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Highlights (Each should be less than 85 characters, including space)

- We investigated thermal response of a subarctic lake to climate change.
- Air temperature and solar radiation contributed to lake surface warming.
- Lake surface temperatures increased whilst deepwaters experienced minimal change.

Multi-decadal change in summer mean water temperature in Lake Konnevesi, Finland (1984-2021)

Roohollah Noori[1,2,*], R. Iestyn Woolway[3], Changhyun Jun[4,*], Sayed M. Bateni[5], Danial Naderian[1], Sadegh Partani[6], Mohsen Maghrebi[1], Merja Pulkkanen[7]

[1]Graduate Faculty of Environment, University of Tehran, Tehran, 1417853111, Iran.

[2]Faculty of Governance, University of Tehran, Tehran, 1439814151, Iran.

[3]School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, LL59 5AB, UK.

[4]Department of Civil and Environmental Engineering, College of Engineering, Chung-Ang University, Seoul, 06974, Korea.

[5]Department of Civil and Environmental Engineering and Water Resources Research Center, University of Hawaii at Manoa, Honolulu, HI 96822, USA.

[6]Civil Engineering Department, Faculty of Engineering, University of Bojnord, Bojnord 9453155111, Iran

[7]Finnish Environment Institute, SYKE, Freshwater Center, Latokartanonkaari 11, 00790 Helsinki, Finland.

*Correspondences:

Roohollah Noori (noor@ut.ac.ir); ORCID: http://orcid.org/0000-0002-7463-8563

Changhyun Jun (cjun@cau.ac.kr); ORCID: https://orcid.org/0000-0002-9767-9923

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Abstract

Depth-resolved water temperature data on the thermal environment of lakes are often hindered by sparse temporal frequency, limited depth resolution, or short duration that create many challenges for long-term analysis. Where high frequency and depth-resolved data exist, they can provide a wealth of knowledge about how lakes are responding to a changing climate. In this study, we analyzed around 950 profiles of summer mean water temperature (July to September), which includes about 30,600 unique observations, from a subarctic lake (Lake Konnevesi, Finland) to understand the changes in lake surface water temperature (LSWT), lake deepwater temperature (LDWT), and lake volumetrically weighted mean temperature (LVWMT) from 1984 to 2021. Statistical analysis of this dataset revealed a substantial warming of LSWT (0.41 °C decade^{-1}) and LVWMT (0.32 °C decade^{-1}), whilst LDWT remained unchanged (0.00 °C decade^{-1}). Our analysis using a generalized additive model suggested the inter-annual variability in LSWT and LVWMT correlated significantly with the upward trends of summer mean air temperature and solar radiation, but suggested no significant effect of observed changes in ice departure dates and near-surface wind speed. None of the investigated predictors correlated with the change in the LDWT. Due to the variable response of lake surface and bottom water temperature to climate change in this subarctic lake, our data suggest a substantial increase in lake thermal stability. Our study supports the growing literature on lake thermal responses to climate change, and illustrates the unique contrast of climate change impacts at the surface and at depth in lake ecosystems, with deep waters acting as a potential thermal refuge to aquatic organisms within a warming world.

Keywords: Climate change; Limnology; Warming trend; Generalized additive model.

1. Introduction

Climate change has resulted in several impacts on the Earth's intricate systems. Particularly, empirical evidence underscores a substantial warming trend across various facets of the hydrological cycle, most notably within lakes, with significant implications for global biodiversity (Stachowicz et al., 2002; Arhonditsis et al., 2004; Cantin et al., 2010; Shimoda et al., 2011; O'Reilly et al., 2015; Behrenfeld et al., 2016; Woolway and Merchant, 2019; Jane et al., 2021). The severity of warming observed in lake ecosystems during the 20th and 21st centuries is undeniable (O'Reilly et al., 2015; Anderson et al., 2021; Noori et al., 2022a). These temperature shifts have resulted in several consequences for aquatic ecosystems. Specifically, climate-induced alterations have triggered notable changes in various physical and biogeochemical processes within lakes, all of which are acutely sensitive to temperature fluctuations. These alterations encompass: (i) changes in mixing and stratification patterns (Woolway and Merchant, 2019; Stetler et al., 2021; Noori et al., 2022b; Yaghouti et al., 2023), (ii) an increased severity of algal blooms (Vilhena et al., 2010; Li et al., 2015; Modabberi et al., 2020) and thus a deterioration of water quality, (iii) A decline in viscosity and a consequential shift in the competitive dynamics between sinking phytoplankton species and buoyant cyanobacteria, bearing severe consequences for the ecological functions of lakes (Wilhe and Adrian, 2008; Sharaf et al., 2019; Molot et al., 2022), and (iv) the production of potent greenhouse gases within lake sediments (Adrian et al., 2009; Marotta et al., 2014; Kraemer et al., 2015; Jane et al., 2022) with far-reaching implications for the global carbon budget (Cardille et al., 2009). Moreover, the observed warming at the lake's surface can contribute to increased lake evaporation (Wang et al., 2018; Woolway et al., 2020). When coupled with other anthropogenic pressured, such as water abstraction for irrigation, this phenomenon can precipitate dramatic consequences for the availability of surface freshwater (Gao et al., 2011; AghaKouchak et al., 2015; Ravilious, 2016; Wurtsbaugh et al., 2017; Tal, 2019; Maghrebi et al., 2023). These multifaceted consequences underscore the urgency of addressing the intricate relationship between climate change and lake ecosystems, as well as the imperative to safeguard these vital natural resources.

Lake water temperature is influenced by a diverse array of climatic drivers, including air temperature, solar radiation, and wind speed, all of which can exert a significant increase (O'Reilly et al., 2015; Schmid and Köster, 2016; Woolway et al., 2019; Noori et al., 2021). Among these climatic drivers, air temperature is often considered the most important. Air temperature is not only involved causally in the emission of long-wave radiation from the atmosphere and in the exchange of sensible and latent heat across the lake surface, but is also strongly correlated with other meteorological variables that influence lake surface water temperature (LSWT). Consequently, as global air temperatures rise, lakes typically, but not always, follow the same direction (O'Reilly et al., 2015). Crucially, the most pronounced warming of global air temperatures is occurring at high latitudes (Alexander et al., 2013). This phenomenon has a direct ripple effect on the surface temperature of lakes in these regions, resulting in rapid warming rates that often exceed the global average (O'Reilly et al., 2015; Woolway and Merchant, 2017). However, it is important to recognize that lake water temperature is not solely dictated by climatic factors. A myriad of morphometric attributes such as lake depth and surface area, water quality indices(e.g., transparency), and the timing of seasonal ice cover, also exert substantial influence (Pilla et al., 2020; Richardson et al., 2017; Pilla et al., 2020; O'Reilly et al., 2015). This intricate interplay between air and water temperature drivers results in significant heterogeneity in the magnitude and even the direction of temperature change across different lakes (Kraemer et al., 2015; O'Reilly et al., 2015; Pilla et al., 2020; Noori et al., 2021). The unique combination of these diverse influences underscores the complexity of lake temperature dynamics and highlights the need for a nuanced understanding of the factors shaping their response to the evolving climate.

