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RESEARCH ARTICLE

Drivers of spatio-temporal variations in summer surface water temperatures of Arctic Fennoscandian lakes (2000–21)

Mingzhen Zhang,[1] Matti Leppäranta,[2] Atte Korhola,[1,3] Nina Kirchner,[4,5] Annika Granebeck,[4,5] Frederik Schenk,[4,6,7] Kaarina Weckström,[1,3] Maija Heikkilä[1,3] & Jan Weckström[1,3]

[1]Faculty of Biological and Environmental Sciences, University of Helsinki, Helsinki, Finland; [2]Institute for Atmospheric and Earth System Research, University of Helsinki, Helsinki, Finland; [3]Helsinki Institute of Sustainability Science, University of Helsinki, Helsinki, Finland; [4]Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden; [5]Department of Physical Geography, Stockholm University, Stockholm, Sweden; [6]Department of Geological Sciences, Stockholm University, Stockholm, Sweden; [7]Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland

Abstract

The Arctic region is covered with numerous small lakes whose ecosystems are vulnerable to current climate warming and resultant changes in water temperature, ice-cover duration and lake levels. Data on thermal features of these lakes are sparse, which hinders our understanding of the possible ecosystem impacts of the warming climate and climate feedbacks at larger spatial scales. We investigated spatial–temporal variations of lake surface water temperatures (LSWT) in 12 Arctic lakes in north-west Finnish Lapland and explored the predominant drivers of LSWTs by continuous year-round observations. The lake surface temperature data were recorded using thermistors at bi-hourly resolution during the years 2000, 2007–08 and 2019–2021. A large regional heterogeneity was observed in the timing of the maximum and minimum LSWTs and the overall patterns of the annual cycle. Our results reveal that July air temperature, maximum lake depth and altitude explained most of the variance in the summer LSWT (>85%). The remaining variance was related to geographic location (longitude and latitude), lake morphometric features, such as lake area and catchment area, and certain physico-chemical characteristics, such as Secchi depth and dissolved organic carbon content. Our results provide new insights into thermal responses of different types of small Arctic lakes to climate change.

Keywords

Climate change; Arctic lakes; water temperature; topography; geochemistry; morphometry

Correspondence

Mingzhen Zhang, Faculty of Biological and Environmental Sciences, University of Helsinki, FI-00014 Helsinki, Finland. E-mail: mingzhen.zhang@helsinki.fi

Abbreviations

AIC: Akaike information criterion
ANOVA: analysis of variance
BIC: Bayesian information criterion
BP: birch–pine forest (birch dominant)
DOC: dissolved organic carbon
ICC: intraclass correlation coefficient
JulLSWT: mean July LSWT
logLik: log-likelihood
LSWT: lake surface water temperature
MaxLSWT: summer maximum LSWT
PCA: principal component analysis
PB: pine–birch forest (pine dominant)
SD: Secchi depth
SPB: spruce–pine–birch forest
TD: treeless tundra
TN: total nitrogen
TP: total phosphorus

To access the supplementary material, please visit the article landing page

Introduction

The Arctic is warming three to four times faster than the global average: 0.6–0.8°C per decade compared to 0.2°C per decade (Benson et al. 2000; Adrian et al. 2009; O'Reilly et al. 2015; Rantanen et al. 2022). This is predominantly due to Arctic sea-ice loss (open water reflects less sunlight than sea ice), atmospheric heat transport from the Equator to the Arctic, and the lapse rate feedback—a phenomenon known as Arctic amplification (Serreze et al. 2009; Previdi et al. 2021). As a response to the warming climate, seasonally ice-covered lakes across the Northern Hemisphere also exhibit warming trends, but with heterogeneous heating rates (Edmundson & Mazumder 2002; O'Reilly et al. 2015; Zhong et al. 2016; Sharma et al. 2019). LSWT is a critical physical parameter for the heat exchange between lakes and the atmosphere and for the regional and local hydrological cycles (Terry et al. 2017). Since temperature plays a vital role in biochemical reaction rates, a change in LSWT can lead to a series of effects on, for example, greenhouse gas fluxes, photosynthesis and respiration rates, biological growth rates, organism size and the frequency of toxic algal blooms. Thus, surface warming influences the whole lake ecosystem (Atkinson 1994; Butterwick et al. 2004; Yvon-Durocher et al. 2012; Huang et al. 2017; Kraemer et al. 2017).

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The importance of LSWT for lake ecosystems and climate feedbacks has prompted studies to observe spatial and temporal trends in LSWT and to determine its drivers in the Northern Hemisphere over the recent decades. Milder winters, with elevated air temperatures and earlier exposure to solar radiation due to earlier ice-off in spring and summer, as well as the increased brownification of lake waters, have been found to be the main driving mechanisms for the rapid warming of the surface water in mid- and high-latitude lakes (Fink et al. 2014; Piccolroaz et al. 2015; Schmid & Köster 2016; Zhong et al. 2016). Recently, Noori et al. (2022) explored the LSWT change of a boreal lake in Finland by using an in situ data set from 1964 to 2020 and attributed the LSWT increase mainly to the increase in the local air temperature. Several studies have reported that lake location (e.g., elevation and latitude) and morphology (e.g., lake surface area and depth) could additionally affect the strength of the LSWT trend (Schmid et al. 2014; Kraemer et al. 2015; O'Reilly et al. 2015; Magee & Wu 2017; Leppäranta & Wen 2022). In complex mountain terrain, changes in snowmelt or glacial runoff may even show a temporal cooling in lakes in response to atmospheric warming through increasing runoff, as indicated by recent observations from the Arctic–alpine Lake Tarfala in northern Sweden (Kirchner et al. 2021). Other physicochemical factors, such as water transparency, influenced largely by turbidity and water colour, may also play a role in the LSWT variation (Edmundson & Mazumder 2002; Ptak et al. 2018). Furthermore, water colour and turbidity are affected, in turn, by many chemical variables, such as TP and DOC (Molot & Dillon 1997; Håkanson 2002; Shock & Pratt 2003; Lewis et al. 2007). As Edmundson & Mazumder (2002) suggested, a regional and hierarchical framework should be considered for better understanding lake response to the rapidly warming climate and the drivers behind the LSWT changes.

So far, most studies dealing with the variation of surface water temperature in Arctic lakes have focused on individual lakes, often large and deep, on the basis of long-term in situ observations (Woolway & Merchant 2018; Anderson et al. 2021). However, over 90% of the Earth's lakes are smaller than 0.01 km^2 (Downing et al. 2006), and a vast majority of these small lakes are located in remote Arctic regions and lack data on their thermal features. Marked regional gradients in climate and vegetation across the circumpolar area bring about differential drivers of LSWT, and their varying contributions are poorly understood. This limits a more comprehensive understanding of the varying impacts of climate warming on Arctic lake ecosystems and their climate feedbacks. To begin filling this gap, we conducted continuous year-round observations of the surface water temperatures in 12 Arctic lakes in north-west Finland during the years 2000, 2007–08 and 2019–2021. The objectives of our study were: (1) to investigate the spatio-temporal patterns in summer LSWT and (2) to determine qualitatively and quantitatively the environmental and climatic factors affecting the cycle of summer LSWTs. The results of this study will provide new data on how small Arctic lakes across a climate and vegetation gradient respond to climate change.

