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Key Points:
- We investigated the thermal response of Lake Inari, northern Finland, to climate change from 1961 to 2020
- Surface water temperatures increased considerably (+0.25°C decade^{-1}), but no significant trends were observed at depth
- Lake surface temperatures were influenced by the long-term change in summer air temperature and solar radiation as well as the timing of annual ice loss

Supporting Information:
Supporting Information may be found in the online version of this article.

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Six Decades of Thermal Change in a Pristine Lake Situated North of the Arctic Circle

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Abstract The majority of lake temperature studies have investigated climate-induced changes occurring at the lake surface, primarily by analyzing detailed satellite images of surface water temperature. Whilst essential to observe long-term change, satellite images do not provide information on the thermal environment at depth, thus limiting our understanding of lake thermal responses to a warming world. Long-term in situ observational data can fill some of the information gap, with depth-resolved field measurements providing a detailed view of thermal change throughout the water column. However, many previous studies that have investigated multi-decadal changes in lake temperature, both at the surface and at depth, have typically focused on north temperate lakes. Relatively few studies have investigated temperature variations in lakes situated north of the Arctic Circle, which is one of the most rapidly warming regions on Earth. Here, using a 60-year (1961–2020) observational data set of summer water temperature (July–September) from Lake Inari (Finland), we investigate changes in the thermal environment of this pristine lake. Our analysis suggests a statistically significant summer warming trend at the lake surface (+0.25°C decade^{-1}, p-value <0.1), whilst deepwater temperatures remain largely unchanged. This contrasting thermal response of surface and bottom water temperature to climatic warming has likewise resulted in a strengthening of summer stratification in this high latitude lake. Implications of the observed change in both temperature and stratification on the lake ecosystem will likely be extensive, including impacts on aquatic organisms which this lake supports. Our work builds on the ever-growing literature regarding lake thermal responses to climate change.

1. Introduction

Water temperature has an important influence on the physical environment of lakes (Kraemer et al., 2015; Woolway & Merchant, 2019), with knock-on effects on, among other things, food web dynamics (Blois et al., 2013), the distribution of aquatic organisms (Comte & Olden, 2017; Kraemer et al., 2021; Woolway & Maberly, 2020), and biogeochemical processes (Demars et al., 2016; Kraemer et al., 2017; Modabberi et al., 2020; Noori et al., 2019). Climate-induced changes in water temperature can thus have a considerable influence on the structure and functioning of lake ecosystems worldwide. A detailed understanding of long-term change in lake water temperature, and its associated drivers, is therefore important for climate change impact studies, and for anticipating the repercussions of climate change on lake ecosystems.

Previous studies, notably those involving detailed satellite images, have suggested that lake surface water temperatures are increasing globally (O'Reilly et al., 2015; Schneider & Hook, 2010; Woolway et al., 2020), with deep lakes situated at high-latitude typically experiencing the greatest change (Woolway & Maberly, 2020; Woolway & Merchant, 2017). The rapid warming of high-latitude lakes under climatic change partially reflects the substantial increase in air temperature in polar regions (Noori, Bateni, et al., 2022; Post et al., 2018; Stuecker et al., 2018). However, some high-latitude lakes, as well as many others situated at lower latitudes, also experience summer surface temperature trends that are sometimes greater than local changes in air temperature (O'Reilly et al., 2015; Schneider et al., 2009). This suggests an additional source of warming for lakes, such as an increase in incoming solar radiation (Schmid & Köster, 2016) or changes in water transparency which can influence the depth at which solar radiation is absorbed within a lake (Persson & Jones, 2008; Read & Rose, 2013; Rose et al., 2016). In some cases, an earlier break-up of winter ice cover (Sharma et al., 2021) and/or an earlier onset of thermal stratification (Woolway et al., 2021) can lead to rapid lake surface warming due to a lengthening of the summer stratified season (Austin & Colman, 2007; Woolway & Merchant, 2017). In addition, some lake regions have experienced a decline in near-surface wind speed in recent decades (Stetler et al., 2021; Woolway et al., 2019), which not only reduces turbulent heat loss from the lake surface but also influences vertical mixing and the vertical distribution of heat which can contribute to amplified surface warming.

In addition to the changes observed at the lake surface, many studies have suggested a long-term warming trend at depth (Dokulil et al., 2006; Perroud & Goyette, 2010; Richardson et al., 2017). Globally, deep water temperatures are changing at a much slower rate than those observed in the near-surface layer, with some lakes even experiencing a cooling trend of deepwater temperatures (Pilla et al., 2020). The drivers of change in lake bottom temperature include many of the aforementioned climatic drivers of surface temperature change, notably air temperature, wind speed, and transparency. However, the response of bottom water temperature to climatic warming differs between lakes depending on, for example, their seasonal mixing regime (Anderson et al., 2021). Specifically, bottom temperatures in polymictic lakes follow closely the seasonal and inter-annual variations in air temperature. Seasonally stratified lakes on the other hand, have bottom waters that are, for most of the year, separated from the warmer layer above (and thus also from air temperature) by a density gradient known as the thermocline. Because the thermocline limits the downward penetration of heat, bottom waters in these lakes receive the vast majority of heat during the period of homothermy in winter/spring, with some additional heat gained during the stratified period via vertical diffusion. A change in transparency in these lakes could influence bottom temperatures during summer, with both increasing and decreasing trends widely reported (Bartosiewicz et al., 2019; Pilla et al., 2018; Read & Rose, 2013; Rose et al., 2016). In oligomictic and meromictic lakes, bottom water is, to a large extent, shielded from much of the influence of air temperature. In these lakes, the temporal evolution of bottom temperature is characterized by a slow increase via the downward diffusion of heat (Ambrosetti & Barbanti, 1999; Verburg & Hecky, 2009). In the case of oligomictic lakes, bottom temperatures can cool abruptly during extreme cold winters (Livingstone, 1997). Ultimately, the relationship between climate (e.g., air temperature) and bottom water temperature differs across lakes and is influenced by the seasonal evolution of stratification or the lack thereof.