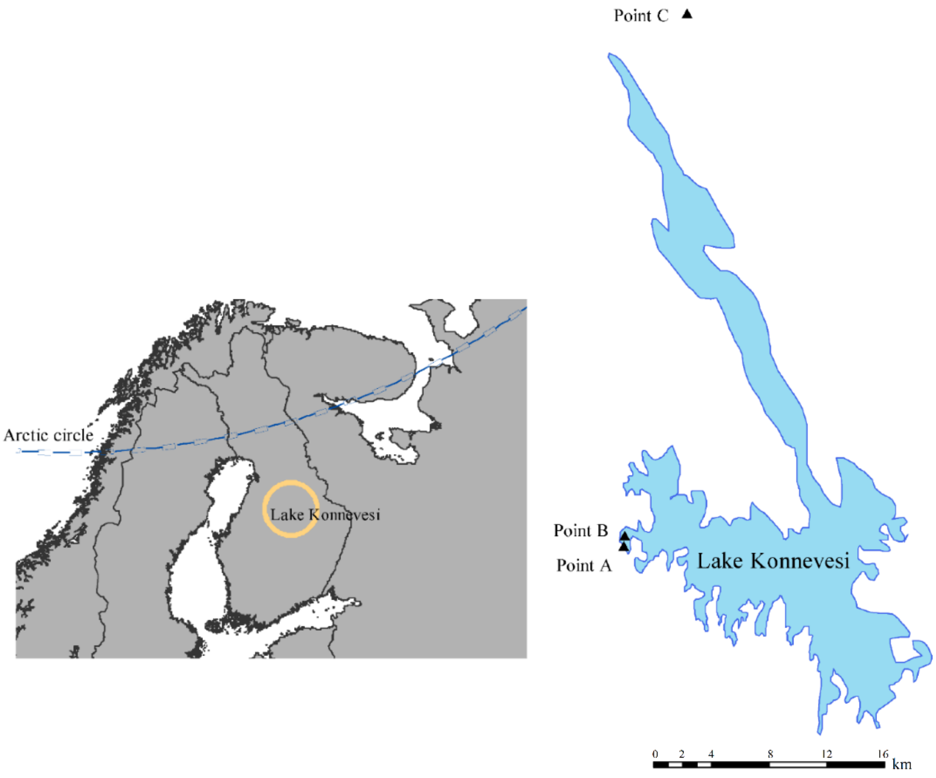
Comprehending the intricate responses of lakes to climate change necessitates access to detailed depth-resolved water temperature data. However, such data often suffer from limitations such as infrequent temporal sampling, restricted depth profiling, or short observational durations. Using a long-term database, this study aims to contribute in in-depth analysis of changes in the LSWT, lake deepwater temperature (LDWT), and lake volumetrically weighted mean temperature (LVWMT) in a subarctic lake situated in the Northern Europe. Our study focuses on scrutinizing alterations in critical parameters, including lake surface water temperature (LSWT), lake deep-water temperature (LDWT), and lake volumetrically weighted mean temperature (LVWMT). To gain insight into the complex interplay of factors influencing these temperature variations, we employ a Generalized Additive Model (GAM) (Hastie and Tibshirani, 1986 and 1990). This analytical framework enables us to dissect the impact of atmospheric variables—namely air temperature, solar radiation, and wind speed—as well as lake-specific drivers, such as the timing of ice departure, on the observed fluctuations in LSWT, LDWT, and LVWMT.

Our findings align with the expanding body of literature concerning the responses of lakes to climate-induced thermal changes. Specifically, our observations underscore a robust warming trend at the lake's surface. In contrast, the water temperature at greater depths remains largely unaffected by these environmental shifts. This distinction in temperature dynamics bears the potential to reverberate throughout the thermal structure and ecological functioning of the lake, making it a matter of paramount importance for future research and conservation efforts.

2. Materials and methods

2.1. Study area

Lake Konnevesi is a dimictic lake (i.e., mixes vertically twice per year) situated in central Finland (62° 38′ N and 26° 24′ E) at a surface elevation of 95 m above sea level (Fig. 1). This medium-sized lake has a surface area of 187 km^2, and an average and maximum depth of 11 m and 56 m, respectively.



(a) (b)

Figure 1. Location of the Lake Konnevesi in (a) Finland and (b) the sampling sites A to C, in which the data investigated in this study were observed.

Lake Konnevesi can be divided into northern and southern parts (Fig. 1). The northern part of the lake is oblong-shaped through northwest to southeast with an average and maximum depth of 7.5 and 44 m, respectively. The lake's bedrock in the north is mainly covered by acidic and barren rocks (e.g., granite, granodiorite and quartzite). The northern zone's coastal areas are dominated by forested mineral soil (or wooded) and drained marshland. Natural forests mostly surround the north region of the lake, with rarely agricultural arable lands scattered in the riparian zone. This relatively northern island-free part is exposed to strong winds, leading to an upper mixed layer that commonly reaches up to 20 m below the lake surface during summer. Mean summer water color at the surface of north Lake Konnevesi is typically low, making the lake as a limpid waterbody. Given mean summer chlorophyll-*a* and total phosphorus of about 4.2 μg/L and 6 μg/L at uppermost 2 m layer, the trophic state in this lake varies from mainly oligotrophic to sometimes mesotrophic. In general, the visible depth of the lake varies from 5 to 6 m or even up to 11 m in its northern part. The southern part of the lake with a surface area twice as large as the northern part is a diverse waterbody, which includes numerous islands, mainly large woody islands. The average and maximum depths in the southern part of the Lake Konnevesi are 12.5 m and 56 m, respectively (https://www.fishinginfinland.fi/lake_konnevesi; Kuha et al., 2016). The winter dissolved oxygen saturation throughout the water mass in the south Lake Konnevesi is more than 50% whilst it further falls across the water column in the northern part of the lake and even quite weak close to the bottom. The south of Konnevesi contains protected zones of the Finnish worth rocky areas and old forests. There are around 1,530 ha of valuable lands reserved for state conservation intentions in the southern region of the Lake Konnevesi (https://www.jarviwiki.fi/w/index.php?title=Konnevesi_(14.711.1.001)).