Methods

Study sites

The study lakes stretch across a steep climatic and vegetational gradient (67.85°–69.17° N, 21.05°–24.18° E) in north-west Finnish Lapland (Fig. 1). We used temperature data available from two meteorological stations in the area: Enontekiö Kilpisjärvi and Muonio Parish (Fig. 1). According to the data from these stations, the range of July mean air temperature and July precipitation during the climate normal period 1991–2020 were 11.6–14.3°C and 73–81 mm, respectively (Jokinen et al. 2021). The climatograms (1991–2020) for the weather stations Enontekiö Kilpisjärvi and Muonio Parish reveal that both monthly mean air temperature and monthly mean precipitation typically reach their annual monthly maxima in July, with 11.6°C, 73 mm and 14.3°C, 75 mm, respectively (Fig. 2). Moreover, the study lakes spread over different vegetation zones: from the northern boreal zone (SPB, PB and BP) in the south to TD in the north (Fig. 1, Table 1), potentially affecting local climate.

In addition to spanning a steep climatic and vegetational gradient, the study lakes also vary in geographic location, elevation, topographic setting, catchment properties and physicochemical water characteristics (Table 1). All the lakes are small (surface area 0.013–0.204 km^2) and shallow (maximum depth 1.9–15 m), and most of them have highly transparent water. They are situated at varying elevations between 249 and 1009 m a.s.l. Their catchment areas vary greatly in size (5.9 to 215.3 km^2), as does the proportion of mire area in each catchment (0 to 58.8%). All lakes have low turbidity (0.2–1.7 FTU), but the ranges in colour (2.5–80 Pt mg/L), DOC (0.9–8.5 mg/L), TN (110–1200 µg/L) and TP (1–100 µg/L) are wide. Furthermore, wfl4 and wfl55 are well mixed during the summer, whereas wfl3, 5, 6, 11, 12, 13, 30, 54 and 56 can be characterized as discontinuous cold polymictic lakes that stratify during the warm season for the periods of several days (to weeks), with irregular interruption by complete mixing (Lewis 1983; Zhang et al. unpubl. data) due to frequent weather changes, such as a sudden drop in air temperature and strong wind in the tundra area.

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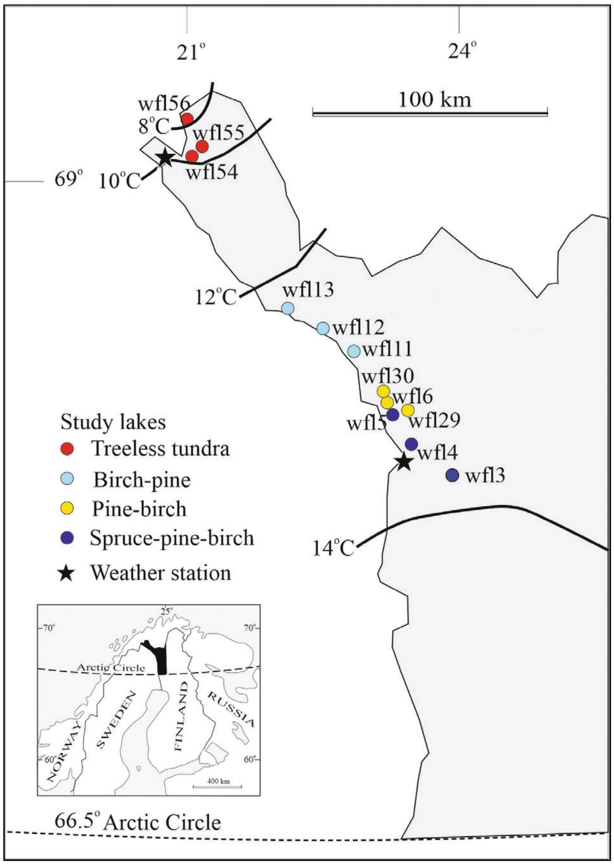

Fig. 1 Location of the study lakes across vegetational and climatic gradients.

Data collection

The in situ measurements of LSWT were carried out in May–September 2000, May 2007–September 2008, and May 2019–September 2021. The thermistors (HOBO Water Temperature Pro v2 Data Logger with a nominal temperature resolution and accuracy of 0.02 and ± 0.21°C, respectively) were installed on buoys to keep the sensors at about 30 cm below the lake surface, logging LSWT at every two hours. The meteorological data—air temperature, precipitation and global radiation—were derived from the Finnish Meteorological Institute's ClimGrid, which is a gridded daily climatology data set at a 10 × 10 km spatial resolution (Aalto et al. 2016). Wind speed was obtained from Copernicus Climate Data Store, but data were available for only 2019–2021. These data provide modelled wind speed at 10-m height from the surface and at the altitude of the grid cells. The data for all climatic variables are projected onto the UTM (Zone 35N) coordinate system with reference to ETRS89 (ETRS-TM35FIN) datum. The daily meteorological data for each individual lake in the study period were derived from the grid by using ArcGIS 10.8, and the monthly data were subsequently calculated. The lake morphometric variables and water quality parameters were measured in July 1995 and 1998 (Weckström & Korhola 2001).

Statistical methods

Daily LSWT and July LSWT of each individual lake were calculated, and a time series analysis was conducted to investigate the annual cycle of LSWT. Summer maximum LSWT (MaxLSWT) and mean July LSWT (JulLSWT) were chosen as the response variables for exploring LSWT dependence on environmental conditions. In the study region, summer comprises the months of June, July and August, and lakes are usually frozen from November to June with the surface temperature being close to the freezing point.

Pearson's correlation analysis and PCA were applied to identify the relationship between summer LSWTs and measured environmental variables. The explanatory variables for the Pearson's correlation analysis included all environmental variables listed in Table 1, combined with July air temperature, July precipitation and July global radiation during the all monitored years and July wind speed during 2019–2021.

Given the high transparency of lakes in our study, we adjusted the SD of some lakes during statistical analysis: if the observed SD exceeded lake maximum depth, we used its theoretical SD, based on colour and turbidity (Brezonik 1978; Table 1). By comparing Pearson correlation coefficients (r) between summer LSWTs and environmental parameters, the most important environmental variables ($r > 0.5$) were selected for the PCA. PCA is used to identify correlated variables by reducing the dimensions of multivariate data; this reduction is achieved by identifying the principal directions (principal components) in which the data vary, and the directions are listed in the order of the variances as PC1, PC2, etc. The amount of variance retained by each principal component is measured by the corresponding eigenvalue (Kassambara 2017). A one-way ANOVA was used to examine differences in summer LSWTs for lakes in different vegetation zones.

