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RESEARCH ARTICLE

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Key Points:

- Our study presents the results from six decades of water temperature measurements in the surface and bottom layers of a boreal lake
- Using Mann-Kendall and Theil-Sen estimator methods we found strong warming rates in both surface and bottom layers of the lake
- The strong warming rate in the lake bottom temperature is not in agreement with null trend reported for deepwater temperature at global scale

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Strong Warming Rates in the Surface and Bottom Layers of a Boreal Lake: Results From Approximately Six Decades of Measurements (1964–2020)

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Abstract High-latitude lakes are warming faster than the global average with deep implications for life on Earth. Using an approximately six-decade long in situ data set, we explored the changes in lake surface-water temperature (LST), lake deep-water temperature (LDT), lake depth-weighted mean water temperature (LDMT), and ice-free days in Lake Kallavesi, a boreal lake in central Finland, when the lake was stratified (June–August). Our results suggest that the LST is warming faster than the local air temperature (AT). As for the LST, fast warming was also observed in the LDT and LDMT, but at rates slower than those in the LST. The number of ice-free days also shows an upward trend, with a rate of about 7 days per decade during the study period. The corresponding local AT is the main driver of the LST, followed by the ice-free days and annual mean AT. Air temperature and ice-free days also mainly contribute to the changes in the LDMT. The LDT is affected more by the North Atlantic Oscillation signals in this freshwater lake. The AT in the prior months does not affect the LDT in Lake Kallavesi although the AT during the prior season, that is, spring, is the main driver of summer LDT. This highlights the local AT impact on the LDT at time scales longer than a month. The warming rates in the lake water are at a minimum in June because the lake is not yet strongly stratified in this month when compared to July and August. These findings improve our knowledge of long-term changes in the lake water temperature in a high-latitude lake, a region with severe environmental consequences due to fast changes in the AT and lake ice phenology.

1. Introduction

At global scale, lakes are warming faster than both the atmosphere and the oceans (O'Reilly et al., 2015). Given that, all lakes are land-locked, these changes could be intensified by the projected changing climate under the future influence of anthropogenic stressors (Jane et al., 2021; Modabberi et al., 2020; Woolway et al., 2021). This could have deep implications for the lake ecological services (Kraemer et al., 2021; Pilla et al., 2020) and threaten both the quantity and quality of the most important sources of freshwater for humankind (Kraemer et al., 2015; Noori et al., 2018). Despite the global warming impact on the lakes, the rate of increase in the lake surface-water temperature (LST) is not consistent with that in the lake deep-water temperature (LDT). O'Reilly et al. (2015) calculated a significant global mean warming rate of 0.34°C per decade in LST, while no such significant warming was found in the LDT at global scale (Kraemer et al., 2015; Pilla et al., 2020). These results suggest a progressive divergence between the LST and LDT at global scale that intensifies both strength and duration of lake thermal stratification (Oleksy & Richardson, 2021).

Although there is consensus on the increase in LSTs globally, the changing rates are not consistent even in a local geographical region. Studies show both cooling and warming trends in the LST in high-latitude lakes (e.g., in Alaska and Northern Europe), high altitude lakes (e.g., in Tibetan Plateau), and temperate lakes (e.g., in Central Europe; Kraemer et al., 2015; O'Reilly et al., 2015; Wan et al., 2018). Regarding the LDT, relatively few long-term databases on freshwater lakes are available compared to the LST. They mainly cover three or four decades. On the other hand, the changes reported in relatively LST-rich databases cannot simply reveal the more complex nature of LDT influenced by multiple stressors. Pilla et al. (2020) concluded that the trends in the LDT were not explained by those observed in the LST and thermal stability. Thus, we understand less about changes in the LDT than the LST (Richardson et al., 2017).

Northern European lakes are warming faster than the global average (Hook et al., 2012; O'Reilly et al., 2015; Pilla et al., 2020; Schneider & Hook, 2010; Woolway & Merchant, 2017). These high-latitude freshwater lakes are exposed to the most significant warming rate in the surface air temperature (AT; Alexander et al., 2013) and to fast changes in ice phenology that both significantly affect lake thermal stratification and lengthening of the time in which the lake warming happens (Sharma et al., 2021; Woolway et al., 2021). Some studies concluded that the changes in the high-latitude lakes' water temperature could also be attributed mainly to solar radiation and large scale climate signals such as the weather conditions generated by the North Atlantic Oscillation (NAO; Blenckner & Chen, 2003; Dokulil et al., 2006; Gerten & Adrian, 2001; Salmaso et al., 2003). However, other factors such as morphometric drivers (e.g., lake surface area and depth; Kraemer et al., 2015; O'Reilly et al., 2015), water transparency (Rose et al., 2016), and anthropogenic activities (Jane et al., 2021; Pilla et al., 2020) can also contribute to the lake heating/cooling, leading to quite heterogeneous changes in the LST and LDT in high-latitude lakes. Therefore, both magnitude and direction of changes in water temperature can be highly variable across the North European lakes (Kraemer et al., 2015; O'Reilly et al., 2015; Pilla et al., 2020).

The present study elucidates the impact of local AT, NAO-based signals and ice phenology data on summer water temperature in Lake Kallavesi, a boreal lake in central Finland, using a six-decade long in situ data set. Given that climate change involves long-term shifts in regional or even global climate patterns, the longer the period of LDT, the more reliable are the results provided on the lake response to the climate change. Therefore, where the long-term LDT does exist, for example, from Lake Kallavesi, it represents a unique source of historical information on the impact of climate change on lakes. Our analyses are limited to warm months when the lake is stratified. In fact, both water temperature gradients at depth and whole lake mean water temperatures are high when the lake is stratified. Therefore, even small changes in the heat exchange rate at the water-air interface lead to considerable changes in the lake thermal stability (Livingstone, 2003). Specifically, we explore (a) the evolution of changes in the LST, LDT, and lake depth-weighted mean water temperature (LDMT) in Lake Kallavesi, (b) the evolution of ice phenology and its contribution to the changes in the lake water temperature, (c) the possible contribution of the NAO index to the LST, LDT, and LDMT, and (d) mutual interaction between the LST and the LDT in the lake.

2. Materials and Methods

As a boreal lake, Kallavesi has a densely forested basin and is located in central Finland (Figure 1). This medium sized lake with a maximum and average depth of 75 and 9.71 m, respectively, is positioned at an elevation about 82 m above sea level. This lake is much longer (maximum length = 60 km) than it is wide (maximum width = 15 km). Kallavesi is a humus-poor lake with a water volume and surface area around 4.86 km^3 and 478 km^2, respectively. Change in the lake water level is very moderate with a negligible amplitude and frequency (Partanen & Hellsten, 2005).

Northern areas of Lake Kallavesi are mesotrophic, while moving southward, and the lake water gradually changes to oligotrophic. The lake water quality changes from good to satisfactory in the north (Partanen, 2007; Partanen & Hellsten, 2005).

We defined the LST and LDT, respectively, as the water temperature measured at the lake near-surface and the depth of 40 m with a digital thermometer at the sampling point A (Figure 1). In addition, we analyzed changes in water temperature measured at distinct depths of 5, 10, 15, 20, and 30 m. The LDMT, as the direct estimation of lake heat content, was also analyzed in the Lake Kallavesi. Having the water temperature measurements at the aforementioned depths, the monthly and summer mean profiles with 1 m intervals were reconstructed by a simple linear regression method. Given the lake volume information corresponding to each depth, the LDMT was calculated by depth-weighted averaging of water temperature measured in depths of 0–40 m. Overall, using the monthly mean data during the lake ice-free period leads to 6485 water temperature measurements from 1964 to 2020 in total. May, with 948 total samples (~17 samples annually), and July, with 1,160 total samples (~20 samples annually), had the minimum and maximum number of water temperature measurements, respectively, during the study period (Table 1). Lake water temperature data sets are stored by the Finnish Environment Institute and deposited (in https://wwwp2.ymparisto.fi/scripts/kirjaudu.asp).