Given a wide range of drivers that influence lake surface and bottom water temperature, the thermal response of lakes to climate change differs considerably worldwide. However, most studies of depth-resolved lake temperature change have typically focused on those in north temperate regions. The magnitude and direction of temperature change in arctic lakes has not been explored as extensively (Lehnherr et al., 2018; Zhang et al., 2021), particularly below the water surface. To fill this fundamental knowledge gap, here we analyze a 60-year data set of the thermal environment of Lake Inari, a pristine lake situated north of the Arctic Circle. In this study, we explore the recent changes in the temperature of surface and deep water in Lake Inari and investigate the main drivers of change. This study aims to improve our knowledge of long-term changes in Arctic lake water temperature and its dominant drivers, which are essential for understanding lake ecosystem responses to climate change.

2. Materials and Methods

2.1. Study Site

Lake Inari, also known as *Inarijärvi*, is located in northern Finland (69.0480°N, 27.8760°E) at an altitude of approximately 117 m above sea level (Figure 1). This dimictic and oligotrophic lake has a mean and maximum depth of approximately 14.3 and 92 m, respectively, and a surface area of 1081.9 km^2. It is the second deepest and the third largest lake in Finland. After Lake Taymyr in Siberia, Russia, Lake Inari is the second largest lake by surface area located above the Arctic Circle. Largest rivers discharging to the lake are River Juutuanjoki and River Ivalojoki whilst River Paatsjoki, a river regulated by hydropower plant, discharges the lake water into Barents Sea. Lake Inari's watershed is about 13,400 km^2. Land use of its watershed dominantly yields forest (mainly pines), followed by open peatlands, waterbodies, and poorly growing woodland shrub (e.g., sparse trees). Some Arctic mountains are located in the basin's northern part, covered by small clusters of Arctic birch. In the municipality of Inari, there are 7,008 inhabitants. Given the lake watershed area, there is a population density of 0.5 inhabitant per 1 km^2. Sanitary facilities cover about 95% of municipal and rural population in lake watershed. With a less populated basin, Lake Inari is positioned far from small industrial centers (no major industry exists) and has only been marginally influenced by anthropogenic disturbances. In turn, Lake Inari's watershed is considered to be in a nearby-pristine state.

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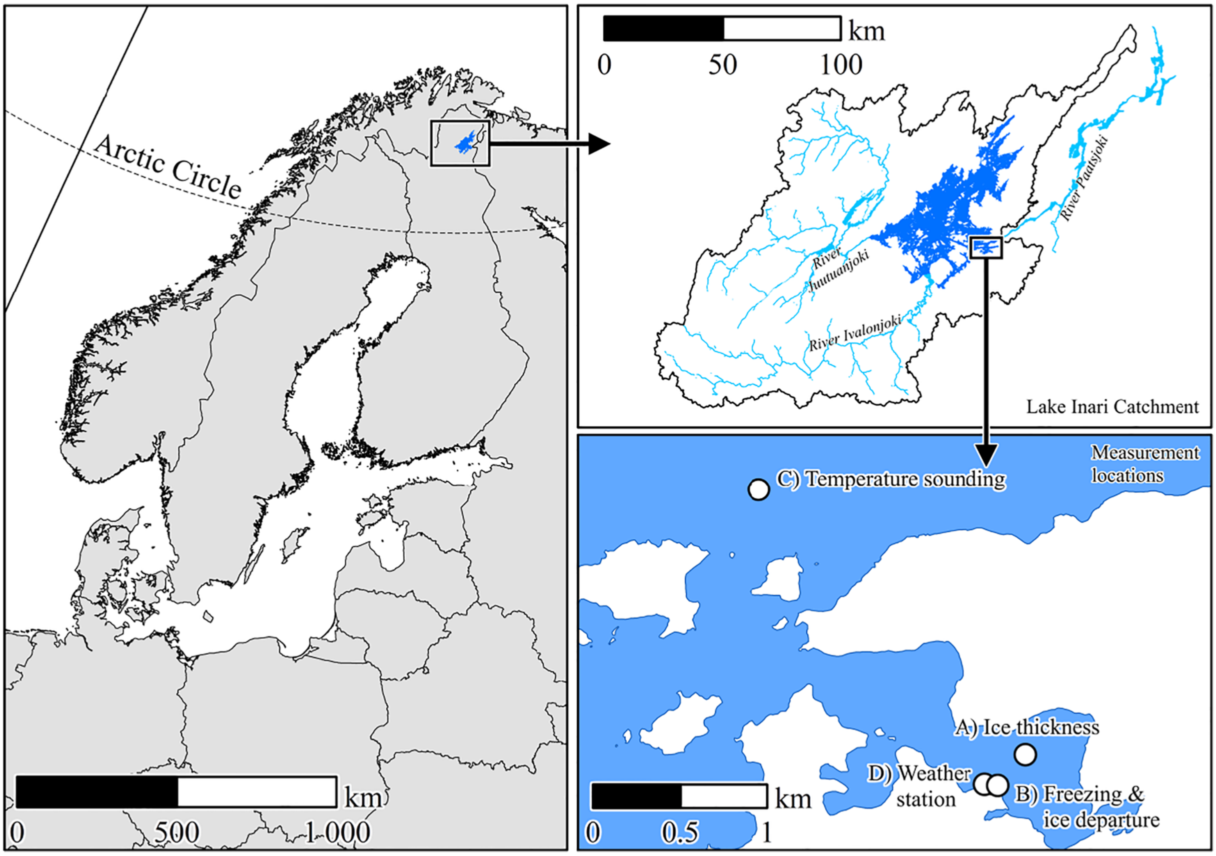

Figure 1. Location of the Lake Inari (Finland) and the sampling sites A to D, where the data investigated in this study were observed.