2.2. In-situ lake observations

Water temperature profiles in Lake Konnevesi have been routinely measured at weekly intervals, or two/three times a month since 1984, using a digital thermometer by the Finnish Environment Institute at sampling location A shown in Fig. 1. Water temperature is sampled consistently with a vertical interval of 1 m from the near-surface to a depth of 20 m and thereafter at 2 m intervals to the lake bottom. In this study, we used water temperature profiles measured at the lake surface (hereafter referred to as the LSWT) to a depth of 40 m (hereafter referred to as LDWT) from 1984 to 2021. To calculate the LVWMT data we first computed the arithmetic average of water temperatures recorded at two adjacent layers. We then computed a mean temperature for the whole lake by weighting the volumes of adjacent layers obtained from the lake hypsometry (Fig. 2a). We used the difference between the LSWT and LDWT to distinguish between "mixed" and "stratified" conditions. Stratified conditions are usually determined as when the LSWT minus LDWT exceeds 1 °C (Stefan et al., 1996; Read et al., 2014; Woolway et al., 2014). Here, we conservatively define stratified conditions (or thermal stability) as when the summer mean difference between LSWT and LDWT exceeds 6 °C.

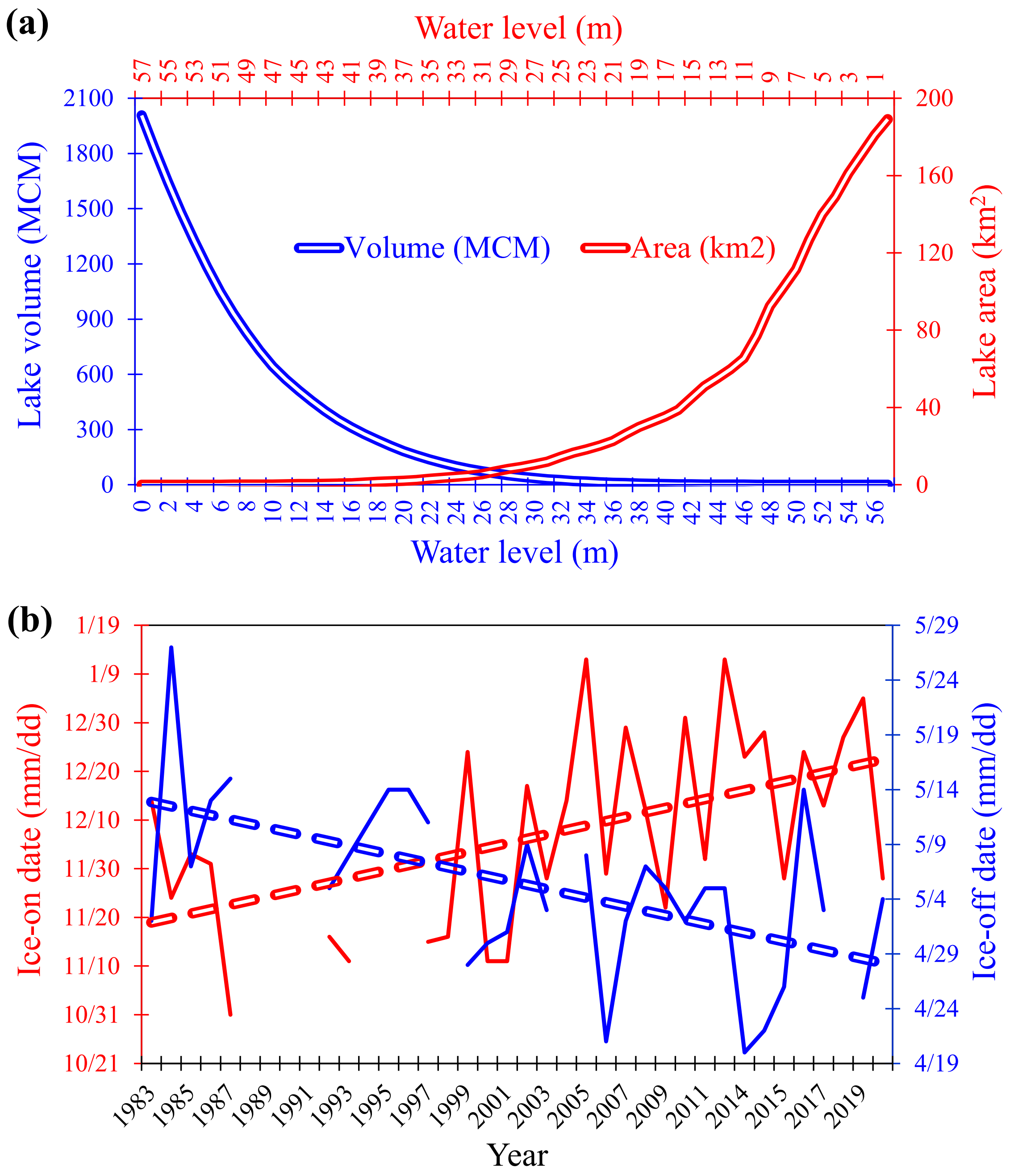


Figure 2. (a) Hypsographic curve of the Lake Konnevesi, Finland, which shows both lake volume (blue color) and lake area (red color) in million cubic meters (MCM) and square kilometer (km^2), respectively, at different depths of the lake. (b) Annual ice-off (blue color) and ice-on (red color) dates measured in Lake Konnevesi from (1984–2020).

As Lake Konnevesi is typically ice-covered from late-autumn to mid-spring (Fig. 2b), we investigated water temperature profiles only during the open-water summer season (July-September), i.e., when the lake is ice-free. Studies on the climate change impact in lakes have also mainly concentrated on the average thermal response of lake surface during these months (Toffolon et al., 2020). Our dataset consists of around 950 profiles of water temperature measured during summer months, and includes 30,600 unique observations, which are publicly available through https://wwwp2.ymparisto.fi/scripts/kirjaudu.asp.

Change in ice departure dates measured at location B (Fig. 1) is also explored in this study from 1984 to 2021. The ice departure dates are consistently reported as the date when ice is no longer observed from the observation site. The ice departure date data are publicly available through https://wwwp2.ymparisto.fi/scripts/kirjaudu.asp.