In this study, we investigated the changes in Lake Kallavesi's water temperature, when the lake was stratified. The first and last months of stratification were computed for Lake Kallavesi during the study period once the

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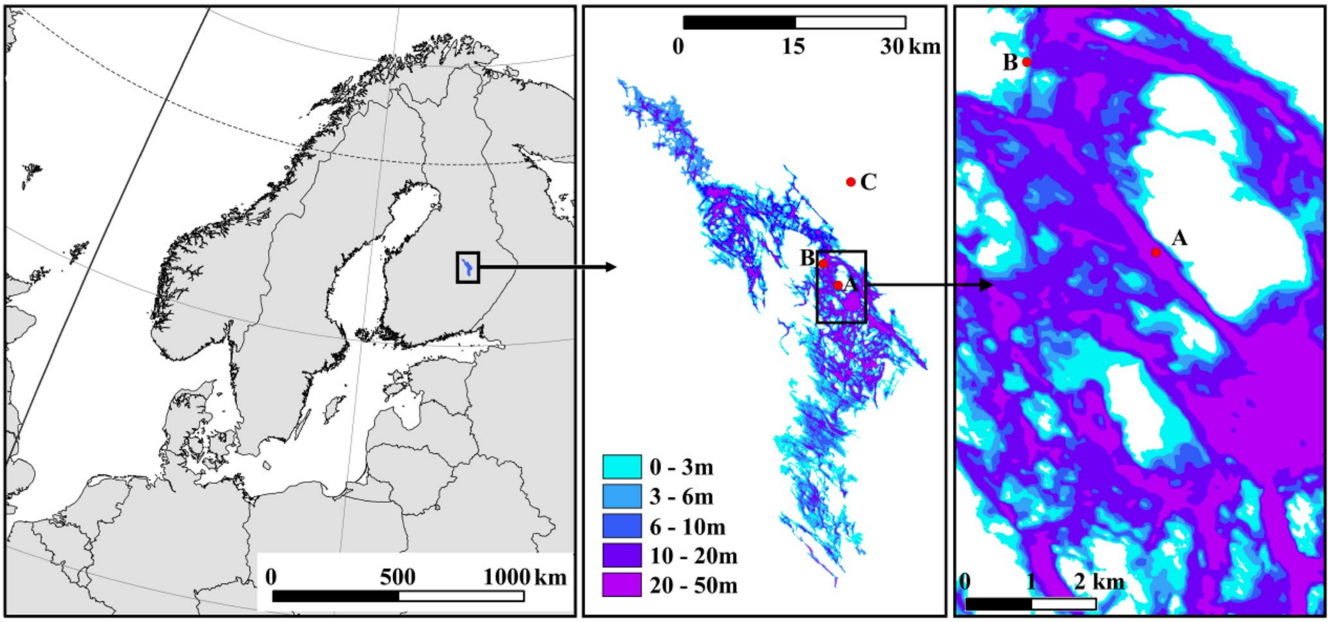

Figure 1. Location of the Lake Kallavesi, depth isobaths, and the sampling points A to C, responsible for recording the water temperature, ice phenology, and air temperature data, respectively, from 1964 to 2020.

lake was ice-free. Schmidt stability index (Hutchinson, 1957; Idso, 1973) is usually used to distinguish between the thermal stratification and mixing processes in lakes. The higher the Schmidt stability index, the more severe stratification. However, it is possible to define a threshold value for maximum water temperature difference between two neighbor layers with 1 m interval to distinguish between mixing and stratification in lakes, as well. Although this threshold value has been suggested to be greater than 1°C (corresponding to a Schmidt stability index of ~800 g cm cm^{-2}; Li, 2016; Noori et al., 2019; Stainsby et al., 2011), much smaller values corresponding to a Schmidt stability index of ~50 g cm cm^{-2} has also been suggested by others (Winder & Schindler, 2004). In our study, the arbitrary threshold value was selected to be greater than 0.40°C of water temperature difference between two neighbor layers with 1 m intervals to distinguish between mixing and stratification in Lake Kallavesi. Although it is a relatively straightforward calculation, it provides useful information on the starting and ending months of thermal stratification in the lake each year.

The impact of three types of drivers on the changes in the lake water temperature was investigated, including the ice phenology-based data, the AT-based variables, and the NAO-based signals as described below:

Table 1
Number of Water Temperature Measurements at Different Depths of the Lake Kallavesi in May–October Over 1964–2020

	Sampling months					
Depth (m)	May	Jun	July	August	September	October
0	135	153	167	147	155	159
5	139	164	170	153	158	167
10	139	164	170	154	158	168
15	139	164	166	154	157	167
20	139	164	169	153	158	167
30	129	152	159	143	144	157
40	128	152	159	143	144	158
Total	948	1,113	1,160	1,047	1,074	1,143

1. The ice-free period, measured at the point B nearshore the Lake Kallavesi (Figure 1) by the Finnish Environment Institute (https://wwwp2.ymparisto.fi/scripts/kirjaudu.asp) from 1964 to 2020, was used as a main index of the lake ice phenology. The ice-free days is calculated as the time span between the date when the ice is not observed over the lake from the point B and the date of stable freeze-up of the entire observable region from the point B.
2. The corresponding AT during each month and season that the lake was stratified was used as a driver of changes in lake water temperature. Given that the lake water temperature likely responded to the AT on longer time scales (Woolway et al., 2015), we also explored the impact of AT in the months and season only prior to the lake becoming stratified. In addition, we used the monthly AT averaged over the period the lake was ice-covered as well as annual mean AT as two other drivers of the lake water temperature. The AT was recorded at a height of 2 m above the ground level at the Kuopio Airport, the closest synoptic station to the water temperature sampling location (point C in Figure 1). The raw AT

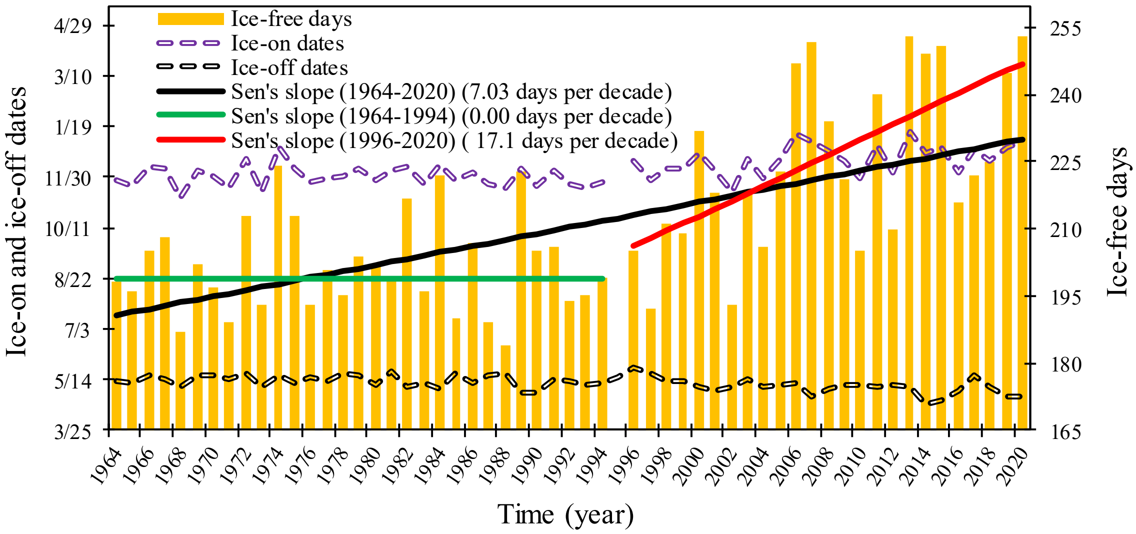

Figure 2. Annual ice-on and ice-off dates and ice-free periods measured at the point B in Lake Kallavesi from 1964 to 2020.

data are freely available through the Data Archive of the Finnish Meteorological Institute (https://en.ilmatieteenlaitos.fi).