2.2. In Situ Lake Observations

Water temperatures investigated in this study were measured at different depths (0, 5, 10, 15, 20, 30, and 40 m) at sampling site A in Lake Inari (see Figure 1) from 1961 to 2020. Water temperatures were measured at weekly intervals (1961–1988) or three times a month (1988–2020) with a reversing mercury thermometer (1960–1970) and a digital thermometer (since early 1970s). Here, we define deepwater temperature as those measured at the deepest point in sampling site A (depth = 40 m). The temperature difference between surface (0 m) and bottom (40 m) water is used in this study as a proxy for lake thermal stability, and to define "stratified" and "mixed" conditions. Oftentimes, stratified conditions are defined as when the top minus bottom lake temperature difference exceeds 1°C (Read et al., 2014; Stefan et al., 1996; Woolway et al., 2014), or according to a number of density-based thresholds (Gray et al., 2020; Wilson et al., 2020). In this study, we use a conservative approach and define stratified conditions as when the summer mean (July–September) temperature difference between surface and bottom water exceeds 3°C. In turn, stratification is only considered during the most stable cases. Temperature data from Lake Inari were combined with summer mean Secchi depth (i.e., used as an indicator of water transparency) observed at site A from 1974 to 2020. We also investigate changes in ice phenology, the number of ice-free days, and the mean snow depth between November and May (hereafter referred to as the cold season), using observations from site B from 1961 to 2020 (Figure 1). The ice-on date of Lake Inari, recorded as it occurred, is reported as the date of permanent freeze-up of the entire observable area from the observation site. The ice-off date, recorded as it occurred, is reported as the date when no ice is observed from the observation site. As the ice-on/off dates in the Lake Inari are typically in the middle of October and June, respectively (Figure S1 in Supporting Information S1), our analysis of water temperature is restricted to July–September (hereafter referred to as summer, in-line with previous lake surface temperature studies; Austin & Colman, 2007; O'Reilly et al., 2015; Schneider & Hook, 2010), when the lake is ice-free.

2.3. Climate Data

To compare with the lake ice and temperature observations, in this study we calculate two indices of climatic conditions during the study period (a) summer mean surface air temperature, and (b) the average air temperature during the cold season. Here, the influence of summer mean wind speed and solar radiation on observed changes in lake temperature are also investigated. Air temperature was measured at the Inari Nellim meteorological station (site C) (Figure 1), the closest station to water sampling location–site A. Both wind speed and ground level solar radiation data (1961–2020) were extracted from the ERA5-Land reanalysis product (Muñoz Sabater, 2019), notably from the 9 km^2 grid at the lake location. Hereafter, we assume that each sampling site is representative of the entire lake.

2.4. Data Analysis

In this study, we use a multivariate linear regression (MLR) model to investigate the influence of a number of predictor variables that we hypothesize might have an effect on water temperature variability in Lake Inari. These drivers include the annual ice-off date, summer mean solar radiation, wind speed, and air temperature. Each of the predictor variables considered has previously been suggested to influence the thermal response of lakes to climate change (Magee & Wu, 2017; Woolway et al., 2020). Although Secchi depth can be also considered as a potential driver of change in lake water temperature (Rose et al., 2016), we had to ignore this variable in our MLR model, as observations were not available throughout the study period. The MLR was performed using the stepwise algorithm (hereafter referred to as stepwise-based MLR model) in the SPSS environment, which selects the most significant drivers based on a threshold p-value (here, p-value <0.1). The variance inflated factor (VIF) criterion was also applied to check the multicolinearity in the stepwise-based MLR model, where the VIF values greater than 10 are usually undesirable and can result in poor performance of the model developed (Noori, Ghiasi, et al., 2022).

We also used the one-way analysis of variance (ANOVA), as a univariate statistical analysis, to explore the significant variations in water temperatures among different depths. This was performed in the SPSS environment. Mann-Kendall (Kendall, 1975; Mann, 1945) and Sen slope estimator (Sen, 1968) methods were applied to determine statistically significant univariate trends in the variables investigated (air and water temperature, solar radiation, ice phenology, wind speed, snow depth, and Secchi depth data). It should be noted that we used all available data, and no reconstruction method was used to fill the gaps. Both Mann-Kendall and Sen slope estimator methods were run using MAKESENS 1.0, a macro code linked to Microsoft Excel developed by the Finnish Meteorological Institute (MAKESENS, 2002), available in https://en.ilmatieteenlaitos.fi/makesens.