2.3. Meteorological data

In our study, the changes in spring and summer mean air temperature, summer mean solar radiation, and near-surface wind speed were investigated. The spring mean air temperature was investigated and compared to changes in the ice departure date. We also investigated the influence of summer mean air temperature on summer water temperatures during the study period. As no meteorological observations with long-term data are available near the lake, here we investigated air temperatures (1984-2021) measured at the Vesanto kirkonkylä meteorological station (Point C; Fig. 1), situated approximately 30 km from the lake, as a proxy for over-lake atmospheric conditions. Surface air temperature data are publicly available through https://en.ilmatieteenlaitos.fi. We also investigated the influence of other meteorological variables, including summer mean solar radiation and near-surface wind speed on the observed change in lake temperature. Time series data of these two variables were obtained from the ERA5-Land re-analysis product (9 km^2 resolution) (Muñoz Sabater, 2019) at the location of Lake Konnevesi from 1984 to 2021. Our investigations revealed that the measured air temperature data were closely related to those obtained from ERA5 (R^2 =0.97).

2.4. Data analysis

In this study, we explored the potential influence of four predictor variables on the inter-annual variability in summer mean water temperature in Lake Konnevesi, using a GAM. The GAM is a nonparametric flexible model, which frees the scholars from the restricting concept of a rigid parametric form (Katsanevakis, 2007; Adde et al., 2023). The predictor variables tested include the summer mean air temperature (SAT), solar radiation (SR), near-surface wind speed (WS) and the ice departure date (IDD), which have all been hypothesized previously to influence the thermal response of lakes to climate change (Woolway et al., 2020). Although other climatic factors (e.g., precipitation, wind speed, surface pressure, and relative humidity) may also contribute to the change in lake water temperature, we did not include them in our analysis as (i) their anticipated impact on lake water temperature in the study site is expected to be much less than the other variables described above, and (ii) to avoid a complex model that can hinder the accurate detection of change in the lake water temperature.

Here, the GAM (Eq. 1) was performed using the "mgcv" package in *R* with a gamma-error distribution and the logarithm-link function *f*:

$$\tau_i = f(\mu_i)^{-1} = f\left(\varepsilon_0 + g_1(\mathrm{SAT}_i) + g_2(\mathrm{SR}_i) + g_3(\mathrm{WS}_i) + g_4(\mathrm{IDD}_i)\right)^{-1} \qquad (1)$$

where, τ_i = the expectation of response variable (here, the summer mean LSWT, LVWMT, and LDWT) for the i^{th} data, μ_i = the linear predictor consists of ε_0 (a constant term) and smooth functions g_l (l = 1 to 4). The inverse of *f* maps values from μ_i to the scale of the response.

We used the penalized cubic regression spline to optimize the smooth functions g_l since it decreases computational costs by using a generalized cross validation method and prevents overfitting by applying a wiggliness penalty matrix to the fitting model (Wood and Augustin, 2002). We also kept the concurvity less than 0.8 to avoid multicollinearity in the GAM modeling process (https://noamross.github.io/gams-in-r-course). The sequence of the analysis was guided by the protocol of Zuur et al. (2009). The residuals from each GAM were first checked for any breach of assumptions. The GAM uses the F-statistics and the effective degree of freedom (EDF) to calculate p-value, leading to determination of statistically significant variables. Here, coefficient of determination (R^2) and deviation (or variance) were used to judge about the GAM model performance. R^2 varies between 0 and 1 whilst deviance (%) is a number between 0 and 100. The more the R^2 and deviance, the more the model accuracy (Saghafi et al., 2009; Wood and Augustin, 2002). Detailed information on the method used are given by Wood and Augustin (2002) and Wood (2013).

To describe the long-term patterns of change in water temperature as well as the changes in air temperatures, solar radiation, wind speed, and ice departure date, we calculated the magnitude of long-term trends using Sen's slopes (Sen, 1968). Moreover, a Mann-Kendall test (Mann, 1945; Kendall, 1975) was used to distinguish between significant and non-significant trends in the dataset. Both statistical tests were performed in MAKESENS 1.0 software, a user-friendly code developed by the Finnish Meteorological Institute (MAKESENS, 2002) in the Microsoft Excel environment.

3. Results and discussion

3.1. Changes in meteorological data and ice departure date

Our data suggests a substantial warming of spring (0.47 °C, decade^{-1}) and summer (0.60 °C, decade^{-1}) air temperatures in the region of Lake Konnevesi from 1984 to 2021 (Table 1). These trends are consistent with previous studies that have reported a significant increase in surface air temperature in Finland in recent decades (Tuomenvirta, 2004; Räisänen, 2019; Ruosteenoja and Räisänen, 2021; Ruosteenoja and Jylhä, 2021). The region of the Lake Konnevesi is warming approximately 2.6 and 3.3 times faster in spring and summer, respectively, than the decadal increase in global air temperature since 1981 (0.18° C) (NOAA, 2021). Furthermore, our analysis reveals an increasing trend in summer average solar radiation (3.1 W m^{-2} decade^{-1}), likely due to the change in atmospheric conditions (e.g., cloud cover percentage). Wind speed in the study region remained relatively unchanged (0.01 m s^{-1} decade^{-1}) (Table 1). While we lacked observational data to directly investigate the influence of atmospheric conditions, particularly cloud cover percentage, on the upward trend of solar radiation in Lake Konnevesi, we hypothesize that a potential decline in cloud cover during the summer months may have contributed to the observed long-term increase in solar radiation. Another significant consequence of the increase in spring and summer air temperature is the earlier loss of ice cover in Lake Konnevesi. This phenomenon is underscored by a statistically significant negative rate of –3.5 days decade^{-1} (Table 1). This observation aligns with the broader understanding of rapid changes in ice phenology within boreal lakes, as documented in previous studies (Korhonen, 2006; Benson et al., 2012; Sharma et al., 2019 and 2021; Noori et al., 2022b).

To highlight the uncertainty in the presented results, we also added the upper and lower limits of the confidence interval for magnitude of the trends in climatic factors and ice departure date to Table 1. These confidence interval bands were calculated by considering a significant level of 0.05 (i.e., α =0.05) in the calculation of Sen's slope process.

Table 1. Slope of Sen's regression line for the surface air temperature (SAT), water temperature (WT), annual deicing, wind speed (WS), and anomalies of solar radiation (SR) over Lake Konnevesi from 1984 to 2020. Statistically significance changes (*p*-value <0.05) have been superscripted by "*". LSWT, LVWMT, and LDWT are the lake surface water temperature, lake volumetrically weighted mean temperature, and lake deepwater temperature, respectively. Q_{max95} and Q_{min95} are the upper and lower limits of the 95% confidence interval of the computed Sen's slope (L), respectively.