3. Two different NAO-based indices were applied to explore their possible impacts on Lake Kallavesi's water temperature. The first was the station-based NAO (S-NAO) signals calculated using the difference between sea level pressures measured in Lisbon and Reykjavik/Stykkisholmur, Iceland (available from: https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based). The sea level pressure data were normalized using their long-term mean and standard deviation values. The second index was the principal component-based NAO (PC-NAO) signals (available from: https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based). We also explored the impact of S-NAO and PC-NAO signals on the changes in the lake water temperature in the antecedent months and season that the lake was stratified. Annual S-NAO and PC-NAO signals, and those averaged over the cold months, were also included as main drivers of the lake water temperature. Detailed information on the NAO-based signals used in this study are given by J. Hurrell (2003).

The level of statistical significance and slope of the trends in the AT, the lake water temperatures, and the lake ice-free period, were investigated using the Mann-Kendall (MK; Kendall, 1975; Mann, 1945) and Theil-Sen estimators (ThSE; Sen, 1968), respectively. Note that we used all available data and no reconstruction method was applied to fill the gaps except for the LDMT. This allowed us to obtain the most robust trends for comparison with the trends in the objective parameters. MK and ThSE methods were executed by "MAKESENS 1.0", a code developed by the Finnish Meteorological Institute (MAKESENS, 2002; available from https://en.ilmatieteenlaitos.fi/makesens).

3. Results and Discussion

3.1. The First and End Months of the Lake Stratification

The annual changes in ice-on and ice-off dates in Lake Kallavesi are shown in Figure 2. The annual ice-on and ice-off dates vary from 9 November (in 1968) to 12 January (in 2007) and 19 April (in 2014) to 25 May (in 1996), respectively. Lake Kallavesi freezes during cold months that usually last from early November until the end of May.

From late spring, that is, May, the lake becomes ice-free and isothermal. Our observations suggest that the thermal difference over the depth of the lake is less than 4°C during May in 38 of the 57 years under investigation. The warmer the ambient AT, the greater the difference in temperature between top and bottom layers in the lake. Starting from June, the thermal difference over the depth of the water column becomes larger than 4°C and this

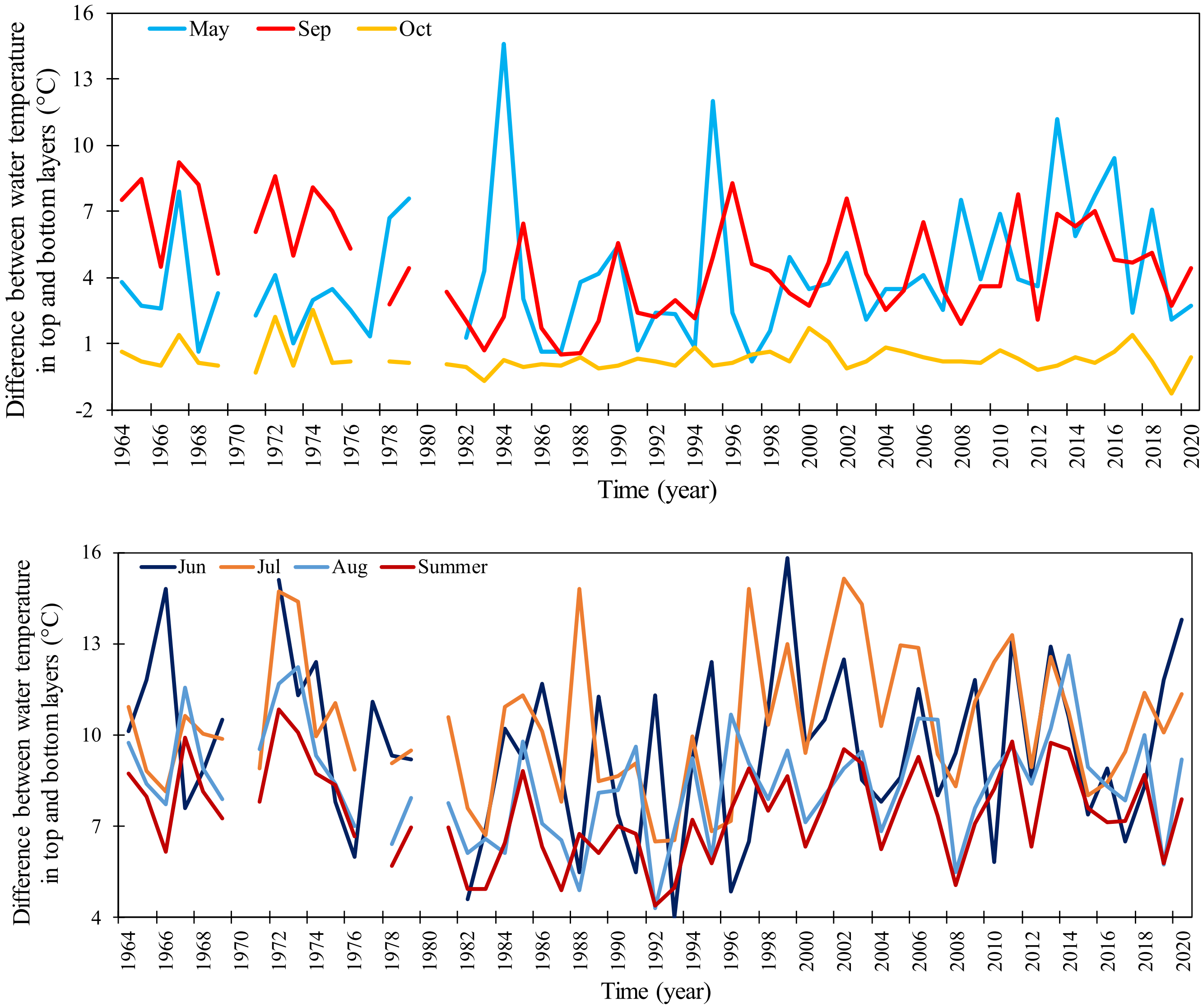

Figure 3. Difference in monthly mean water temperature between top and bottom layers in Lake Kallavesi during the lake ice-free period (May–October) from 1964 to 2020.

condition lasts until the end of August during the study period (Figure 3). In the late summer, cold ambient AT reduces the thermal difference between the LST and LDT to less than 4°C and the lake gradually mixes thereafter. However, our findings showed that the maximum water temperature differences between two adjacent layers with 1 m intervals in June, July, August, and summer season were greater than the arbitrary threshold value selected in this study, that is, 0.40°C. The maximum water temperature difference between two adjacent layers with 1 m intervals in June varied from 0.41 (in 2007) to 1.44 (in 1966). This value in July, August, and summer season varies from 0.7 (in 1978) to 1.96 (in 1966), 0.65 (in 1968) to 1.81 (in 2020), and 0.61 (in 2004) to 1.58 (in 2020), respectively (Figure 4). On the contrary, the same analysis in other ice-free months (i.e., May, September, and October) resulted in the maximum water temperature differences less than 0.22, which is less than the stability threshold used in our study. Therefore, our results suggest the Lake Kallavesi is a dimictic lake that annually mixes in spring and fall and stratifies in the warm (June–August) and cold (November–April) months. It is noteworthy that although selection of an arbitrary threshold value put the thermal stratification in a binary process (i.e., the lake is either stratified or mixed), the stratification is a mechanism that gradually starts in a lake water column (Aradpour et al., 2020; Stainsby et al., 2011).