3. Results

Our results show a statistically significant increase in spring (April to June) (0.27°C $decade^{-1}$; p-value <0.1) and summer (0.27°C $decade^{-1}$; p-value <0.1) air temperatures in Lake Inari, as well as a rapid warming of air temperature during the cold-season (0.48°C $decade^{-1}$; p-value <0.1). No statistically significant trend was observed in solar radiation nor wind speed (p-value >0.1) (Figure 2). Within this period of long-term change, we also calculated corresponding variations in ice phenology. Our observations suggest a statistically significant long-term change in the timing of ice-off (–1.89 days $decade^{-1}$, p-value ≤0.1), snow depth during the cold season (–1.65 cm $decade^{-1}$; p-value <0.1), and in the duration of the ice-free period (3.22 days $decade^{-1}$, p-value ≤0.1) whilst the date of ice-on remained largely unchanged (+1.33 days $decade^{-1}$, p-value >0.1) (Figure 3). Furthermore, using the summer mean water temperature data we found that the temperature difference between the lake surface and deepwater were frequently greater than 3°C during the study period, suggesting summertime stratification in this high-latitude lake. Our analysis also shows a substantial and statistically significant long-term change in lake thermal stability (Figure 4), which has increased at a rate of 0.29°C $decade^{-1}$ (p-value <0.1) from 1961 to 2020.

In-line with observed changes in air temperature and lake ice conditions, our observations suggested a significant warming of lake surface water temperature during summer (Figure 5). The observed increase in summer lake surface water temperature (0.25°C $decade^{-1}$; p-value <0.1) is comparable to the magnitude of long-term change in summer air temperatures (0.27°C $decade^{-1}$; p-value <0.1). However, below the water surface, our results reveal a somewhat muted lake thermal responses to climate change, particularly compared to near-surface temperatures. Most notably, our data suggests that the magnitude of long-term change in water temperature decreases with

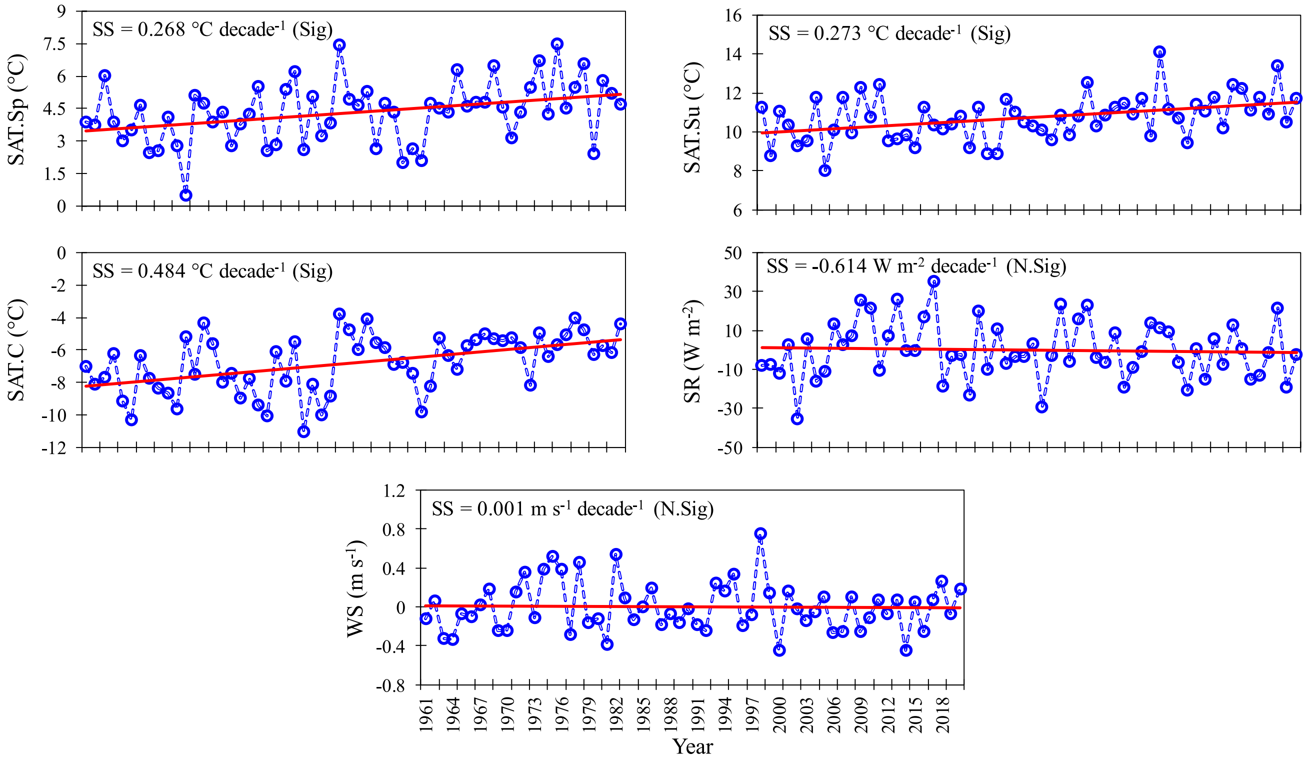

Figure 2. The calculated magnitude and direction of change in summer and spring mean air temperature (°C) (SAT.Su and SAT.Sp), the mean air temperature during the cold season (November–May) (SAT.C), the mean summer solar radiation and wind speed. "SS" indicates slope of Sen's regression line. "Sig" and "N.Sig" indicate the statistically significant and non-significant trends, respectively.

increasing depth (Figure 5), and that at a depth of 30 m or more, lake temperatures are not changing in a statistically significant manner (p-value >0.1). Interestingly, our data also shows higher warming rates at depths of 5 and 10 m, compared to the lake surface (Figure 5), which could reflect changes in the depth of the upper mixed layer that could not be quantified in this study (i.e., given the vertical spacing of the water temperature data). A one-way ANOVA suggested that the difference between the warming rates calculated at the lake surface and at