Variable	Sen slope	Q_{min95}	Q_{max95}
Spring mean SAT (°C decade^{-1})	0.47^*	0.10	0.76
Summer mean SAT (°C decade^{-1})	0.60^*	0.23	0.90
Summer mean LSWT (°C decade^{-1})	0.41^*	0.04	0.81
Summer mean LVWMT (°C decade^{-1})	0.32^*	0.07	0.56
Summer mean LDWT (°C decade^{-1})	0.00	-0.18	0.16
Annual deicing (day decade^{-1})	-3.5^*	-5.71	-2.26
Summer mean WS (m sec^{-1} decade^{-1})	0.01	-0.03	0.05
Summer mean SR (W m^{-2} decade^{-1})	3.1^*	-0.61	7.47

3.2. Changes in lake water temperature

The vertical distribution and temporal variations of summer mean water temperature in Lake Konnevesi measured from 1984 to 2021 are shown in Fig. 3. According to this figure, summer mean water temperature varies from 5.8 to 18.9 °C during the study period. Interestingly, maximum water temperature at the lake surface is observed between 1998 and 2012, a period suggested as experiencing a global air warming hiatus, where the Earth's warming rate decreased whilst CO_2 emission continued to increase (Medhaug et al., 2017). To explore the impact of the global air warming hiatus on LSWT, we conducted a focused analysis. Specifically, we separately calculated the rate of LSWT increase for the period preceding the hiatus (1984-1997) and juxtaposed it with the rate observed during the hiatus itself (1998-2012). Our findings reveal that the rate of warming in LSWT prior to the hiatus was 0.42°C per decade, which was noticeably lower than the rate recorded during the hiatus (0.65°C per decade). These results contrast with the report by Winslow et al. (2018), which did not identify a significant change in surface water temperatures in global lakes during the hiatus period. It is important to note that air temperature in subarctic regions are experiencing a far more rapid warming trend than the global average air temperature (Alexander et al., 2013; O'Reilly et al., 2015; Woolway and Merchant, 2017). Given the direct relationship between the lake surface and air temperature, this accelerated warming of air temperatures in subarctic regions likely contributes to the pronounced warming rate observed in the lake surface, even during the hiatus period. Further investigations conducted in our study unveiled that air temperature exhibited a similar warming rate to that of LSWT during the hiatus period in the region of Lake Konnevesi, although it was accompanied by a simultaneous decrease in solar radiation. This concurrent air warming likely offers an explanatory framework for the observed warming trend in lake surface water temperature during the years spanning 1998 to 2012.

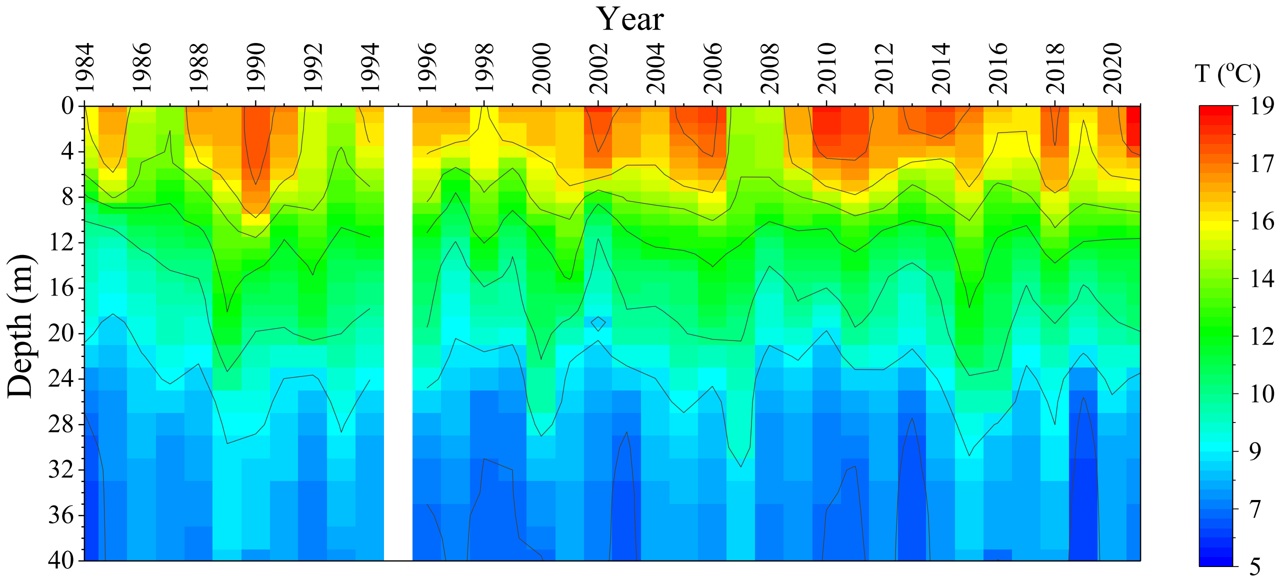
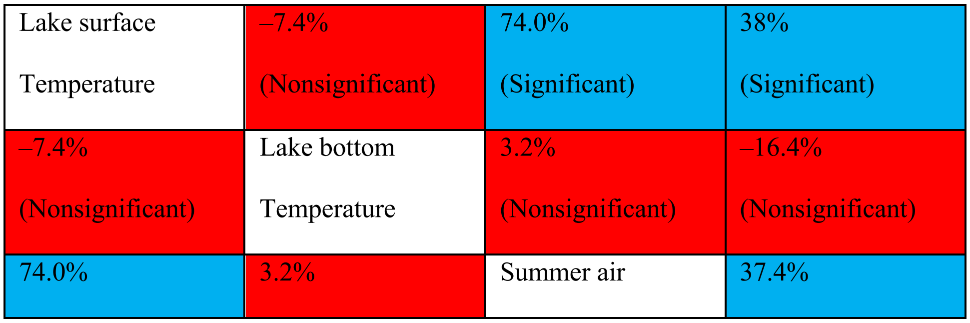


Figure 3. Vertical distribution and temporal variability of summer mean water temperature in Lake Konnevesi measured from 1984 and 2021. No data was available in summer 1995 (shown with white color in the figure).

The rapid warming of Lake Konnevesi's surface water temperature in recent decades can be attributed to several factors, including the observed increase in summer air temperature, elevated solar radiation, and an earlier ice departure date. Our analysis reveals a notable warming rate of 0.41°C per decade (Table 1), surpassing the global average summer lake surface temperature increase of 0.34°C per decade reported by O'Reilly et al. (2015) for the period spanning 1985 to 2009. It's worth noting that an earlier loss of ice cover can lead to an extended ice-free season within a given year, which, in turn, can significantly influence water temperature trends in lakes due to a lengthening of the warming season (Austin and Colman, 2007; Noori et al., 2022b). Our observations indicate that the rate of change in LSWT is approximately 0.87 times the increase in local air temperature. The observed change in the LSWT thus agrees with our expectations, particularly according to previous predictions which suggest that the LSWT should warm by 75–90% of the increase in air temperature (Schmid et al., 2014). Our observations also align with the results of Woolway et al. (2017), which investigated changes in LSWT of central European lakes in recent decades.