Moreover, to further confirm the relative importance of the main environmental drivers in PCA and to quantify the relationship between these drivers and the summer LSWT, linear mixed models were applied to fit the data. A linear mixed model can be represented as:

$$Y = X\beta + Z\mu + \alpha,$$

where Y is the response variable, β and μ are the unknown vectors for fixed effects and random effects,

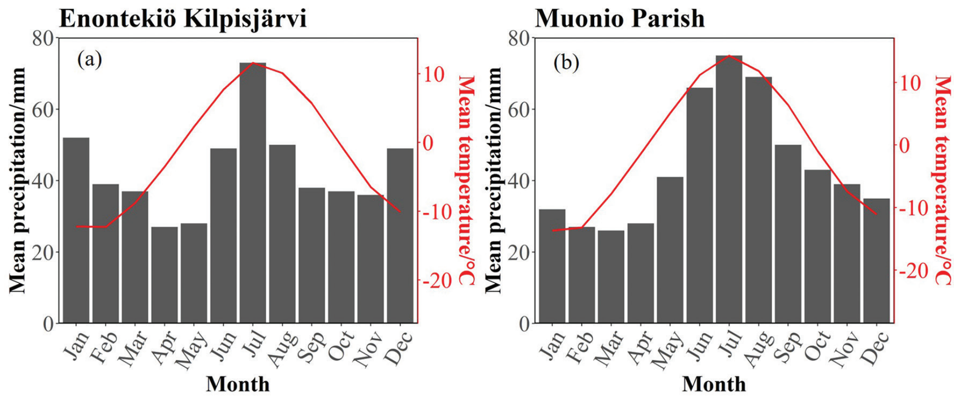

Fig. 2 Climate normals (1991–2020) for the weather stations in (a) Enontekiö Kilpisjärvi and (b) Muonio Parish. The red curves show air temperature, and the columns show precipitation.

respectively, X and Z are known design matrices relating the observations Y to β and μ, respectively, and α is the random error. The term $X\beta$ is fixed describing the response variable Y as a function of the explanatory variables via $\alpha + \beta_1 \times X_1 + \ldots + \beta_q \times X_q$ in the linear regression, and $Z\mu$ is the random part containing components that allow for heterogeneity, nested data (random effects), temporal correlation, spatial correlation and a real random term (Zuur et al. 2009). Because some lakes are located very close to each other, their summer LSWTs and some environmental factors are spatially correlated. Therefore, lakes were included in the model as random effects, and a linear mixed model was used instead of fitting a linear regression to the data (Zuur et al. 2009; Meteyard & Davies 2020). The explanatory variables (fixed effects) included in the full models were the environmental variables in the PCA. To unify the fixed intercept and fixed effects' slopes, all variables were scaled to have the same unit before fitting the models. Backward stepwise selection was implemented to choose the optimal model on the basis of p values, AIC, BIC and logLik estimating the quality of each model relative to each of the other models (Aho et al. 2014). Technically, the lower the AIC or the BIC value, or the higher the logLik value, the better a model fits a data set. The final model was tested by ANOVA for linear model fits (χ^2 test). A variance inflation factor greater than three was used as the selection criterion for variable collinearity (Gunst & Webster 1975).

The yearly JulLSWT and the yearly MaxLSWT (in total 72 observations per variable) were loaded into the PCA and linear mixed model analysis with fixed lake morphometric variables and water quality parameters and changing meteorological data. Version 4.1.3 of the R statistical package was used for all data processing and analyses, as well as for plotting the results.

Results

Spatio–temporal changes of summer LSWT and regional climate over two decades

The temporal variations of the daily LSWT (May–September) in 12 Arctic lakes are shown in Fig. 3. During the recorded six years, the annual cycle of summer water temperature followed the pattern of warming up from May to July (or August) until the water temperature reached its maximum, after which it decreased until freezing in fall. However, the detailed patterns of annual cycles varied amongst these lakes. Three groups (I, II and III) were identified on the basis of similarities in the LSWT in all the study years (Table 1). Group I includes nine lakes (wfl3–wfl30), for which the warming period lasted until July and the water temperature reached its maximum on nearly the same day (Fig. 3). These lakes have different morphometric and geochemical features, but all are located at low elevations (<400 m a.s.l.) within the northern boreal vegetation zone (Table 1). Groups II (wfl54 and wfl55) and III (wfl56) both differ from group I by their later start of warming. They are located at high elevations (>700 m a.s.l.) in the TD, and their summer LSWTs are much lower than in the lakes in group I. Whilst these lakes are located relatively close to each other, the annual cycles of surface water temperature differed regarding the date of maximum temperature: wfl54 and wfl55 (group II) reached their maximum temperature on nearly the same day in July as the lakes in group I, whereas wfl56 (group III)—the deepest lake and the lake at the highest location—did not reach its maximum temperature until early August (Fig. 3).

Table 2 demonstrates the variability in summer LSWTs and local climate between the three lake groups

Table 1 Physical and chemical characteristics of the study lakes across vegetational and climatic gradients. Where SD exceeds maximum depth, the lake bottom is visible.

Lake code	Latitude (north)	Longitude (east)	Elevation (m a.s.l.)	Area (km²)	Catchment area (km²)	Lake max depth (m)	SD (m)	Theoretical SD (m)	DOC (mg/L)	Colour (Pt mg/L)	Turbidity (FTU[a])	TN (µg/L)	TP (µg/L)	Mire area (%)	Forest zone	Group
wfl3	67.85	24.18	268.0	0.071	31.0	3.0	>3.0	3.43	8.3	40.0	0.7	360	10	40.0	SPB	I
wfl4	67.98	23.68	262.0	0.107	59.1	3.0	>3.0	3.91	7.1	20.0	0.8	280	9	28.8	SPB	I
wfl5	68.01	23.40	249.0	0.043	50.9	3.4	2.7	1.91	8.5	80.0	1.7	350	100	46.0	SPB	I
wfl6	68.12	23.37	252.0	0.015	5.9	4.3	>4.3	2.87	7.0	20.0	1.5	1200	25	4.4	PB	I
wfl11	68.40	22.85	313.0	0.022	21.7	4.0	>4.0	5.81	6.5	5.0	0.4	400	8	2.4	BP	I
wfl12	68.42	22.58	332.0	0.020	8.8	1.9	>1.9	3.11	8.3	35.0	1.0	430	10	58.8	BP	I
wfl13	68.47	22.43	322.0	0.026	14.2	4.0	>4.0	4.16	5.2	25.0	0.6	320	8	25.8	BP	I
wfl29	68.10	23.42	249.0	0.040	18.3	8.5	3.0	2.72	8.4	70.0	0.7	240	10	12.0	PB	I
wfl30	68.13	23.37	253.0	0.013	10.7	4.0	3.1	4.96	8.0	5.0	0.7	460	11	0	PB	I
wfl54	69.03	21.13	796.4	0.093	100.2	8.0	7.0	6.75	2.0	2.5	0.3	160	4	0	TD	II
wfl55	69.06	21.05	774.0	0.204	215.3	2.0	>2.0	5.81	1.9	5.0	0.4	160	6	0	TD	II
wfl56	69.17	21.05	1009.0	0.096	133.5	15.0	>15.0	6.99	0.9	2.5	0.2	110	1	0	TD	III

[a]Formazin turbidity unit.

during the study years. Variations in summer LSWTs showed large spatial heterogeneity amongst lakes in different groups, and interannual variability in MaxLSWT is greater than that in JulLSWT. The lake-specific July air-temperature record separates two groups: the first is the same as group I of the LSWT records, whilst the second group comprises both LSWT groups II and III. July precipitation, solar radiation and wind speed (based on limited available data) are similar for all lakes (Table 2). Precipitation, however, shows more variability at high altitudes (groups II and III). Table 2 also displays the significant difference of MaxLSWT and JulLSWT over the study period, with an average difference of about 4°C.