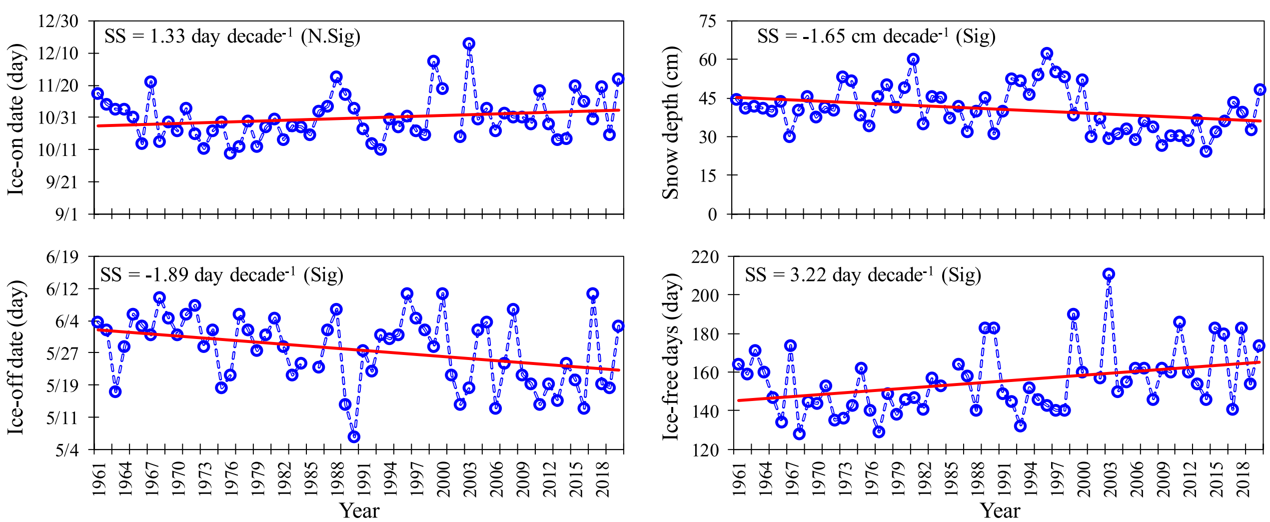

Figure 3. The calculated magnitude and direction of change in the dates of ice-on and ice off, the mean snow depth during the cold season, and the number of annual ice-free days. "SS" indicates slope of Sen's regression line. "Sig" and "N.Sig" indicate the statistically significant and non-significant trends, respectively.

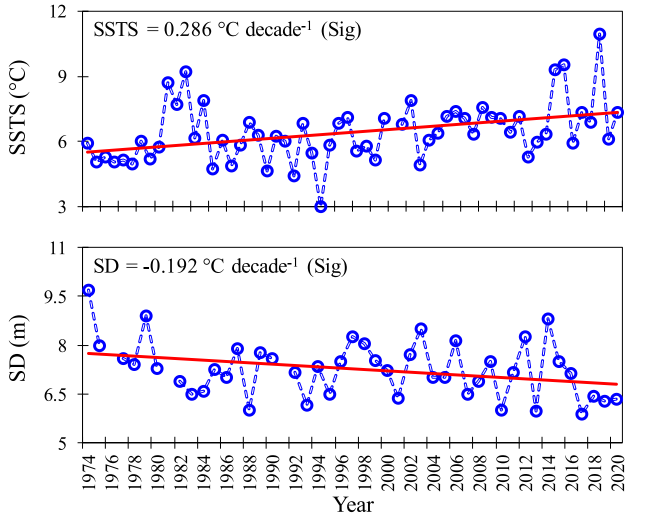

Figure 4. Time series and slope of Sen's regression line for the strength of summer thermal stratification (1961–2020) and Secchi depth (1974–2020) in the Lake Inari. Noted that the strength of summer stratification was calculated as difference between water temperatures in the top (depth of 0 m) and bottom (depth of 40 m) layers in the lake. "SS" indicates slope of Sen's regression line. "Sig" and "N.Sig" indicate the statistically significant and non-significant trends, respectively.

a depth of 5 m were statistically significant (p-value <0.1), whereas those at 10 m were not (p-value >0.1).

To offer insights about the dominant drivers of change in lake surface and bottom water temperature in Lake Inari, we investigated the influence of four predictor variables that we hypothesized might have an effect (Figure 6). Our investigation revealed that the most important driver of surface water temperature was summer air temperature (p-value <0.1), followed by summer mean solar radiation (p-value <0.1), and the date of ice-off (p-value <0.1). No statistically significant relationships were observed between the lake surface water temperature and the summer mean wind speed (p-value >0.1). The variables shown here to have a statistically significant influence on lake surface water temperature, could alone explain 81% of the changes in the lake surface temperature (VIF <1.20). With respect to deepwater temperatures, the only statistically significant driver, of the variables tested, was the date of ice-off (I.Off.D; p-value <0.1), with earlier ice break-up coinciding with warmer bottom temperatures. The date of ice-off could explain 22% of the variability in deepwater temperature (VIF <1.01). Thus, our data showed no significant relationship between summer deepwater temperature and summer mean air temperature, solar radiation or wind speed (p-value >0.1) (Figure 6).

4. Discussion

Our investigation suggested a statistically significant and rapid warming of air temperature at Lake Inari during both spring and summer, as well as during the cold-season from 1961 to 2020. Our results agree with previous studies which have suggested that Arctic lakes are exposed to some of the most rapid climatic warming rates in recent decades (Alexander et al., 2013). In particular, previous studies have suggested a substantial warming of air temperature in Finland since the 1970s (Räisänen, 2019; Ruosteenoja & Räisänen, 2021; Tuomenvirta, 2004) with a maximum warming during the cold-season (Tuomenvirta, 2004).