With respect to the LDWT in Lake Konnevesi, our observations show minimal change from 1984 to 2021 (0.00 °C, decade^{-1}; *p*–value >0.1), notwithstanding considerable inter-annual variability (Table 1). Whilst some previous studies have reported significant change in LDWT, including a warming and cooling trend across lake regions (Vollmer et al., 2005; Richardson et al., 2017), our observations largely align with global studies which have suggested that LDWTs have experienced little seasonal-average change in recent decades (Pilla et al., 2020). Due to the null (0.00 °C, decade^{-1}) and warming (0.41 °C, decade^{-1}) trends observed in LSWT and LDWT, respectively, LVWMT has warmed at a rate of 0.32 °C decade^{-1} (Table 1). The lower warming rate of LVWMT compared with that in the lake surface is due to the attenuation of light in the lake water column, which decreases the energy received by deep layers in the lakes (Pilla et al., 2020; Noori et al., 2022a).

With respect to the relationships between LSWT and LDWT, no significant correlation coefficient was calculated (Fig. 4), likely indicating no mutual interaction between the lake bottom and surface during the summer season. In fact, the summer warming trend observed at the lake surface over the time is attenuated at depth in Lake Konnevesi, resulting in a null trend in LDWT. No mutual interaction between the water temperature trends in surface and bottom layers were also reported by Pilla et al. (2020) in the analysis of global lakes' deepwater temperature.



Lake surface Temperature	–7.4% (Nonsignificant)	74.0% (Significant)	38% (Significant)
–7.4% (Nonsignificant)	Lake bottom Temperature	3.2% (Nonsignificant)	–16.4% (Nonsignificant)
74.0%	3.2%	Summer air	37.4%

(Significant)	(Nonsignificant)	temperature	(Significant)
38.0% (Significant)	–16.4% (Nonsignificant)	37.4% (Significant)	Spring air temperature

Figure 4. Correlation coefficient (%) plots of lake surface temperature, lake bottom temperature, summer air temperature and spring air temperature. Statistically significant and nonsignificant changes are shown by blue and red colors, respectively (p–value <0.05).

The differences between summer mean LSWT and LDWT were typically greater than 6 °C in Lake Konnevesi, suggesting the lake was strongly stratified during the study period (1984-2021). Indeed, our long-term time series of LSWT minus LDWT reveal a significant upward trend in thermal stability in Lake Konnevesi (0.41 °C decade^{-1}) (Fig. 5). This can have a considerable impact on the lake ecosystem (Noori et al., 2018; Hampton et al., 2008; O'Beirne et al., 2017; Pilla et al., 2020). For example, thermal stratification reduces the mixing in lakes and limits transport of nutrients and dissolved oxygen between surface and deeper layers. This mechanism could impact water quality, aquatic species populations, and food webs in global lakes (Woodward et al., 2010), especially in subarctic lakes. Reduced dissolved oxygen in lake bottom further induces the emission of greenhouse gases (Woszczyk and Schubert, 2021) and can increase nutrient release from lake sediments (Noori et al., 2021) that can likely result in eutrophication during the fall overturn (Shinohara et al., 2021b).

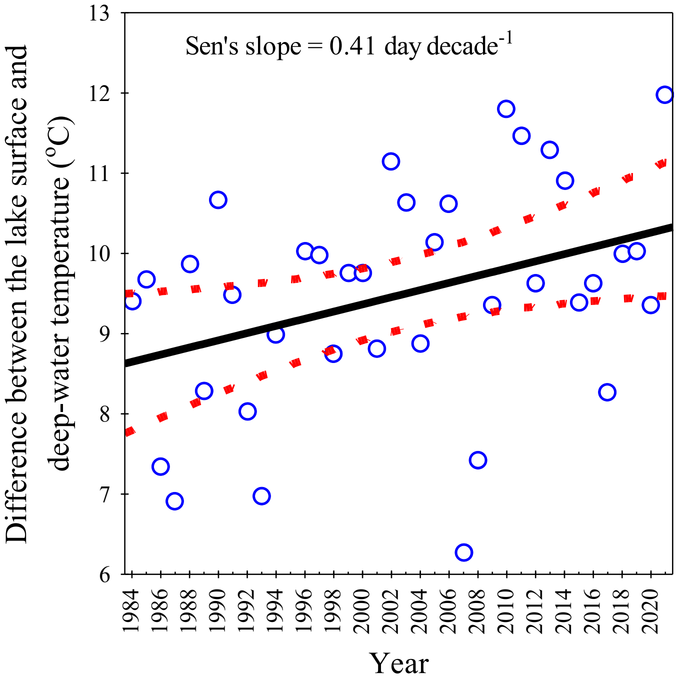


Figure 5. Magnitude and direction of change in the difference in observed warming between the surface and bottom waters in Lake Konnevesi from 1984 to 2021.

3.3. Main drivers of the lake water temperature

The application of the GAM to analyze LSWT variations, yielded in a strong adjusted R^2 value of 0.73, which explained an acceptable deviance of 82.6%. The GAM partial dependence diagrams (GAM-PDDs) for LSWT are shown in Fig. 6. These diagrams offer insights into the estimated smoothness of the exploratory variables, including SAT, SR, WS, and IDD. Our statistical analysis, leveraging the GAM, highlights that the most influential predictor of long-term changes in summer surface water temperature is summer mean air temperature (SAT) with the largest *F*–statistic of 8.47 and an EDF of 4.03 (Fig. 6; *p*–value <0.0002). Following closely behind is the summer mean solar radiation (SR) with an *F*–statistic of 3.70 and EDF of 7.76 (Fig. 6; *p*–value <0.008). These finding are in-line with the dominant drivers on the surface temperature in the Lake Zurich, where around 60% and 40% of the summer lake surface warming were induced by air temperature and solar radiation, respectively (Schmid and Köster, 2016). The dominant influence of air temperature and solar radiation on the lake surface warming resonates with studies conducted at local, regional, and global scales (Fink, 2014; O'Reilly et al., 2015; Schmid and Köster, 2016; Woolway et al., 2020; Shinohara et al., 2021a; Noori et al., 2022a). In contrast, ice departure date (IDD) and the summer mean wind speed (WS) do not exhibit a clear relationship with LSWT and are characterized by considerable uncertainty, implying a limited impact. From a statistical perspective, IDD and WS did not demonstrate a statistically significant influence on LSWT in our analysis (Fig. 6; p–value <0.05). Whilst some previous studies have suggested that IDD or WS may influence LSWT (Magee et al., 2016; Rose et al., 2016; Richardson et al., 2017), our observations generally align with other research indicating a lack of significant effect of these drivers on LSWT in high-latitude lakes (Noori et al., 2022a,b).