Environmental drivers affecting LSWT

Pearson correlation analysis reveals the relationship between summer LSWTs and measured environmental variables during the studied period (Fig. 4). The correlations between the environmental variables and summer LSWTs, characterized by MaxLSWT and JulLSWT, were overall similar, although JulLSWT correlations were higher. Altitude had the highest correlation (JulLSWT –0.94 and MaxLSWT –0.91), and July air temperature had the second highest correlation (0.82 and 0.85, respectively), followed by latitude (–0.81 and –0.84, respectively) and longitude (0.78 and 0.81, respectively). As for water quality, DOC had the highest correlation (JulLSWT 0.86 and MaxLSWT 0.85), followed by SD (–0.79 in both cases). The lake morphometric parameters—maximum lake depth, lake area and catchment area—had correlations of 0.5–0.7 with summer LSWTs. In addition, significant differences are seen between the lakes in the forest zones (BP, PB, SPB) and those in the TD in relation to MaxLSWT and JulLSWT, although the type of forest vegetation did not seem to have any major influence on summer LSWTs, as indicated by the means and the standard deviations of summer LSWTs amongst three forest zones (BP, PB and SPB; Table 3).

The relationships between the main environmental drivers and summer LSWTs were explored first by means of PCA (Fig. 5). The first two principal components explain 88% of the total variance, with PC1 and PC2 representing 76.2 and 11.9%, respectively. PCA categorized the lakes into two groups according to vegetation zones, where the left group consists of BP, PB and SPB and the right group of TD (Fig. 5a). In the right group, lake morphometry further distinguishes wfl55 from wfl54 and wfl56 (Fig. 5b). PC1 is strongly negatively correlated with summer LSWTs, whereas PC2 shows a weaker positive correlation. Amongst explanatory variables, PC1 is positively correlated with altitude, latitude and SD, but negatively correlated with July air temperature, longitude and DOC. PC2 is largely negatively correlated with lake maximum depth, whereas lake area and lake catchment area show intermediately positive correlations with PC1 and PC2 (Fig. 5b). Climatic factors, DOC concentration and SD have higher correlations with summer LSWTs, compared to lake morphometric features (Fig. 5b).

The quantitative relationship between summer LSWTs and environmental drivers

Linear mixed models were employed to further investigate how the main environmental drivers identified in the PCA influence summer LSWT and to determine their quantitative relationships. July air temperature, lake geographic parameters (altitude, latitude and longitude), lake morphometric features (maximum depth, lake area and lake catchment area) and certain physicochemical characteristics (DOC and SD) were selected as the fixed effects. The results of the model selection are shown in Table 5. No statistical difference was found between the full and final models (p = 0.478 and 0.448; Table 4), which indicates that adding the deleted variables (latitude, longitude, area, catchment area, DOC and SD) in the model would not improve the model fit (R^2). Additionally, for the final model, both AIC and BIC values were smaller, and logLik values were higher, compared to that of the full model, which confirms the representativeness of the final model (Table 4). The final model for predicting the MaxLSWT based on the analysed lakes explains 87.6% of the total variance, with July air temperature, maximum lake depth and altitude combined explaining 86.8%.

According to the final model for predicting JulLSWT, fixed effects (July air temperature, maximum lake depth and altitude only) explain 92.3% of the total variance. Moreover, the proportion of variance explained by the lakes was 6.1%, suggesting a high correlation amongst the studied lakes (ICC = 0.90), which justifies considering lakes as random effects. The coefficients of the three predictors are extremely close to MaxLSWT on the account of the very high correlation between MaxLSWT and JulLSWT.