In response to the rapid warming of near-surface air temperature in spring and during the cold-season, as well as a decline in snow depth in Lake Inari, our analysis suggested a significant trend in the number of ice-free days as well as in the timing of ice-off, both of which are in-line with previous studies (Benson et al., 2012; Brown & Duguay, 2010; Korhonen, 2006; Sharma et al., 2019, 2021). More specifically, Korhonen (2006) reported an increase in the duration of ice-free conditions across Finnish lakes. Furthermore, an earler ice-off date (6.8 days) and a lengthening of the ice-free season (17.0 days) across 60 Northern Hemisphere were reported by Sharma et al. (2021). These changes are less than those calculated here for Lake Inari from 1961 to 2020. Our findings thus suggest a more rapid decline of ice cover in Arctic systems. This follows our expectation given the rapid warming of the Arctic in recent decades (Alexander et al., 2013). We also expect that the observed changes in snow depth in Lake Inari contributed to the changes in ice break-up dates, with a decline in snow depth leading to reduced ice thickness and consequently earlier ice loss (Brown & Duguay, 2010). That being said, our analysis suggests no statistically significant trend in the timing of ice formation (p-value >0.1). This is consistent with the results of Korhonen (2006) who identified delayed ice-on dates in only 15% of the Finnish lakes studied, whereas ice-off dates occurred consistently earlier. Moreover, Duguay et al. (2006) reported significant trends in earlier ice-off dates across lakes in Canada (1951–2000) whilst ice-on dates showed incoherent trends. In a study conducted over 13,300 Arctic lakes, more earlier ice-off dates were reported than those previously noticed (Šmejkalová et al., 2016). Similar results were also reported for Lake Hazen, Canada, where rapid spring warming resulted in ice-off dates changing at a rate three times greater than the delay observed in the ice-on date (Lehnherr et al., 2018).

Our analysis of summer water temperatures in Lake Inari showed that the lake surface has warmed at a rate of 0.247°C decade^{-1} (p-value ≤0.1) from 1961 to 2020. This rate of change is comparable to that observed in local summer air temperature during the same period (0.273°C; p-value <0.1). The observed change in surface water temperature thus agrees with our expectations, particularly according to previous predictions which suggest that lake surface temperatures should increase by 75%–90% of the increase in air temperature, if all other forcing