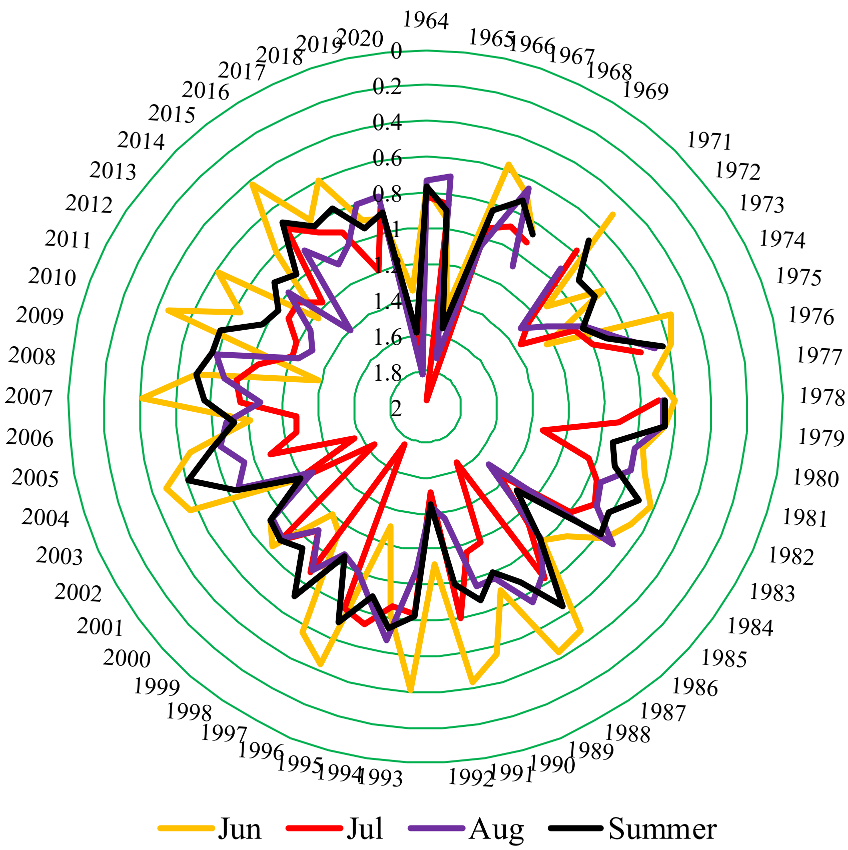

Figure 4. Radar diagram showing the maximum water temperature differences between two adjacent layers with 1 m intervals calculated during June, July, August, and summer season in Lake Kallavesi from 1964 to 2020. All the calculated differences are greater than the arbitrary threshold value selected in this study, that is, 0.40°C, concluding occurrence of thermal stability in the lake in June, July, August, and summer season during the study period.

3.2. Decadal Changes in the Surface Air Temperature and Ice Phenology Data

Given the thermal stratification period (June–August), we investigated the changes in the monthly mean water temperature over that time as well as the summer mean water temperature (averaged from June to August) in Lake Kallavesi. Given information provided in Section 2, the monthly AT from May to August, spring and summer mean AT, the AT averaged from November to April (ice-covered period), and the annual mean AT were selected as the possible drivers of changes in the lake water temperature. The changes in these AT-based drivers are given in Table 2. The largest warming trend is observed in the AT averaged from November to April, when the lake is ice-covered (0.880°C per decade), followed by the annual AT (0.611°C per decade). Prior studies also demonstrated a significant warming in the AT in Finland during recent decades (Räisänen, 2019; Ruosteenoja & Räisänen, 2021; Tuomenvirta, 2004) with maximum warming during cold seasons (Tuomenvirta, 2004). In addition, our study period (1964–2020) covers a time span influenced by anthropogenically driven warming at global scale (Hartmann et al., 2013; Myhre et al., 2013; Ruosteenoja & Räisänen, 2021). However, the warming rate in the AT is near zero in June, in line with the results reported by Räisänen (2019) and Ruosteenoja and Räisänen (2021).

Table 2
Magnitude and Direction of Changes Observed in the Air Temperature Over Lake Kallavesi From 1964 to 2020

Time	Surface air temperature	S.L	Time	Surface air temperature	S.L
May	+0.353	<0.05	Spring	+0.483	<0.001
June	−0.043	>0.10	Summer	+0.268	<0.1
July	+0.167	>0.10	Nov to Apr	+0.880	<0.05
August	+0.275	<0.001	Annual	+0.611	<0.05

Note. S.L is the significance level of changes.

Our observations suggest a significant upward trend in the ice-free period over Lake Kallavesi with a magnitude of 7.03 days per decade from 1964 to 2020 (Figure 2). This number is a multiple of the change in ice-covered period in the lake from 1834 to 2002 (~1.5 days per decade), reported by Korhonen (2006). This inconsistency is due to the difference in the time