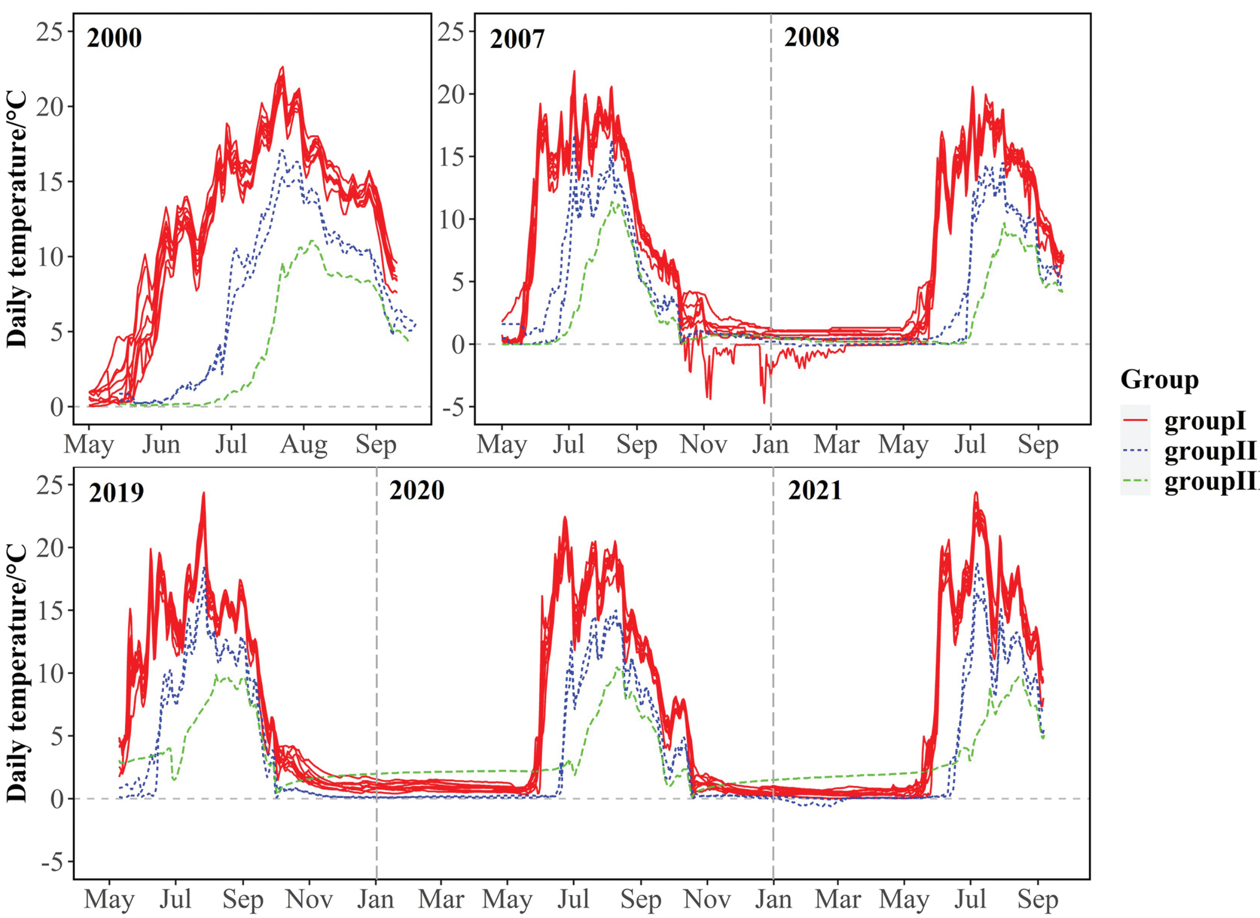

Fig. 3 Time series of LSWT in three groups of 12 Arctic lakes during the observation period. Group I comprises low-elevation lakes (<400 m a.s.l.); groups II and III are high-elevation lakes (>700 m a.s.l.).

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Table 2 Basic statistics for summer LSWTs and July air temperature, precipitation and radiation in all recorded years, as well as wind speed during 2019– 2021.

Lake code	MaxLSWT[a] (°C)					JulLSWT[b] (°C)					JulAT[c] (°C)				JulPre[d] (mm)				JulRad[e] (kJ/m^2)				JulWS[f] (m/s)			
	Max	Min	Mean	St.dev[g]	Mean	Max	Min	Mean	St.dev[g]	Mean	Max	Min	Mean	St.dev[g]	Max	Min	Mean	St.dev[g]	Max	Min	Mean	St.dev[g]	Max	Min	Mean	St.dev[g]
wfl3	23.8	19.42	21.71	1.73		19.22	16.87	17.60	0.97		15.90	12.90	13.73	1.14	76.72	48.10	60.67	10.40	21469.31	15621.02	17821.48	1994.08	5.42	0.96	2.91	0.93
wfl4	23.36	19.55	21.56	1.63		19.19	16.88	17.66	0.93		15.90	13.00	13.87	1.09	71.22	46.99	59.18	10.69	21537.60	14872.81	17444.68	2370.29	5.60	1.18	2.98	1.00
wfl5	23.74	20.02	22.05	1.51		19.04	17.10	17.71	0.85		15.60	12.90	13.63	1.06	72.18	44.02	59.24	12.34	21555.42	14974.11	17463.62	2329.24	5.52	1.18	2.97	1.00
wfl6	23.22	18.81	21.30	1.67		19.76	17.49	18.18	0.91		15.50	12.80	13.57	1.06	73.40	42.81	58.40	12.98	21534.69	15055.19	17475.52	2282.80	5.48	1.10	2.98	1.01
wfl11	22.81	18.86	21.19	1.47		19.06	16.65	17.60	0.86		14.90	12.60	13.33	0.92	83.64	38.56	59.85	17.68	21547.75	15235.24	17460.78	2222.84	5.92	1.12	3.25	1.16
wfl12	23.47	19.48	21.80	1.47	19.69	18.24	16.23	17.12	0.75	15.67	14.60	12.30	13.15	0.91	88.27	40.85	62.20	18.26	21587.23	15257.71	17475.36	2228.86	5.87	1.19	3.20	1.14
wfl13	22.57	18.72	21.18	1.50		18.15	16.19	17.09	0.69		14.50	12.30	13.23	0.86	87.60	38.37	59.72	18.07	21606.75	15307.22	17473.34	2220.53	5.87	1.19	3.20	1.14
wfl29	22.53	19.03	20.65	1.44		18.32	15.68	16.76	0.99		15.50	12.80	13.57	1.06	73.40	42.81	58.40	12.98	21534.69	15055.19	17475.52	2282.80	5.52	1.18	2.97	1.00
wfl30	24.41	20.58	22.72	1.49		19.80	17.80	18.45	0.79		15.50	12.80	13.57	1.06	73.40	42.81	58.40	12.98	21534.69	15055.19	17475.52	2282.80	5.74	1.14	3.20	1.12
wfl54	16.58	13.39	15.08	1.14		13.16	10.76	11.68	0.86		11.40	9.70	10.60	0.62	70.36	22.71	50.23	19.52	21645.11	15401.21	17370.35	2228.02	5.75	0.98	3.00	1.18
wfl55	18.76	14.33	16.73	1.79		13.89	11.49	12.77	0.80		11.70	9.90	10.78	0.64	67.45	17.13	46.12	20.04	21686.02	15420.54	17393.42	2234.11	5.89	1.15	3.04	1.18
wfl56	11.37	9.68	10.35	0.73		6.30	5.01	5.43	0.45		11.10	9.20	10.17	0.68	73.15	25.69	52.15	19.55	21629.53	15388.00	17340.17	2231.89	5.84	1.13	2.77	1.02

[a]Summer maximum LSWT. [b]Mean July LSWT. [c]July air temperature. [d]July precipitation. [e]July radiation. [f]July wind speed. [g]Standard deviation.

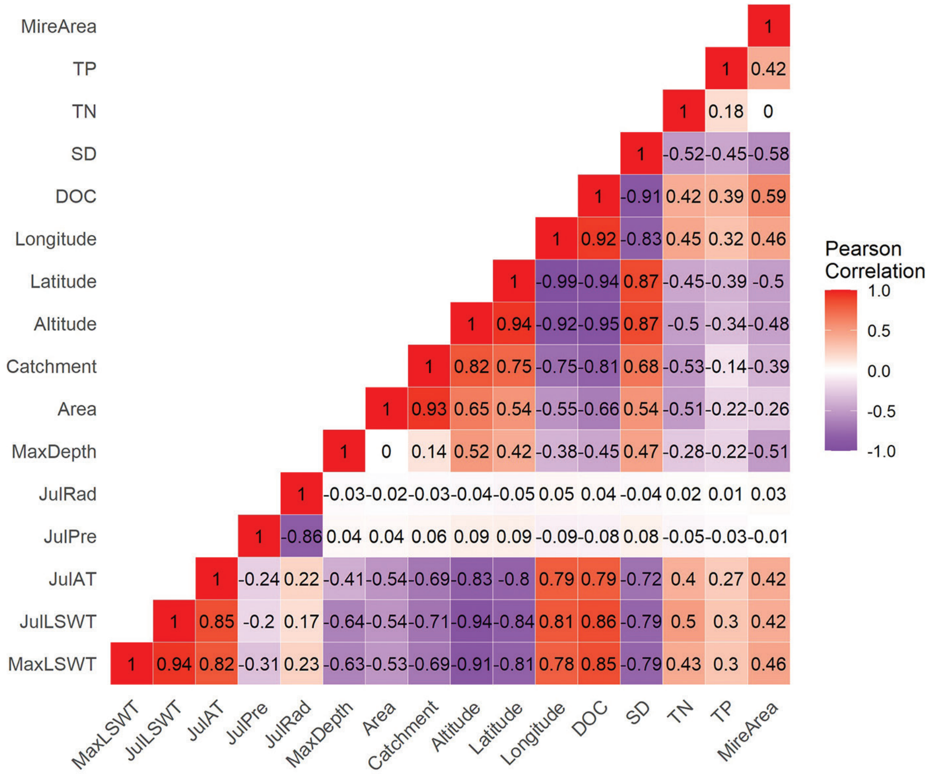

Fig. 4 Pearson correlation matrix between summer LSWT and environmental parameters.