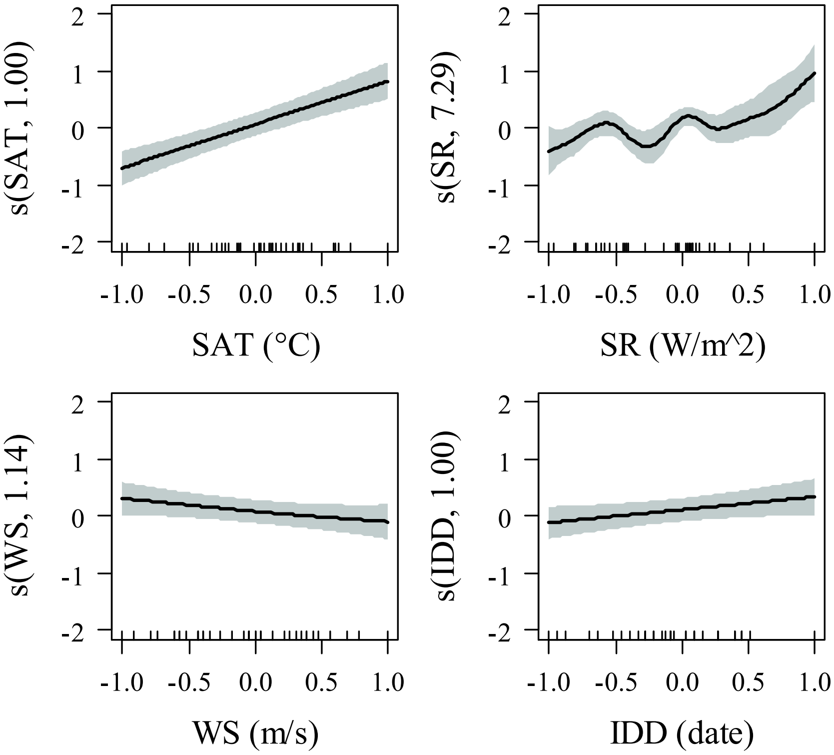


Figure 6. Generalized additive model (GAM) partial dependence diagrams (PDDs) for the lake surface water temperature (LSWT). Each diagram reveals a covariate and its partial dependence

on the changes in LSWT in the context of the GAM model. The shaded grey zones represent the 95% confidence interval.

The GAM developed for LVWMT and its relationship with the explanatory variables demonstrate a notable explanatory power, elucidating 78.6% of the variance. The robust performance is reflected in a moderately high adjusted R^2 value of 0.64. Much like the findings for LSWT, our analysis identifies the most influential predictors driving long-term changes in summer LVWMT. Summer Mean Air Temperature (SAT) emerges as the primary driver, exhibiting the largest F-statistic of 7.92 and an Effective Degrees of Freedom (EDF) of 2.70 (Fig. 7; p-value < 0.0008). Following closely, Summer Mean Solar Radiation (SR) displays an F-statistic of 2.94 and an EDF of 7.32 (Fig. 7; p-value < 0.02) as secondary but still significant contributors to the observed changes in summer LVWMT.

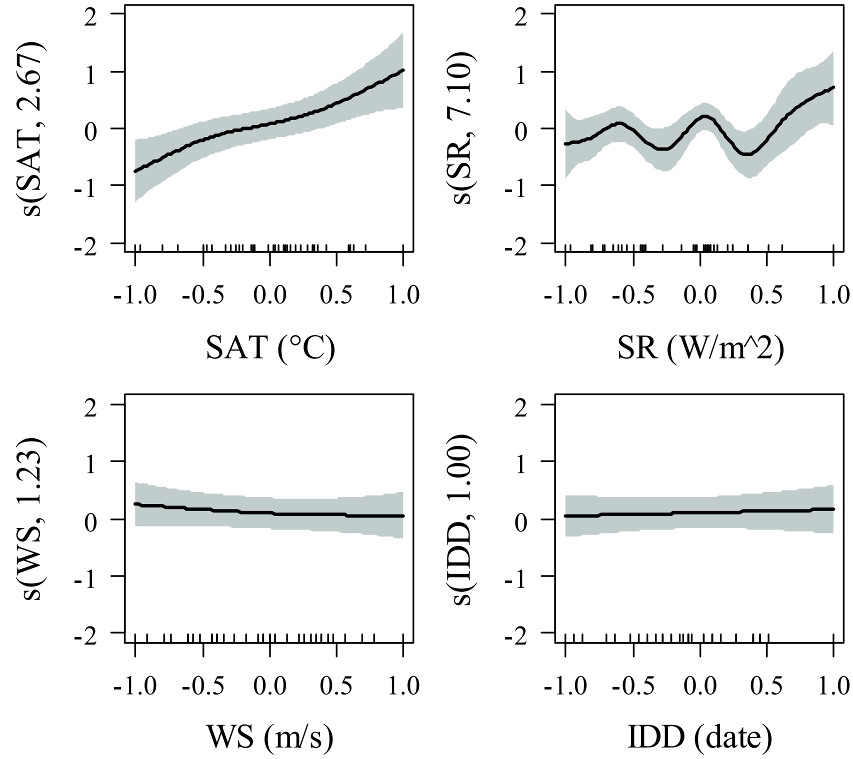


Figure 7. Generalized additive model (GAM) partial dependence diagrams (PDDs) for the lake volumetrically weighted mean temperature (LVWMT). Each diagram reveals a covariate and their partial dependence on the changes in LVWMT in the context of the GAM model. The shaded grey zones represent the 95% confidence interval.