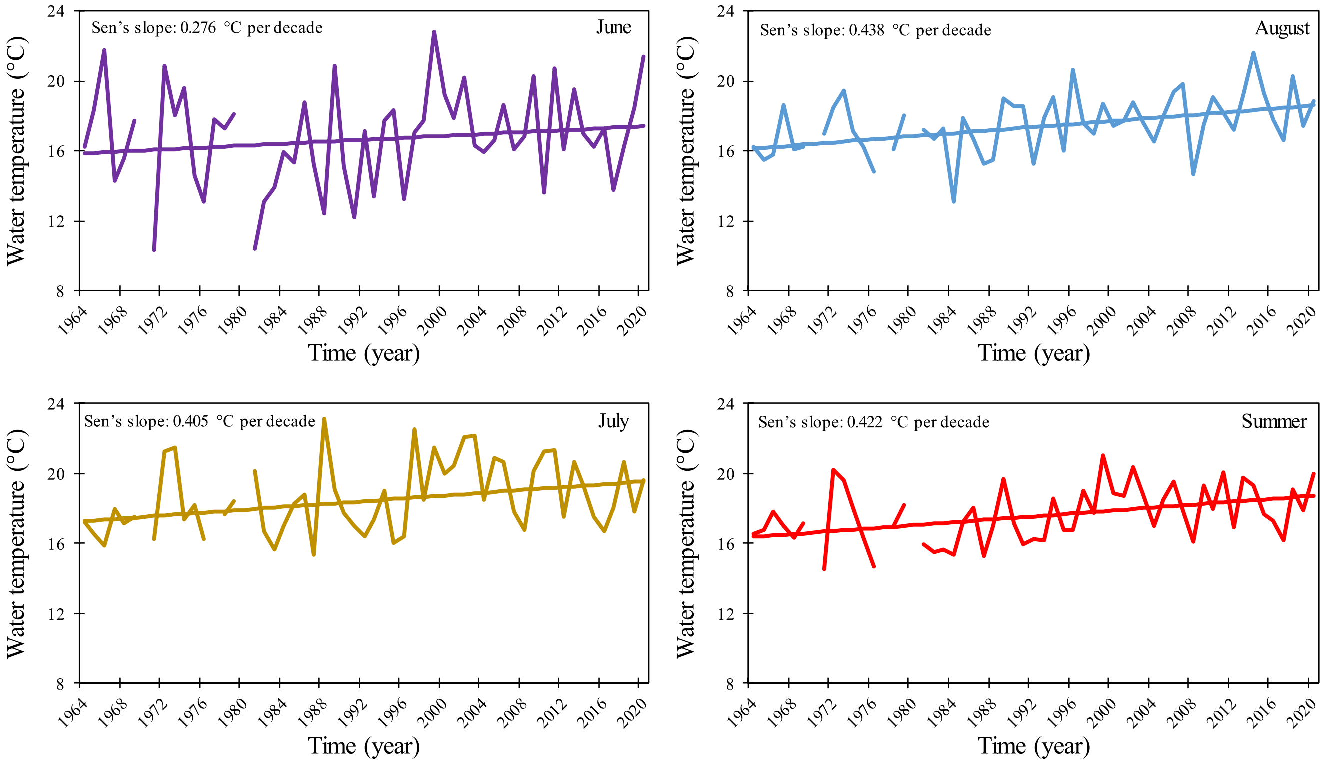

Figure 5. Time series and Sen's regression lines for monthly and summer mean lake surface water temperature in Lake Kallavesi from 1964 to 2020.

spans used by Korhonen (2006) and our study. The latter spans 1964–2020, a period that is strongly influenced by anthropogenically driven warming at global scale (Hartmann et al., 2013; Myhre et al., 2013; Ruosteenoja & Räisänen, 2021). In general, high-latitude freshwater lakes (e.g., Lake Kallavesi) are exposed to the significant increasing AT and to fast changes in ice phenology (Alexander et al., 2013; Sharma et al., 2019, 2021). A detailed look at through Figure 2 shows some oscillation with no significant trend for ice-free days with the mean of 199 days from 1964 to 1994. Then, a sudden increase with a magnitude of 17.1 days per decade is observed for ice-free days from 1996 to 2020. However, increases in the duration of the annual ice-free period may influence the freshwater lake thermal stratification with deep implications for the ecological services of the Lake Kallavesi (Pilla et al., 2020).

3.3. Warming Rates in the LST and LDMT

Our observations suggest a fast and statistically significant upward trend in both LST and LDMT when the lake is stratified, that is, from June to August (Figures 5 and 6). The warming rate is minimum in June, with a rate of 0.276°C and 0.108°C per decade in LST and LDMT, respectively, because the lake is not yet strongly stratified in this month compared to July and August as specified in Figure 4.

Our findings show that changes in the LDMT and especially in the LST are faster than those in the corresponding AT (Table 2; Figures 5 and 6), except for LDMT in summer. These findings suggest that other factors contribute to the additional heat observed in the LST and LDMT. These factors are likely wind speed, solar radiation, water transparency, and the lake ice-free period (O'Reilly et al., 2015; Rose et al., 2016; Schmid & Köster, 2016). For example, Schmid and Köster (2016) concluded that approximately 40% and 60% of the summer warming in the Lake Zurich's surface water were induced by solar radiation and AT, respectively. Kirillin et al. (2012) and Magee and Wu (2017) reported that the changes in wind speed influence the mixing regime and ice phenology in lakes, which can contribute to the changes in both LST and LDMT. Also, changes in water transparency can act to suppress or amplify the impact of climate warming on the LST and LDMT, depending on its directional change (Rose et al., 2016). We didn't have wind speed, solar radiation, and water transparency measurements to investigate their impacts on the LST and LDMT in Lake Kallevesi. However, upward trend observed in the

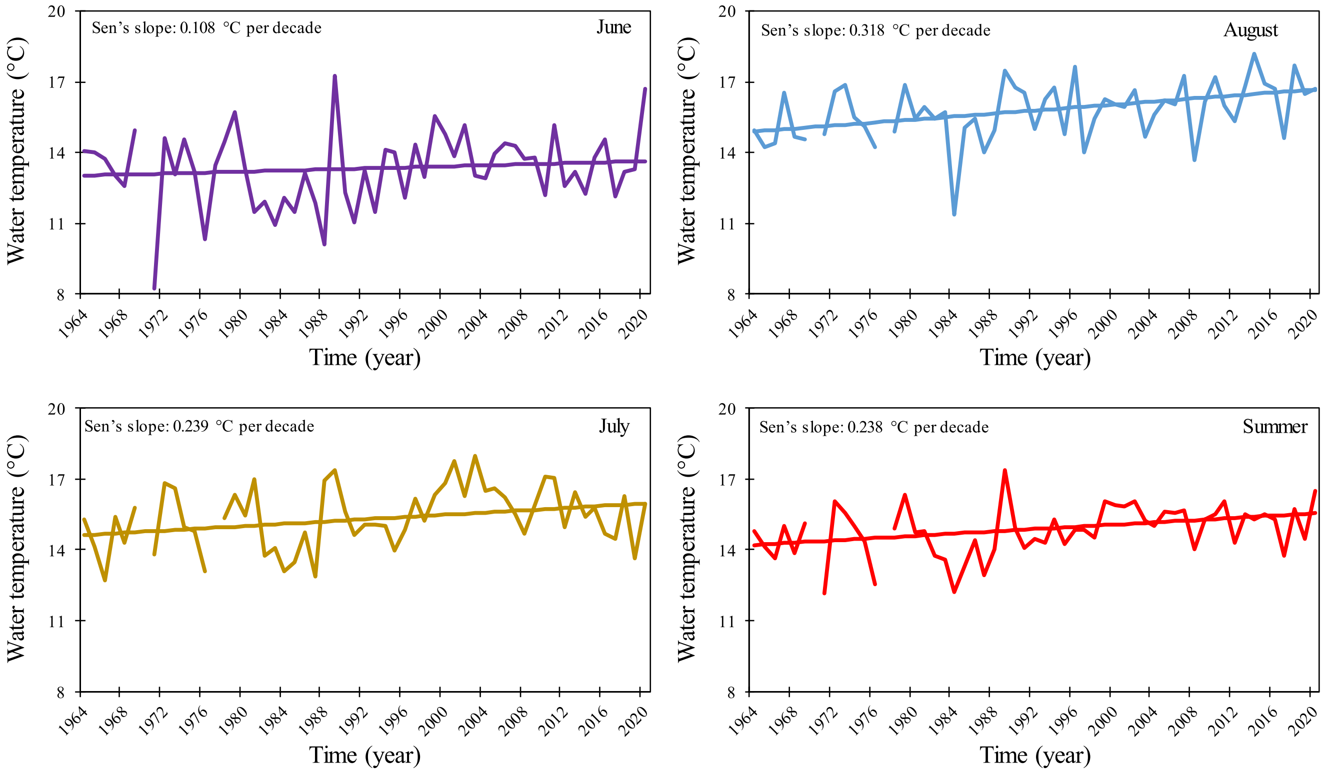

Figure 6. Time series and Sen's regression lines for monthly and summer mean lake depth-weighted mean water temperature in the Lake Kallavesi from 1964 to 2020.

ice-free period (Figure 2), in response to warming rate in AT during the cold (November–April) and spring seasons (Table 2), further exposes the lake surface to the warming period. This contributes to the faster warming rates observed in the LDMT and especially in the LST.