Table 3 Basic statistics for variations of summer LSWT in the four vegetation zones.

Forest zone	MaxLSWT (°C)				JulLSWT (°C)			
	Max	Min	Mean	St. dev[a]	Max	Min	Mean	St. dev[a]
TD	18.76	9.68	14.22	3.04	13.89	5.01	9.45	3.40
BP	23.47	18.72	21.10	1.42	19.76	16.23	18.00	0.76
PB	24.41	18.81	21.61	1.69	19.80	15.68	17.74	1.14
SPB	23.80	19.42	21.61	1.54	19.22	16.87	18.05	0.86

[a]Standard deviation.

On the basis of the results of the linear mixed model, July air temperature, maximum lake depth and altitude capture most of the variation in the summer LSWT (>85%), which indicates the importance of these three environmental drivers in predicting variability of summer LSWTs in the study area.

Discussion

Spatio-temporal differences in summer LSWT over two decades

Prior studies have shown that summer LSWTs have increased over the past several decades because of global warming. For instance, Arvola et al. (2009) analysed long-term temperature records from 25 European lakes, concluding that their surface temperatures have increased in recent decades, but the patterns of change vary locally and regionally. O'Reilly et al. (2015) investigated summer LSWT change across 235 globally distributed lakes between 1985 and 2009. They discovered that most lakes were warming, although the trends showed large spatial heterogeneity, so that both warming and cooling occurred in high-latitude lakes from the same region (e.g., Alaska). The highest warming rates occurred, according to O'Reilly et al. (2015), in seasonally ice-covered lakes that are subject to a combination of shorter ice-cover duration, decrease in cloud cover, and increase in both summer air temperature and shortwave radiation. Zhong et al. (2016) explored the recent accelerated warming of the

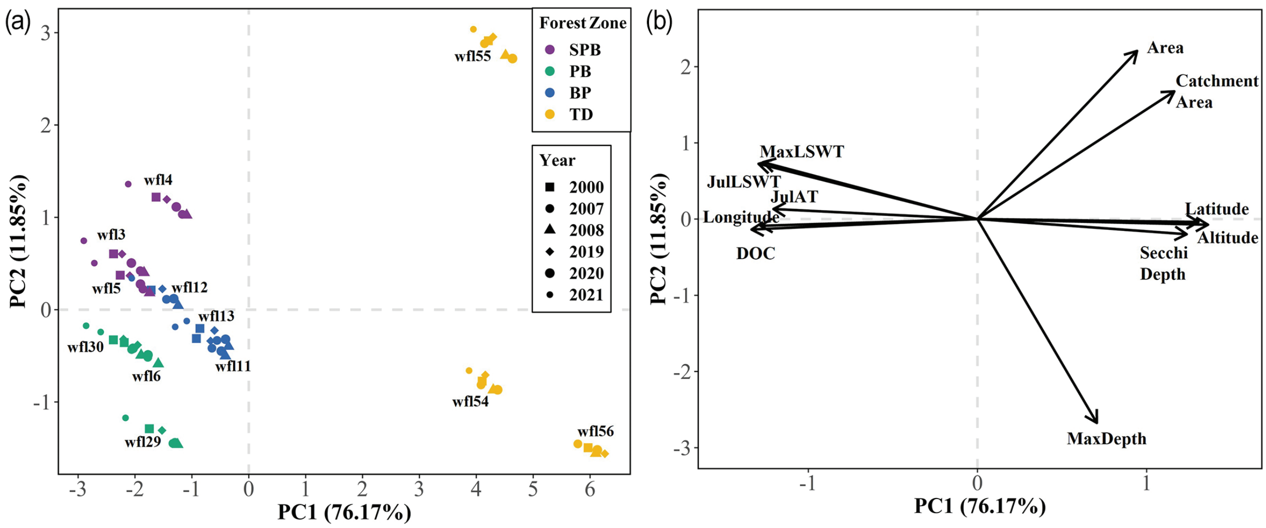

Fig. 5 PCA of summer LSWTs and environmental parameters in 12 Arctic lakes: (a) lake ordinations (the position of lake codes is the approximate position of their markers); (b) summer LSWTs and environmental drivers.

Table 4 ANOVA test between the full and final models for summer LSWTs.

Model	npar[a]	AIC	BIC	logLik	deviance	χ^2	Df[d]	*p* value
MaxLSWT								
Full model[b]	12	266.34	293.66	−121.17	242.34			
Final model[c]	6	259.87	273.53	−123.94	247.87	5.53	6	0.478
JulLSWT								
Full model[b]	12	154.05	181.37	−65.024	130.05			
Final model[c]	6	147.83	161.49	−67.917	135.83	5.78	6	0.448

[a]Number of parameters. [b]LSWT ~ JulAT + Altitude + Latitude + MaxDepth + Area + Longitude + Catchment + DOC + SD + (1 | fLake). [c]LSWT ~ JulAT + Altitude + MaxDepth + (1 | fLake). [d]Degrees of freedom.

Laurentian Great Lakes from 1982 to 2012 and revealed that lakes Superior and Erie, two of the Great Lakes located in different geographical and climatic settings, experienced different warming rates in summer LSWT. Ptak et al. (2018) carried out a study that recorded the daily water temperature of 14 Polish lakes, with different locations, morphometric parameters, water transparency and other features, between 1972 and 2016. They concluded that summer LSWTs had increased markedly but also showed that the lakes had different warming rates; these depended on local environmental factors, including the length of the ice-cover duration, location of the lakes, their morphometric parameters, wind speed, water transparency and water exchange time. Although there is a consensus on the increasing summer LSWT globally, the rates are not consistent even on local to regional scales. As the Arctic is warming three to four times faster than the global average (Rantanen et al. 2022), Arctic lakes can act as sentinels for climate warming and its effects on freshwaters. In our study, no clear warming trend was observed in summer LSWTs, possibly because of the temporally limited data set, but variations in summer LSWTs showed large spatial heterogeneity (Table 2, Fig. 3), which is consistent with the aforementioned studies.