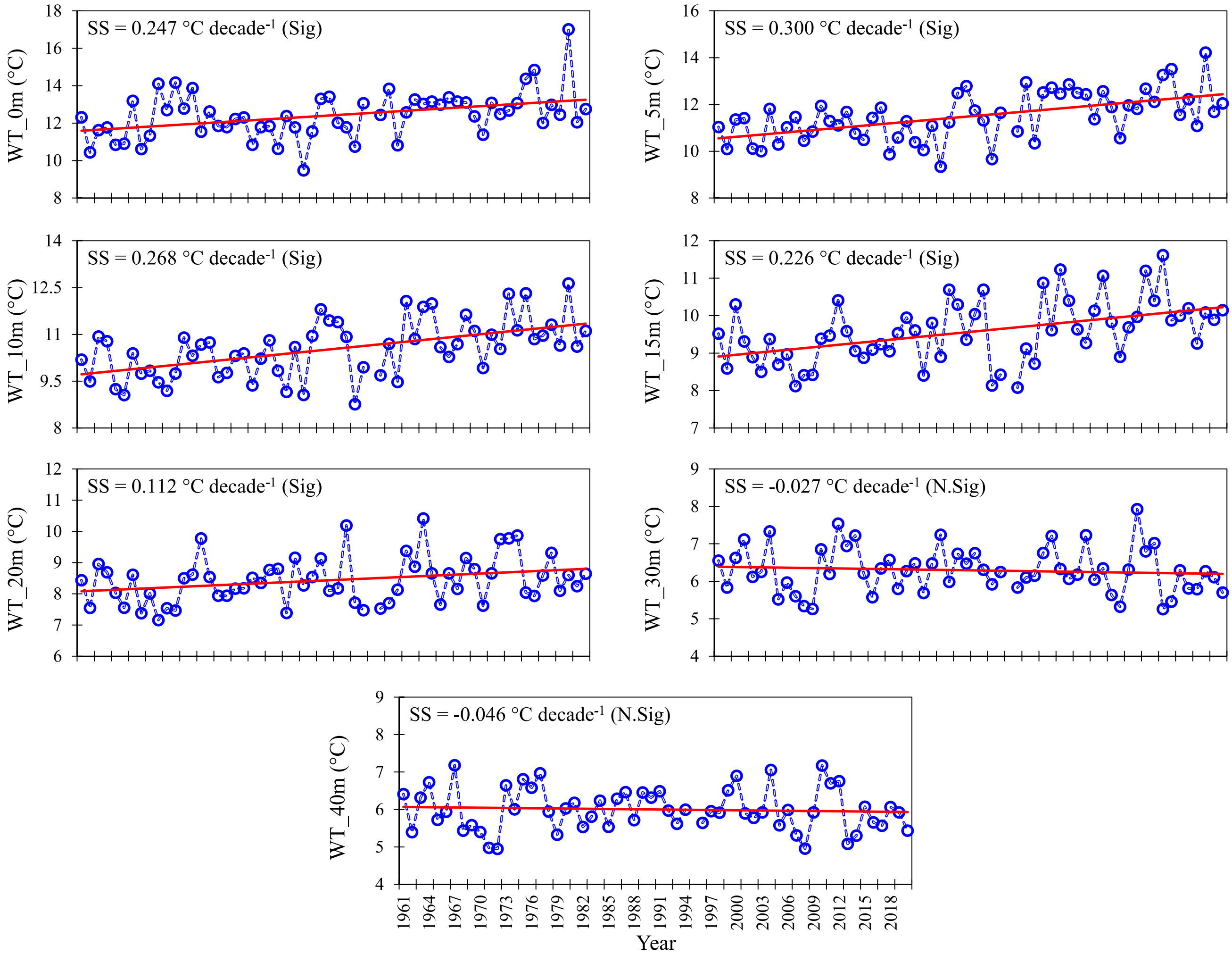

Figure 5. Decadal changes in summer mean water temperatures at top layer (depth of 0 m) (WT_0m), depths of 5 m (WT_5m), 10 m (WT_10m), 15 m (WT_15m), 20 m (WT_20m), and 30m (WT_30m), and bottom layer (depth of 40 m) (WT_40m) of the Lake Inari from 1961 to 2020 (significant change with *p*-value ≤0.1). "SS" indicates slope of Sen's regression line. "Sig" and "N.Sig" indicate the statistically significant and non-significant trends, respectively.

variables remain unchanged (Schmid et al., 2014). Interestingly, our results also showed that summer mean wind speed and solar radiation, as other main forcing variables influencing lake surface temperature, have remained unchanged during the study period. Our observations align with both regional (Woolway et al., 2017) and global-scale (O'Reilly et al., 2015) studies that have unequivocally demonstrated an increase in lake surface temperature in recent decades. However, in the deep zone of Lake Inari, our analysis suggested that water temperatures have remained unchanged (−0.046°C decade^{-1}; *p*-value >0.1). This is opposite to that suggested for other lakes at local to regional scales, which have primarily reported a warming trend (Ambrosetti & Barbanti, 1999; Anderson et al., 2021; Vollmer et al., 2005). However, a large-scale study by Pilla et al. (2020) suggested that lake bottom temperature trends are highly variable worldwide, with both warming and cooling trends frequently observed (Kraemer et al., 2015; Pilla et al., 2020). Our observations of warming at the lake surface and no change in deepwater temperatures suggests that the strength of thermal stratification has increased in recent decades. Most notably, our analysis suggested that the temperature difference between surface and bottom waters has significantly increased at a rate 0.29°C decade^{-1} during the study period (*p*-value <0.1). A strengthening of summer stratification is an expected lake thermal response to climate change (Butcher et al., 2015; Kraemer et al., 2015; Oleksy & Richardson, 2021; Vinnå et al., 2021), and our results agree with these expectations.

We investigated the dominant drivers of lake temperature change in Lake Inari using a stepwise-based MLR model. Our results suggested that the most important driver of change in lake surface temperature was the mean

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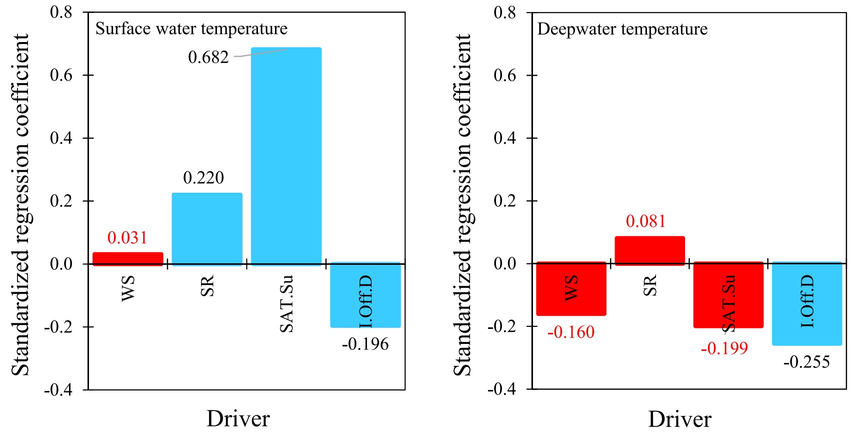

Figure 6. Standardized regression coefficients of the potential drivers of the lake water temperature, that is, the lake surface (left panel) and lake bottom (right panel) in the Lake Inari based on the data from 1961 to 2020. Significant changes with p-value <0.1 are shown in rectangular shape filled with the blue color. Non-significant changes (p-value >0.1) are given in rectangular shape filled with the red color. The bigger absolute value of standardized regression coefficients, the more important drivers of lake water temperature. SAT.Su: Mean surface air temperature in summer (July–September), WS: Mean near-surface wind speed in summer, SR: Mean solar radiation in summer, and I.Off.D: Annual ice-off dates.

summer air temperature followed by the summer mean solar radiation and the date of ice-off. This is in agreement with previous studies that have investigated lake thermal responses to climate change (Austin & Colman, 2007; O'Reilly et al., 2015). In some cases, summer lake surface temperatures have increased at a faster rate than local air temperatures (O'Reilly et al., 2015; Schneider et al., 2009). Earlier ice-off date can accelerate lake surface warming due to a lengthening of the summer stratified season (Austin & Colman, 2007; Sharma et al., 2021; Woolway et al., 2021), which can expose surface waters to longer periods of atmospheric heating and incoming solar radiation (Huang et al., 2017). In our study, lake surface temperature was well described ($R = 0.81$) by an MLR model containing the three drivers. Regarding the change in bottom water temperature, our analysis suggested that the date of ice break-up was the only statistically significant predictor. In our study, we also observed a strengthening of thermal stratification during summer driven by the contrasting thermal response of surface and bottom water temperature to climate change in this Arctic lake. Factors such as changes in Secchi depth (as a main indicator of water transparency) may have also contributed to changes in the thermal environment of Lake Inari, specifically in deepwater temperatures. For example, increases or decreases in Secchi depth could act to lead to an increase or decrease in deepwater temperature, respectively (Rose et al., 2016). While we excluded Secchi depth data in our statistical analysis due to a substantial gap in the data record during the study period, our trend analysis results showed that this variable has decreased from 1974 to 2020 (Figure 4). Therefore, it could be suggested that the decreasing trend in Secchi depth during the study period contributed to the stagnant nature of bottom water temperature.