The summer LST warming rate in Lake Kallavesi (0.422°C per decade) during the study period (1964–2020) is larger than the corresponding warming rate reported for lakes at global scale from 1985 to 2009 (0.34°C per decade; O'Reilly et al., 2015). Also, the summer LDMT warming rate in the lake (0.238°C per decade) is somewhat larger than the corresponding warming rate reported for the mean water column temperature in global lakes from 1970 to 2009 (0.19°C per decade; Pilla et al., 2020). It should be noted that Pilla et al. (2020) used the arithmetic mean temperature from surface through the lake bottom temperature instead of the lake depth-weighted mean water temperature, due to the lack of lake bathymetric data. However, these results highlight the significant warming rates in the LDMT and especially in LST in a high-latitude freshwater lake, and confirm prior concerns about the changes in ice phenology as well as the water warming rates in northern latitude lakes (Sharma et al., 2019). Warmer winters in Finland (Tuomenvirta, 2004) and longer ice-free periods (Figure 2) attenuate the lake albedo, lead to earlier onset of the lake stratification, and elongate the duration of energy absorption, all leading to increased summertime warming in the lake (O'Reilly et al., 2015; Zhong et al., 2016). Note that although lakes have globally shown an upward trend in LST, some individual lakes have experienced a cooling rate (Kraemer et al., 2015; O'Reilly et al., 2015). In general, the trajectories of the changes in summer LST have ranged from −0.74°C per decade in Lake Balaton, Hungary, to 1.35°C per decade in Fräcksjön, a natural Swedish lake (O'Reilly et al., 2015). These results clearly show the complex nature of changes in lake water temperature that can vary from one lake to another even in a local geographical region. Therefore, an improved understanding of the changes in water temperature in individual lakes such as Lake Kallavesi is important, since even small temperature changes can lead to cascading effects through the ecosystem (Adrian et al., 2009).

Given the lake stratification period that lasts from June to August, we investigated the impact of AT- and NAO-based stressors in the corresponding months and season (i.e., June to August, and summer) on the changes in LST and LDMT (Figure 7). In addition, we explored the impact of these drivers on LST and LDMT over monthly (i.e., May as the month prior to stratification), seasonal (spring as the season prior to stratification), and annual

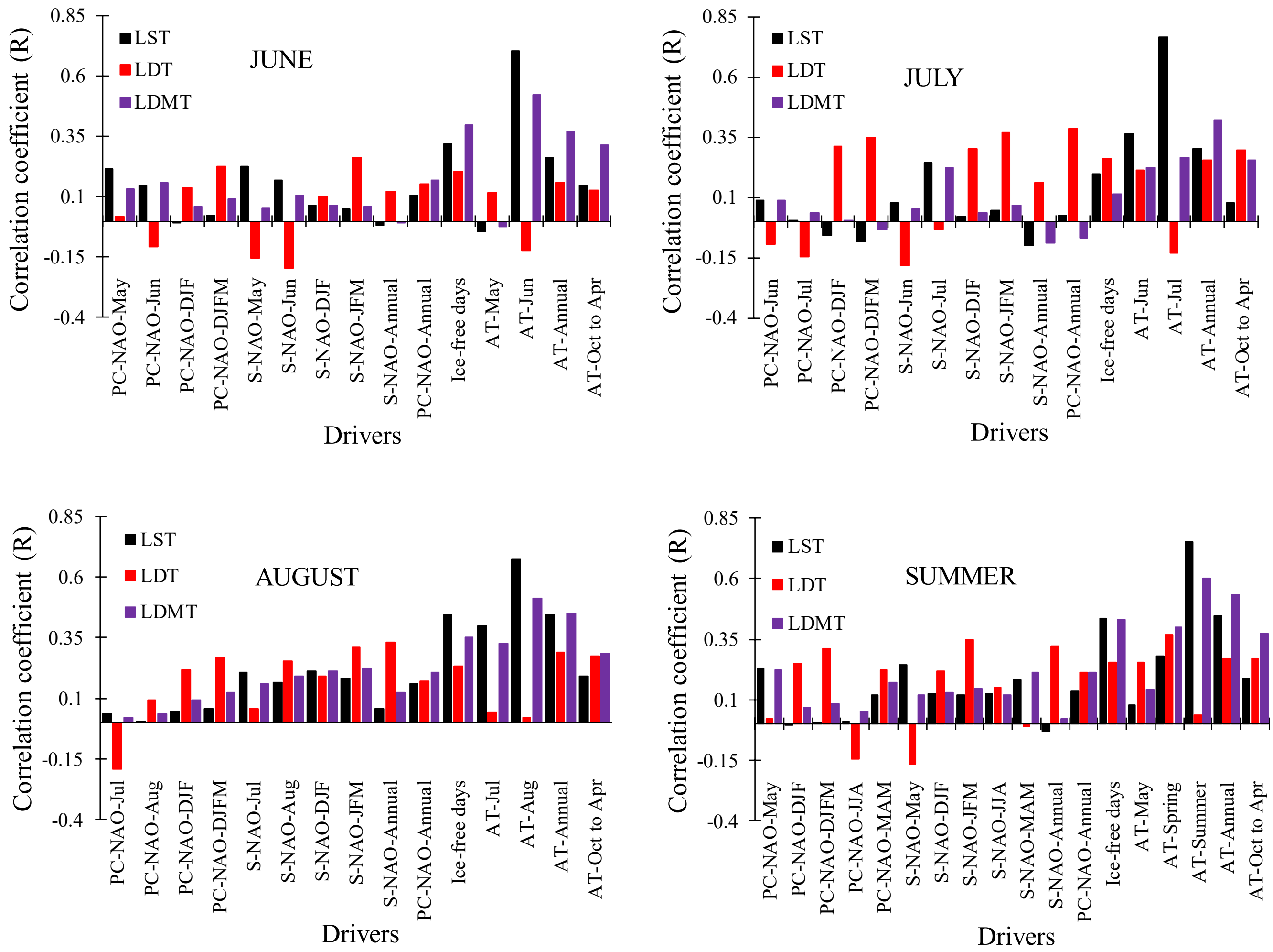

Figure 7. Impacts of station-based North Atlantic Oscillation (S-NAO), principal component-based NAO (PC-NAO), ice-free period (Ice-free days), and air temperature-based (AT) drivers on the lake surface water temperature (LST), lake deep water temperature (LDT), and lake depth-weighted mean water temperature (LDMT) in Lake Kallavesi in June, July, August, and summer.

time scales (Figure 7). Figure 7 also shows how AT averaged over the months when the lake is fully ice-covered (October to April), NAO-based drivers averaged over the cold months (December to February, January to March, and December to March), and annual ice free-days, all have impacts on the water temperature in Lake Kallavesi. According to Figure 7, the most important drivers of LST and LDMT in June, August and during the summer season are the corresponding ATs (i.e., AT-June, AT-August, and AT-Summer), with correlation coefficient values equal to 0.70 and 0.52, 0.68 and 0.51, and 0.75 and 0.60, respectively. In July, AT-July and AT-Annual are the main drivers of LST and LDMT, respectively. Ice-free days and annual mean air temperature (i.e., AT-Annual) are other important drivers of LST and LDMT in June, August, and summer although they are a bit different in the case of July (i.e., AT-Annual and AT-June). Other drivers do not strongly influence LST in Lake Kallavesi (their correlation coefficients are less than 0.25) except for August and summer when the air temperature in prior time scales, that is, AT-Jul and AT-Spring, respectively, act as the third main driver on LST. The AT in prior August (i.e., AT-July) and summer (i.e., AT-Spring), as well as the AT in cold months (AT-Oct to Apr) are also significantly impact the LDMT.