Whilst variations of summer LSWTs in Arctic lakes have been documented, most of the studies have thus far focused on a few individual large and deep lakes. However, a vast majority of Arctic lakes are smaller than 1 ha, and we lack any data on their thermal features (Downing et al. 2006). Therefore, it is of great importance to study summer LSWT changes in small Arctic lakes and compare their thermal responses with summer LSWT changes in larger Arctic lakes. In our study region, Lake Kilpisjärvi is a large lake (surface area 37.1 km^2, maximum depth 57 m and elevation 473 m a.s.l) that is located close to wfl54, 55 and 56 (69.05° N, 20.83° E; Lei et al. 2012). It serves as a good comparison to the smaller lakes that we studied. In Lake Kilpisjärvi, the summer MaxLSWT was about 14°C in August 2007 and 11°C in July 2008, and the JulLSWT about 11°C in 2007 and 10°C in 2008 (Leppäranta et al. 2017). In the present study, the MaxLSWT of wfl54 (796 m a.s.l.),

Table 5 Effects of environmental drivers in PCA on summer LSWTs based on linear mixed models.

Predictors (scaled)	MaxLSWT			JulLSWT		
	Estimates	Confidence interval	p	Estimates	Confidence interval	p
(Intercept)	19.69	19.31 – 20.07	<0.001	15.67	15.11 – 16.23	<0.001
July air temperature	0.95	0.37 – 1.53	0.002	1.12	0.91 – 1.33	<0.001
Altitude	-2.23	–2.89 – –1.57	<0.001	–2.22	–2.90 – –1.54	<0.001
Maximum lake depth	-0.88	–1.33 – –0.44	<0.001	–0.83	–1.49 – –0.18	0.014
Random effects						
σ^{2} [a]	1.84			0.24		
ICC[b]	0.13			0.90		
N_{fLake}	12			12		
Observations	72			72		
Marginal R^2 / conditional R^2 [c]	0.868 / 0.876			0.923 / 0.984		

[a]The residual variance. [b]The correlation amongst random effects. [c]Marginal R^2 is the variance explained only by fixed effects (predictors); conditional R^2 is the variance by the entire model (both fixed effects and random effects). Lakes act as random effects in the models.

wfl55 (774 m a.s.l.) and wfl56 (1009 m a.s.l.) was between 11 and 16°C in August 2007 and between 10 and 14°C in July 2008, and the JulLSWT of wfl54 and wfl55 was between 11 and 13°C in 2007 and 2008, whereas JulLSWT of wfl56 was about 5°C in 2007 and 2008 (Fig. 3). These evident differences in summer LSWTs between Lake Kilpisjärvi and the nearby study lakes show that lake size is not always the main determinant of LSWT, highlighting the importance of elevation (and, hence, air temperature) and lake morphometry in determining summer LSWTs. For the other nine lakes (wfl3–wfl30; 249–332 m a.s.l.), the summer MaxLSWT varied between 19 and 22°C in July 2007 and between 19 and 21°C in July 2008, and the JulLSWT between 16 and 18°C in 2007 and 2008 (Fig. 3), underlining the role of altitude and air temperature in defining summer LSWT.

Roles of environmental variables in summer LSWT

In this study, summer LSWTs were characterized by two parameters, namely, summer MaxLSWT and JulLSWT. JulLSWT can be regarded as a summer equilibrium-state variable, which can reflect an indirect influence of climate. The summer maximum LSWT relates to climate extremes, depending on the variability of summer weather. It is largely an atmospheric climatic characteristic, less sensitive to the lake features. However, more variation is usually observed in small lakes than in large and deep lakes, and small and shallow lakes tend to warm up faster and reach higher temperatures than larger lakes (Dyba et al. 2022). The qualitative analysis of the overall summer LSWT revealed that the climate (July air temperature), geographic setting (latitude and longitude), topography (altitude), lake morphometry (lake maximum depth, lake area and lake catchment area), water quality (DOC and SD) and vegetation zones are regulating the dynamics of lake water temperature in our study lakes (Figs. 4, 5). Furthermore, according to the linear mixed model, July air temperature, altitude and lake maximum depth are the most important environmental drivers affecting summer LSWT (Table 5). July precipitation, July solar radiation, water chemical characteristics and catchment mire area, on the other hand, were not as strong factors as expected in this study.

Climate change

Latitude, longitude and altitude—environmental factors constructing the regional geographic condition—form a strong air-temperature gradient in our study area (ca. 2°C mean annual temperature difference between the southernmost lakes in Muonio and the northernmost in Kilpisjärvi). Particularly, the altitude differences between lakes, ranging 249–1009 m a.s.l., combined with the impact of latitude and longitude (linked with the maritime effect and topographic influences in the studied area), separates two groups in local air temperature (Tables 1, 2), resulting in distinct LSWT groups. Also, altitude has a direct impact on air temperature within an area, creating a season-specific lapse rate (Laaksonen 1976; Livingstone 2005; Huang et al. 2017) that is normally about 0.6°C per 100 m of altitudinal increase in summer.

Air temperature is the key determinant affecting LSWT. Water temperature varies normally corresponding to fluctuations of the mean daily air temperature, which has been shown in many studies (e.g., Benson et al. 2000; Livingstone 2005; Boehrer & Schultze 2008; Palmer et al. 2014; Schmid et al. 2014; Noori et al. 2022). Previous studies have reported the impacts of solar radiation and precipitation on lake surface warming (Schmid & Köster 2016; Zhong et al. 2016; Cheng et al. 2021). Furthermore, solar radiation, depending on latitude and longitude, has a major role in the LSWT via the balance of radiative heat flux (Fink et al. 2014; Huang et al. 2017). However, as the mean and standard deviation of July precipitation and radiation were almost evenly distributed in this study (Table 2), their importance was not revealed in the statistical analysis. In addition, Magee & Wu (2017) reported that correlations between wind speed and lake temperature can be as high as, or higher than, the correlation between air temperature and lake temperature, emphasizing the importance of wind speed in lake temperature changes. According to the available wind data, the variability of wind speed is minor in the study area (Table 2). However, it needs to be emphasized that the coarse scale (approximately 30 × 30 km) of the wind data available is not optimal for local lake-specific wind estimates, and hence, disentangling the influence of wind on changing LSWT. The Pearson correlation matrix using the available wind data indicates that wind speed has a positive relationship with air temperature (r = 0.54, Fig. 6). Supplementary Fig. S1 demonstrates the role of wind in the heat balance between the air and the water surface: whilst the difference between the LSWT and AT appears to increase with wind speed, the large scatter in the data is noteworthy.