Our results revealed that the rate of lake warming at a depth of 5 m exceeded that observed at the lake surface (i.e., at 0 m). Given the significant decline in water transparency in Lake Inari, this factor does not support our observations. Decrease in water clarity typically results in a shoaling of the upper mixed layer as more solar radiation is absorbed near the surface and less is penetrated to deeper waters (Rose et al., 2016). Deepening of the upper mix layer during the study period may contribute to a greater warming rate at depths below the lake surface, as reported previously in the oceans (Sallée et al., 2021). Most notably, if 5 m was below the upper mixed layer at the start of the record, but within the upper mixed layer during the end of the record, this could partly explain a greater rate of warming at this depth. However, a deepening of the upper mixed layer under climate change in both the oceans and in lakes is debated, with some modeling-based studies suggesting that the upper mixed layer should become shallower within a warming world (Behrenfeld et al., 2006; Boyce et al., 2010; Polovina et al., 2008). Other factors that could explain the higher warming rate at 5 m depth are higher wind speeds and/or higher inflows–either would lead to a deepening of the mixed layer (Woolway et al., 2017; Zhang et al., 2014). Although wind speeds remained largely unchanged in the lake location (p-value >0.1), inflows to the lake were not explored due to the lack of available long-term observational data. However, we hypothesize that an increase in inflows to the lake during the open-water period could have contributed to the deepening of the upper mixed

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layer which, in turn, contributes to a greater warming rate at depth of 5 m than that in the lake surface. Our hypothesis is further supported when we note that global warming has further augmented the delivery of meltwaters to Arctic lakes (Overeem & Syvitski, 2010; Peterson et al., 2002), even up to 10 times in the case of the largest Arctic lake, that is, Lake Hazen (compared to that in 2007) (St Pierre et al., 2019). Compared to temperate and tropical lakes, many Arctic lakes are still largely unaffected by anthropogenic stressors such as land-use changes. This means that changes in physical lake properties, such as water temperature and ice phenology, are mainly impacted by climate signals rather than anthropogenic activities. Lake Inari can be considered as an ideal lake for exploring the possible effects of climate change on Arctic aquatic ecosystems since it is a large and deep lake which has a diversity-rich watershed and is located within an area far from human activities. Our study on Lake Inari can improve our knowledge of long-term changes in Arctic lakes' water temperature and their dominant drivers. However, we also note that lake specific factors, such as morphology (Kraemer et al., 2015), trophic state (Read & Rose, 2013), and lake mixing type (Ambrosetti & Barbanti, 1999; Verburg & Hecky, 2009) can modify a lake's response to a warming world, and thus could differ from the results presented here for Lake Inari.

An increase in surface water temperature and no change at depth in Lake Inari resulted in a strengthening of summer stratification. A strengthening of thermal stratification in Lake Inari can result in, among other things, a depletion of dissolved oxygen in the hypolimnion resulting in hypoxic conditions (Klaus et al., 2021; Noori et al., 2018, 2021), with implications for aquatic organisms and biogeochemical processes (Klaus et al., 2021; Wetzel, 2001). These implications can also include greater greenhouse gas production in lake sediments and internal/external cycling of carbon, heavy metals, and nutrients (Aradpour et al., 2020, 2021; Davison et al., 1980; Liikanen et al., 2002). Notably, the annual emission of the potent greenhouse gas methane from Arctic lakes is around 11.9 tones, which was projected to increase by 10.3 and 16.2, respectively, under the representative concentration pathways 2.6 (RCP 2.6) and 8.5 (RCP 8.5) by the end of this century (Tan & Zhuang, 2015). Changes in aquatic food webs and shift in dominant species are other possible impacts of thermal change in the lake, as has previously been observed in other lakes worldwide (Hampton et al., 2008; Lehnherr et al., 2018; O'Beirne et al., 2017; Smol et al., 2005). Because recent studies have suggested an increase in air temperature and ice-off dates (as the primary drivers of changes in Lake Inari's water temperature) in the Arctic (Rinke & Dethloff, 2008; Sharma et al., 2019), the ecological and biogeochemical processes in Arctic lakes will be further altered (Smol & Douglas, 2007).

5. Conclusion

The Arctic has been exposed to the highest rates of air temperature changes (Chylek et al., 2009), which can alter the timing of ice formation and loss in lakes, and subsequently lead to rapid warming of lake surface waters. In this study, we aimed to understand how water temperature responds to climatic and non-climatic drivers in Lake Inari, a Finnish lake located above the Arctic Circle. We found considerable warming at the lake surface but no significant change in bottom water temperature. An increase in the strength of thermal stratification, as a result of diverging temperature trends at the lake's surface and deepwater, may have profound implications for the lake ecosystem. Although this study improves our understanding of the impact of climate change on Arctic lakes, it also highlights important questions regarding the impact of climatic warming on depth-resolved temperature changes and, in turn, the thermal structure of lakes in this climatologically sensitive region.

Conflict of Interest

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

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. The raw data of surface air temperature are publicly available through Data Archive of the Finnish Meteorological Institute https://en.ilmatieteenlaitos.fi. The MAKESENS 1.0 software is freely available in: https://en.ilmatieteenlaitos.fi/makesens. Since the Finnish Environment Institute is in Finnish Language, the related processed data in our study are given in Table S1 in Supporting Information S1.

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