With respect to the NAO-based signals, they do not strongly correlate with the summer LST and LDMT in Lake Kallavesi (Figure 7). In general, the impact of NAO-based signals on the European climate is stronger in winter than summer (J. W. Hurrell, 1995; Livingstone, 2000). Therefore, the contribution of NAO-based signals to the LST and LDMT is likely confined from late winter to the spring. Thereafter, the impact of the past winter's NAO-based signals on the LST, and to some extent on the LDMT, is eliminated with the progress of thermal

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Table 3

Magnitude and Direction of Trends Observed in Both Monthly (June, July, and August) and Summer (June–August) Average Water Temperatures at Different Depths of Lake Kallavesi

Depth (m)	June		July		August		Summer	
	Sen's slope	S.L	Sen's slope	S.L	Sen's slope	S.L	Sen's slope	S.L
0	0.276	<0.10	0.405	<0.05	0.438	<0.1	0.422	<0.01
5	0.062	>0.10	0.272	<0.05	0.363	<0.01	0.288	<0.05
10	0.069	>0.10	0.071	>0.10	0.217	<0.10	0.083	>0.10
15	0.049	>0.10	0.019	>0.10	0.078	>0.10	0.037	>0.10
20	0.102	>0.10	0.050	>0.10	0.032	>0.10	0.054	>0.10
30	0.141	<0.10	0.128	<0.05	0.254	<0.05	0.175	<0.05
40	0.195	<0.05	0.209	<0.01	0.405	<0.001	0.259	<0.01

Note. S.L is the significance level of changes.

stratification from the late spring (Straile et al., 2003). In this regard, our findings are consistent with the poor relationship between NAO-based signals and the LST in 10 Polish lakes and some German lakes during summer (Gerten & Adrian, 2001; Ptak et al., 2018). In fact, due to the strong impact of AT on summer LST in Lake Kallavesi, the NAO-based signals are rapidly masked by dominant weather events. Given the weak impact of winter NAO-based signals on the Northern Hemisphere lakes, other large scale climate patterns such as the Atlantic Multidecadal Oscillation and El-Niño Southern Oscillation may also impact the summer lake water temperature in European lakes (Molinero et al., 2007) such as Lake Kallavesi, but were not investigated in our study.

3.4. Significant Warming Rate in the LDT

Table 3 suggests a breakpoint in warming rates observed at the depth of 15 m in June to August and summer. Warming rates decrease from the lake surface to the depth of 15 m. Below that level, they gradually increase with depth to reach a maximum at the lake bottom, that is, at 40 m depth. Measurements suggest smaller changes in LDT than the warming rates observed in LST in June–August and during summer overall. Given the difference between the warming rates in LST and LDT in Lake Kallavesi, this must lead to a strong increase in the lake thermal stability. However, in contrast with no significant change in LDT in global lakes from 1970 to 2010 (Kraemer et al., 2015) and 1970–2009 (Pilla et al., 2020), the summer LDT in Lake Kallavesi is warming at a rate of 0.259°C per decade (Figure 8). Interestingly, although our results suggest a significant warming rate in LDT in Lake Kallavesi, a significant cooling rate in LDT has been reported for its adjacent lake, that is, Lake Pielinen, over the period from 1970 to 2010 (Kraemer et al., 2015). Lake Pielinen is located at an elevation of 94 m above sea level and at a distance less than 100 km away from Lake Kallavesi. This lake has a maximum and average depth of 61 and 9.9 m, respectively,

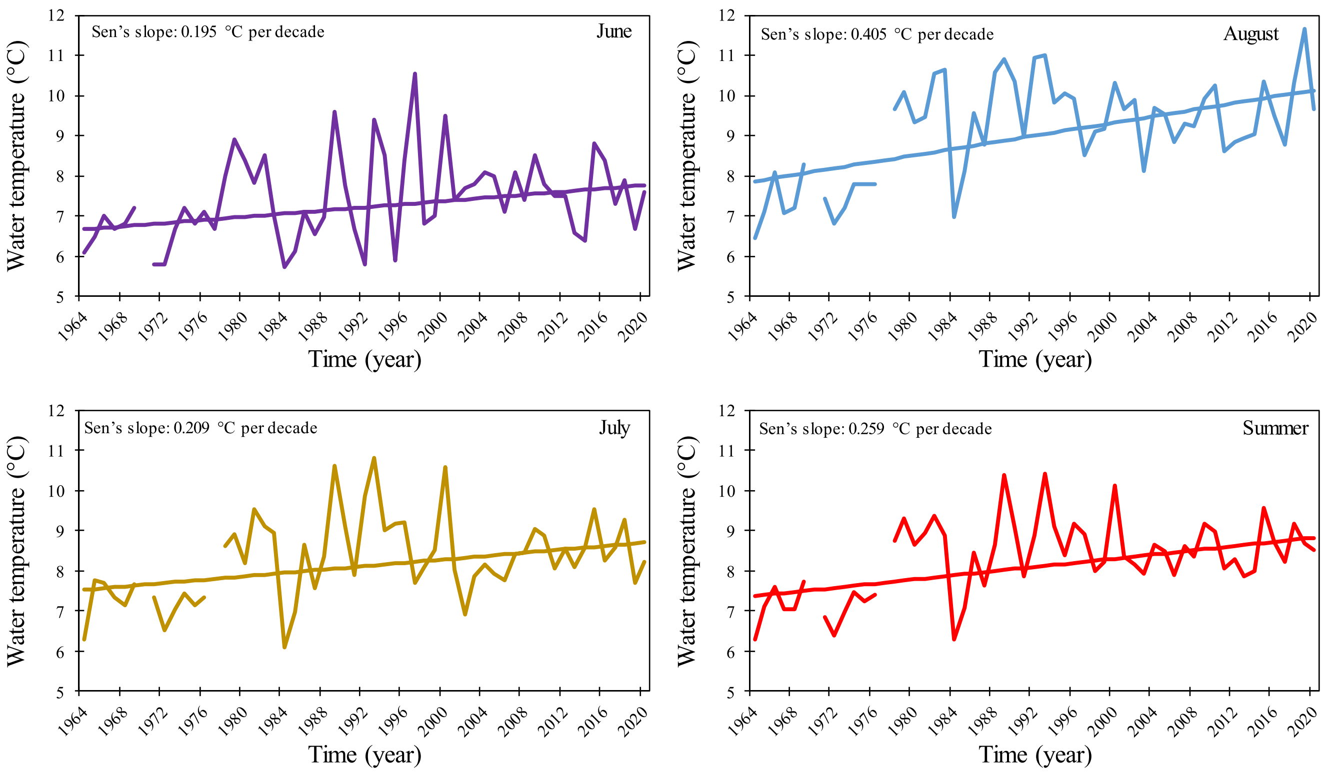

Figure 8. Time series and Sen's regression lines for monthly and summer mean lake deep water temperature in the Lake Kallavesi from 1964 to 2020.

approximately similar to those of the Lake Kallavesi. In general, both lakes have approximately similar morphology, climate conditions, water quality, and land-use patterns. However, different time spans used in our study (1964–2020) and that used in the study conducted by Kraemer et al. (2015), that is, 1970–2010, may contribute to the observed contradictor trends in the LDT in these lakes.

