water cover	Tmin	-0.03	-0.03	-0.03	-0.04	-0.07	-0.06	-0.01	0.04	0.05	0.08	0.04	0.08
Water cover	Tavg	0.02	0.00	-0.05	-0.05	-0.06	-0.02	0.04	0.01	0.02	0.09	0.11	0.07
Water cover	Tmax	-0.02	0.00	0.00	0.02	0.02	0.04	0.00	0.01	0.00	0.00	0.01	0.01

Table S6. Variable importance scores of air temperature (T4) models averaged over the focus areas. Signs of the values are determined by the sign of the corresponding t-statistic value in the model and depict the direction of the effect.

Predictor	T_var	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Elevation	Tmin	0.35	0.39	0.33	0.30	0.25	0.21	0.19	0.12	0.04	0.19	0.11	0.04
Elevation	Tavg	0.16	0.02	0.00	-0.02	-0.12	-0.22	-0.20	-0.18	-0.27	-0.24	-0.27	-0.40
Elevation	Tmax	-0.26	-0.23	-0.35	-0.26	-0.30	-0.19	-0.12	-0.16	-0.24	-0.15	-0.35	-0.46
Solar radiation	Tmin	0.00	0.00	0.00	0.00	0.01	-0.01	-0.01	-0.10	-0.04	-0.01	-0.03	-0.01
Solar radiation	Tavg	0.00	0.00	0.00	0.00	0.25	0.17	0.11	0.00	0.04	0.11	0.22	0.13
Solar radiation	Tmax	0.00	0.00	0.00	0.00	0.21	0.17	0.14	0.14	0.09	0.13	0.20	0.15
Snow cover	Tmin	0.00	-0.01	-0.02	0.00	-0.01	-0.01	-0.01	-0.03	0.00	0.00	0.00	0.00
Snow cover	Tavg	-0.03	-0.07	-0.08	-0.12	-0.10	0.00	0.02	0.00	0.00	0.00	0.00	-0.05
Snow cover	Tmax	-0.02	-0.09	-0.10	-0.19	-0.06	-0.02	0.01	0.01	0.00	0.00	0.00	-0.01
Canopy cover	Tmin	0.05	0.10	0.05	0.04	0.02	0.10	0.12	0.06	0.10	0.05	0.02	0.06
Canopy cover	Tavg	-0.01	-0.01	0.01	-0.08	-0.11	-0.12	-0.13	-0.18	-0.23	-0.11	-0.07	-0.05
Canopy cover	Tmax	-0.07	-0.04	-0.05	-0.07	-0.14	-0.13	-0.11	-0.15	-0.24	-0.17	-0.15	-0.09
TPI	Tmin	0.06	0.04	0.00	0.00	0.06	0.03	0.01	0.07	0.03	0.05	0.03	0.04
TPI	Tavg	0.03	0.06	0.05	0.05	0.07	0.05	0.12	0.22	0.11	0.12	0.10	0.02
TPI	Tmax	0.04	0.03	0.07	0.05	0.02	0.00	0.04	0.06	0.07	0.10	0.12	0.03
Soil moisture	Tmin	-0.02	-0.04	-0.05	-0.07	-0.10	-0.07	-0.11	-0.04	-0.06	-0.03	-0.04	-0.05
Soil moisture	Tavg	-0.05	-0.07	-0.05	-0.15	-0.11	-0.02	-0.05	-0.08	-0.06	-0.10	-0.10	-0.07
Soil moisture	Tmax	-0.05	-0.02	0.00	0.00	0.01	0.05	0.01	0.00	-0.04	-0.06	-0.05	-0.02
Wetland cover	Tmin	-0.28	-0.23	-0.24	-0.28	-0.27	-0.32	-0.29	-0.26	-0.27	-0.35	-0.32	-0.29
Wetland cover	Tavg	-0.11	-0.08	-0.08	-0.14	-0.05	-0.04	-0.02	0.03	0.05	-0.01	-0.02	0.01
Wetland cover	Tmax	0.08	0.11	0.11	0.09	0.04	0.04	0.10	0.08	0.12	0.10	0.10	0.12
Water cover	Tmin	0.04	0.02	0.00	0.01	0.03	-0.04	0.03	0.02	0.05	0.09	0.08	0.02
Water cover	Tavg	0.05	0.01	0.03	-0.02	0.02	-0.02	0.00	0.07	0.08	0.11	0.12	0.14
Water cover	Tmax	0.02	0.05	0.03	-0.02	0.01	-0.01	0.00	0.06	0.02	0.05	0.02	0.06