In contrast to the relatively strong explanatory power observed for LSWT and LVWMT, the GAM applied to analyze LDWT yields a relatively weak adjusted R-squared value of 0.21. This value indicates that the model explains only a modest portion of the variance, accounting for 41.5% of the deviance. The GAM-PDDs for the LDWT are shown in Fig. 8. Our statistical analysis leads to the conclusion that summer deep-water temperature in Lake Konnevesi is not significantly influenced by the drivers investigated in our study (Fig. 8; p-value > 0.05). This observation is particularly intriguing, considering the strong summer stratification observed during the study period, characterized by a substantial temperature difference between LSWT and LDWT exceeding 6°C. This stratification effectively hinders the turbulent heat flux across the thermocline, effectively isolating the hypolimnion from the epilimnion. Despite the statistical significance levels, IDD emerges as the most influential driver of LDWT (Fig. 8). An earlier ice departure date is associated with warmer deep-water temperatures. However, our results indicate no discernible changes in LDWT, despite the lake experiencing a significant shift in IDD. This lack of response in LDWT to the explanatory variables may be attributed to the influence of non-climatic drivers, such as lake morphology, water clarity, and hydrology, or even the impact of large-scale climatic signals on LDWT. For instance, water clarity plays a crucial role, as lakes with reduced clarity absorb more heat beneath the surface, resulting in a shallower thermocline (Persson and Jones, 2008). In contrast, lakes with greater water clarity tend to absorb more heat in deeper layers (Rose et al., 2016). Additionally, hydrological events like floods and changes in groundwater inflow characteristics, including flux and temperature, could contribute to variations in LDWT (Wei et al., 2011; Safaie et al., 2017). Some studies have also highlighted the influence of large-scale climate patterns, such as the North Atlantic Oscillation, on LDWT (Gerten and Adrian, 2001; Blenckner and Chen, 2003; Dokulil et al., 2006). Specifically, Jyväsjärvi and Hämäläinen (2015) reported a significant correlation between LDWT and the North Atlantic Oscillation in Finnish lakes. Noori et al. (2022b) similarly highlighted the significant impact of the North Atlantic Oscillation on LDWT in Lake Kallavesi, Finland. While our study did not investigate the specific influence of non-climatic drivers and large-scale climatic signals on lake water temperature, the absence of a discernible trend in LDWT suggests that the collective impact of these drivers on deep-water temperature trends in Lake Konnevesi is likely negligible.

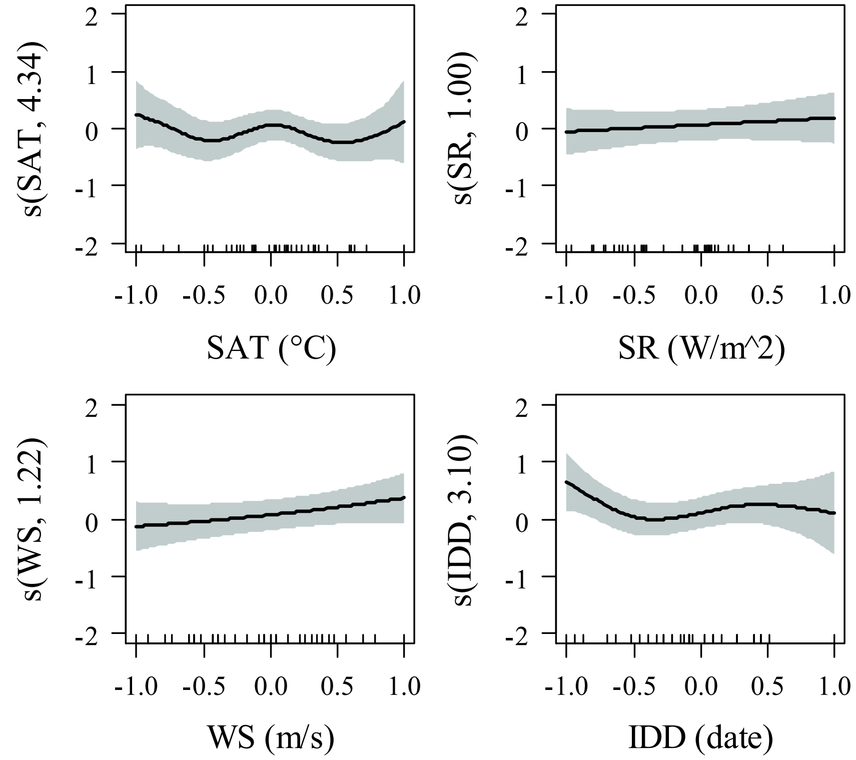


Figure 8. Generalized additive model (GAM) partial dependence diagrams (PDDs) for the lake deepwater temperature (LDWT). Each diagram reveals a covariate and their partial dependence on

the changes in LDWT in the context of the GAM model. The shaded grey zones represent the 95% confidence interval.

4. Conclusion

As air temperatures in (sub)arctic regions continue to rise at an alarming pace, the warming of high-latitude lakes has become a significant concern, carrying substantial implications for these delicate ecosystems. However, it's important to recognize that the relationship between air temperature and lake water temperature can vary among (sub)arctic lakes. In our study, we leveraged long-term water temperature data to delve into the evolving thermal dynamics of Lake Konnevesi. Our analysis identified a progressive divergence between the temperatures of the lake's surface and its deeper layers over the period 1984 to 2021. This divergence was primarily driven by a significant increase in the temperature of the lake surface, influenced by rising air temperatures and solar radiation. In contrast, we observed a flat or null rate of change in deep-water temperature within the lake during the same timeframe. Considering the projected warming trends in air temperature over Finland, we anticipate a further accentuation of the stratification between the bottom and surface layers in Lake Konnevesi during the summer months. This intensification of thermal stratification holds the potential to yield a cascade of consequences for the lake's aquatic ecosystems. These ramifications could include shifts in species compositions, alterations in community structures, modifications in food webs, and changes in the positive functions of the lake, such as fisheries and recreational activities. Our findings underscore the complex interplay between climate change and lake dynamics, emphasizing the need for careful monitoring and management of these vital freshwater resources in the face of evolving climatic conditions. The distinct responses observed in Lake Konnevesi's surface and deep-water temperatures serve as a poignant reminder of the intricate and diverse ways in which lakes can respond to the challenges posed by a warming world.

Author Contributions

Conceptualization: R.N.; Methodology: R.N. and R.I.W.; Software: R.N., C.J., S.M.B. and D.N.; Validation: R.N., R.I.W. and P.M.; Formal analysis: R.N., D.N. and S.P.; Investigation: R.N. and R.I.W.; Resources: R.N.; Data curation: R.N. and M.P.; Writing—original draft preparation: R.N.; Writing—review and editing: R.I.W., M.M. and P.M.; Visualization, R.N., C.J. and D.N.; Supervision: R.I.W.; Project administration: R.N. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Water temperature data are publicly available through https://wwwp2.ymparisto.fi/scripts/kirjaudu.asp. Surface air temperature data are publicly available through https://en.ilmatieteenlaitos.fi. The MAKESENS 1.0 software is available through https://en.ilmatieteenlaitos.fi/makesens.

Conflicts of Interest

The authors declare no conflict of interest.

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