As with LST and LDMT, the minimum decadal warming rates in LDT are observed in June (0.195°C), respectively (Figure 8). In the contrary to LST and LDMT, the NAO-based signals mainly influence LDT in June to August and throughout the summer season in Lake Kallavesi (Figure 7). With respect to LDT in June, the main driver is the annual station-based NAO from January to March (S-NAO-JFM) with a correlation coefficient of 0.26. Other drivers are poorly correlated with LDT in June (correlation coefficient less than 0.25). The main driver of LDT in July is the annual principal component-based NAO (PC-NAO-Annual) with a correlation coefficient of 0.39, followed by S-NAO from January to March (S-NAO-JFM) and principal component-based NAO from December to March (PC-NAO-DJFM) with correlation coefficient values of 0.37 and 0.35, respectively. Other important NAO-based drivers of the LDT in July are shown in Figure 7 (correlation coefficient greater than 0.25). In addition to NAO-based signals, ice-free days, the AT averaged from November to April (AT-November–April), and the annual mean air temperature (AT-Annual) also mainly influence LDT in July. S-NAO-Annual and S-NAO-JFM are the main drivers of the LDT in August. As with LDT in July, the AT-November–April and AT-Annual also significantly contribute to the changes in LDT in August. Regarding LDT in summer, air temperature in the prior season, that is, AT-Spring, is the main driver with a correlation coefficient of 0.37, followed by S-NAO-JFM. Summer LDT is also impacted by the ice-free days, AT-November–April, and AT-Annual. According to these results, air temperature in the prior months does not affect LDT in the Lake Kallavesi although air temperature in the prior season, that is, spring, is the main driver of summer LDT. This highlights how AT impacts the LDT over time scales longer than a month.

Prior investigations concluded that the NAO-based signals had significant impact on LDT in European lakes (Blenckner & Chen, 2003; Dokulil et al., 2006; Gerten & Adrian, 2001; Salmaso et al., 2003). With respect to the Finnish lakes, Jyväsjärvi and Hämäläinen (2015) concluded that LDT was significantly correlated with the NAO signals, a finding that supports our results on Lake Kallavesi. On the contrary to the LST, the LDT does not immediately response to meteorological drivers such as the strong winter NAO-based signals. Lakes usually remove the high-frequency temperature variations with increasing the depth, leading to reflection of AT fluctuations only in the near-surface layers. Conversely, longer-period variations are likely reflected in the LDT when the lake become mixed (Livingstone, 1993; Straile et al., 2003). Spring homothermal state in dimictic lakes exposes the lake water temperature (e.g., the LST, LDT, and LDMT) to any strong winter's NAO-based signals present in the meteorological drivers. Starting from the onset of thermal stratification in late spring/early summer, the deep layers become isolated from the lake surface layers (Noori et al., 2021). Therefore, the LDT during the summer is impacted by the deep layer temperature attained during the spring mixing (Hondzo & Stefan, 1993; Livingstone, 1993; Robertson & Ragotzkie, 1990). Thus, the strong winter's NAO-based signals captured in the lake bottom temperature during spring mixing is likely to remain for some next months (Straile et al., 2003). However, the impact of NAO-based indices on LDT in dimictic lakes depends on the depth of the lake. The deeper the lake, the stronger the impact of NAO-based signals (Gerten & Adrian, 2001). Given that Lake Kallavesi is a medium depth dimictic lake (maximum and average depth of 75 m and 9.71 m, respectively), summer LDT shows an intermediate response to the NAO-based signals (Figure 7). Significant impact of ice-free days and AT-(November–April) on the LDT in summertime (Figure 7) together with significant upward trends in these drivers (Figure 2; Table 2) also imply the earlier ice-breakup date over the lake which further warms the lake water (O'Reilly et al., 2015; Zhong et al., 2016). Despite the statistically significant response of LDT to NAO-based signals, air temperature, and ice-free days, the correlation coefficient values are less than 0.40. Therefore, other natural and even anthropogenic stressors likely drive LDT in Lake Kallavesi as well. Given thermal stratification during summer and deep areas close to the sampling point A (Figure 1), warm surface waters are unlikely to effectively penetrate to the bottom layers. However, the mean depth of 9.71 m and location of water temperature measurements that is close to the lands (see Figure 1) may further influence the lake water temperature by lands and anthropogenic inputs. Changes in water transparency can also impact the LDT warming rate by regulation of vertical penetration of heat (Read & Rose, 2013). However, the LDT in very deep lakes is not likely influenced by water transparency changes due to little impact of solar radiation in bottom layers of these lakes. Also, the LDT in shallow lakes (depth < 3 m) is relatively insensitive to water transparency trends due to frequent mixing in shallow lakes. The most impact of water transparency changes on the LDT warming rate has been reported in lakes with intermediate depth ranged from 3 to 18 m (Rose et al., 2016). Given the mean depth of Lake Kallavesi, that is, 9.71 m, the possible changes in water transparency could explain the observed changes in the LDT, but we didn't have the data to investigate it in Lake Kallevesi. Therefore, we suggest further investigations to fully understand LDT in this boreal lake, a conclusion also reached by Pilla et al. (2020) in the study of global lakes.

Despite warming rates in both the surface and bottom layers of the lake, no significant correlation was observed between the LDT and LST measurements in Lake Kallavesi (correlation coefficient less than 0.25). Given that LDT may respond to LST over longer time scales (Woolway et al., 2015), we further investigated the possible relationship between the LDT data and LST measurements in prior months (May–July) and prior season (spring). We did not find any statistically significant correlation. These findings suggest that LDT could be influenced by different drivers than those that affect LST in Lake Kallavesi (e.g., NAO-based signals), as discussed above (see Figure 7). This conclusion also supports prior findings by Pilla et al. (2020).

4. Conclusions

The impact of global warming on lakes during the Anthropocene has become a serious concern in many regions of the world. Given the wide range of drivers influencing the lake water temperature, it is not easy to understand the trajectories of the lake temperature changes in order to inform mitigation strategies. This is more complicated for LDT and LDMT than LST, since our knowledge of the deep-resolved lake temperature is far less than that of the lake surface. In this study, a long-term, in situ database of Lake Kallavesi was used to investigate the exact changes in the lake water temperature under the warming impact of local air temperature, large-scale climatic fluctuations as represented by NAO-based signals, and an increase in ice-free days in the lake. Our results show that the lake surface has warmed about two times faster than the local air, although the magnitude of deep water warming was consistent with the local air. Drivers of changes in LDT were not the same as those that mainly affected LST and LDMT in Lake Kallavesi, suggesting further studies should be done to fully understand the mechanism of changes in LDT in this boreal lake. Given the rapid warming rate in LDT, and especially in LST, profound implications are predictable for the lake water quality and its ecological functions.

Data Availability Statement

The raw data of water temperature, ice-on/off date, and ice-free period are publicly available via Data Archive of the Finnish Environment Institute (https://wwwp2.ymparisto.fi/scripts/kirjaudu.asp). This website is available in Finnish. The users should be first registered by click on: "*Rekisteröityminen*." Then, select: "*Ympäristötiedon hallintajärjestelmä Hertta*" in the registered personal page. Finally, they can access to the lake water temperature and ice phenology databases by selection of "Vesivarat." The raw data of surface air temperature are publicly available through Data Archive of the Finnish Meteorological Institute (https://en.ilmatieteenlaitos.fi). The station and principal component-based NAO index values, respectively, are publicly available (via https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based and https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based). The MAKESENS 1.0 software is freely available (in: https://en.ilmatieteenlaitos.fi/makesens).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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