Lake morphometry

Lake morphometry has also been shown to be an important variable in explaining variations of LSWTs (Adrian et al. 2009; Van Cleave et al. 2014). The heat storage capacity of a lake is related to its depth: shallow lakes have lower heat storage capacity and respond faster to short-term and extreme climatic variations (Arvola et al. 2009). Lake area has an influence on LSWT because the mixed layer deepens when wind speed and surface waves become larger at long effective fetches. Lake catchment area properties are related to heat input and water renewal. Pearson's correlation analysis suggested that lake morphometric parameters were negatively correlated to summer LSWTs ($|r| > 0.5$; Fig. 4), which agrees well with previous studies (Huang et al. 2017; Ptak et al. 2018). However, only lake maximum depth was included in the final linear mixed models, highlighting that depth has a strong impact on summer LSWTs. Magee & Wu (2017) studied the response of water temperature and stratification to changing climate in three lakes with different morphometry and concluded that lake surface area has an impact on hypolimnion temperature, hypolimnetic heating, and the start and breakdown of stratification, whereas lake depth has an impact on differences in the surface heat flux. The lakes in the present study were small, shallow and mainly clear-water (Table 1) and were therefore usually completely mixed and isothermal during the open water period. This explains the strong explanatory power of lake maximum depth. Lake area can also be an important parameter in the regional water temperature variation in Arctic lakes (Hinkel et al. 2005; Huang et al. 2017), but here, it was precluded from the final model, most likely because of the small size and limited size range of the studied lakes. Similarly, the size of the lake catchment area could explain some of the variance in summer LSWTs (Figs. 4, 5), but—most likely because of the homogeneous catchment area sizes—it only had weak explanatory power and was excluded from the final model.

Water quality

Heat accumulation in the surface water layer is related to water transparency determined by water colour and turbidity (Edmundson & Mazumder 2002; Ptak et al. 2018), both of which are predicted to increase in Arctic lakes along with increasing temperatures, precipitation and permafrost thaw (Blanchet et al. 2022). Water colour can be affected by many chemical variables, such as TP, via influencing algal growth, and DOC by its coloured fraction (Molot & Dillon 1997; Håkanson 2002; Shock & Pratt 2003). Turbidity is affected by the amount of minerogenic particles and particulate organic matter (Lewis et al. 2007; Bright et al. 2018; Pilla et al. 2018). Therefore, water quality characteristics, including SD, DOC, TP and TN, and the catchment mire area were also included in the analysis. Pearson's correlation analysis showed that DOC was strongly positively correlated, and SD strongly negatively correlated, with summer LSWT ($r > 0.8$ and $r = -0.79$, respectively; Fig. 4), which can be interpreted as lower water clarity increasing the LSWT. The optical depth of the water equals the summer mixed layer depth in the absence of wind mixing, and a shallow mixed layer results in a high LSWT warming rate (Read & Rose 2013). It is therefore important in general to consider the impacts of DOC and SD on LSWT, even though they were not included in the final mixed linear models (Tables 4, 5), perhaps because of the fixed DOC and SD values. In this study, we have assumed that DOC and SD have not changed in the study lakes over the past 30 years because these lakes are located in one of the cleanest areas of Europe, in terms of air pollution, there is scarcely any human activity in their catchment area and they have generally not experienced any clear changes in their catchment vegetation cover. However, evidence of the brownification of northern lakes due to various drivers, such as changes in atmospheric S and N deposition, has increased over the recent decade

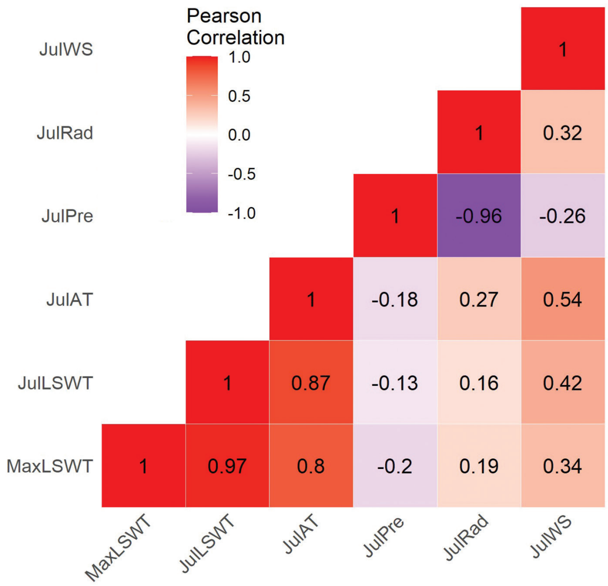

Fig. 6 Pearson correlation matrix between summer LSWT and climatic parameters in 2019–2021.

(Finstad et al. 2016; Puts et al. 2023), along with observations of tundra greening (Frost et al. 2023). Therefore, the fixed DOC and SD values may limit the model's ability to assess the potential roles of DOC and SD in influencing lake surface temperatures.

It is also important to note that in this study SD for most lakes was calculated as a theoretical value based on colour and turbidity; therefore, the strong correlation between SD and summer LSWTs includes the effects of water colour and turbidity on LSWTs. The most significant difference in the thermal features of the study lakes occurred between the forested zones and the TD (Table 3). Vegetation has a strong impact on the catchment inputs to a lake, as nutrients and DOC in oligotrophic and mesotrophic lakes usually originate from the catchment (Tanentzap et al. 2017; Hayden et al. 2019). Large-scale vegetation zones are primarily controlled by climatic conditions (Gottfried et al. 2012; Vazquez-Ramirez & Venn 2021). Therefore, the role of vegetation in changing summer LSWTs is integrated into the impact of environmental variables related to climate change, such as altitude and latitude.

On the regional scale, the combined effects of climatic, morphometri, and geographic factors explained well the changes in the summer LSWT (Table 5). In small and shallow lakes, the entire water column responds to fluctuations in air temperature, so these lakes are likely to respond fast to short-term variations in the weather (Arvola et al. 2009). Our study used local air temperatures, which are influenced by topography, i.e., latitude, longitude and altitude. Additionally, local climatic conditions can be modified by morphometric properties, which are modulated further by water quality characteristics. Shallow lakes, like our 12 study lakes, are often mixed, isothermal lakes, in which water quality plays a minor role in modifying the LSWT. Water transparency, however, can be an important variable when considering stratification or mixing in somewhat deeper lakes. Moreover, the air–lake heat exchange characteristics may change with wind, humidity or cloudiness; therefore, more comprehensive meteorological data need to be collected for predicting the surface water temperature trends in Arctic lakes.

Conclusion

Our study of small lakes in north-western Finland shows that summer LSWT had considerable regional heterogeneity regarding the timing of the maximum and minimum temperatures and the overall patterns of annual cycle. July air temperature, maximum lake depth and altitude explained >85% of the variance of the summer LSWT. The strong explanatory power of altitude is partly because of vegetation changes and resultant catchment inputs (DOC), in addition to the important role of air-temperature change with altitude. The remaining variance resulted from the lake's geographic location (i.e., longitude and latitude) and its morphometric features (lake area and catchment area). July precipitation and radiation, as well as other water quality parameters (e.g., TP and TN) had weak impacts on changes in summer LSWTs.

Reporting new lake temperature data from the Arctic, this study offers insights into the climate sensitivity of small Arctic lakes under current climate change. Research at larger spatial and temporal scales is needed to better understand changes of the thermal regime in small and shallow Arctic lakes and to predict the often complex relationship between lakes and climate change.

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Disclosure statement

The authors report no conflict of interest.

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Data availability statement

LSWT and lake bottom water temperature data will be published at the Bolin Centre database, University of Stockholm, Sweden, after acceptance of the manuscript.

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