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, 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 globally. Here, using a sixty-year (1961-2020) observational dataset of summer water temperature from Lake Inari (Finland), we investigate changes in the thermal environment of this pristine lake. Our analysis suggests a significant summer warming trend at the lake surface (+0.247 °C decade^{-1}) and a marginal cooling trend (–0.027 °C decade^{-1}) at depth. The contrasting thermal response of surface and bottom water temperatures 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 in which this lake supports. Our work builds on ever-growing literature regarding lake thermal responses to climate change.

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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 (+0.247 °C decade^{-1}), with a marginal cooling trend observed at depth (–0.027 °C decade^{-1}).
- Lake surface temperatures were influenced by the long-term change in summer air temperature as well as the timing of annual ice loss.
- The strength of summer stratification increased at a rate of +0.286 °C decade^{-1}.

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, 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 globally. Here, using a sixty-year (1961-2020) observational dataset of summer water temperature from Lake Inari (Finland), we investigate changes in the thermal environment of this pristine lake. Our analysis suggests a significant summer warming trend at the lake surface (+0.247 °C decade^{-1}) and a marginal cooling trend (–0.027 °C decade^{-1}) at depth. The contrasting thermal response of surface and bottom water temperatures 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 in 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 and Merchant, 2019), with knock-on effects on, among other things, food web dynamics (Blois et al., 2013), the distribution of aquatic organisms (Comte and Olden, 2017; Woolway and Maberly, 2020; Kraemer et al., 2021), and biogeochemical processes (Demars et al., 2016; Kraemer et al., 2017; Noori et al., 2019; Modabberi et al., 2020). 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 (Schneider and Hook, 2010; O'Reilly et al., 2015; Woolway et al., 2020), with deep lakes situated at high-latitude typically experiencing the greatest change (Woolway and Merchant, 2017; Woolway and Maberly, 2020). The rapid warming of high-latitude lakes under climatic change partially reflects the substantial increase in air temperature in polar regions (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 (Schneider et al., 2009; O'Reilly et al., 2015). This suggests an additional source of warming for lakes, such as an increase in incoming solar radiation (Schmid and Köster, 2016) or, indeed, changes in water transparency which can influence the depth at which solar radiation is absorbed within a lake (Persson and Jones, 2008; Read and Rose, 2013; Rose et al., 2016). In some cases, a later 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 and Colman, 2007; Woolway and Merchant, 2017). In addition, some lakes have experienced a decline in near-surface wind speed in recent decades (Woolway et al., 2019; Stetler et al., 2020), 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 and 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 (Read and Rose, 2013; Rose et al., 2016; Pilla et al., 2018; Bartosiewicz et al., 2019). 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 and Barbanti, 1999; Verburg and 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 north temperate lake ecosystems. The magnitude and direction of temperature change in arctic lakes has not been explored as extensively (Lehnherr et al., 2018), particularly below the water surface. To fill the fundamental knowledge-gap, in this study we analyze a sixty-year dataset of the thermal environment of Lake Inari, a pristine lake situated north of the Arctic circle. Here, 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 (Fig. 1). This dimictic lake has a mean and maximum depth of 92 m and 14.3 m, respectively, and a surface area of 1081.9 km^2. It is the second deepest and the third largest lake in Finland. With a less populated basin, Lake Inari is a pristine water body that has only been marginally influenced by anthropogenic disturbances.

2.2 In-situ lake observations

Water temperature 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 Fig. 1) from 1961 to 2020. Water temperatures were measured at weekly (1961-1988) or three times a month (1988-2020) intervals 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). Difference between the lake surface (0 m) and deepwater (40 m) temperature are used as a proxy of lake thermal stability. Temperature data from Lake Inari were combined with summer mean Secchi depth (i.e., as an indicator of water transparency) observed at site A from 1974 to 2020. We also investigate changes in ice phenology and the number of ice-free days, using observations from site B from 1961 to 2020 (Fig. 2). The ice-on date of Lake Inari is reported as the date of permanent freeze-up of the entire observable area from the observation site. The ice-off date 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 (Fig. 2), our analysis of water temperature is restricted to July-September (hereafter referred to as summer) 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 (i) summer mean surface air temperature and (ii) the average air temperature during the cold season, defined as the average temperatures between November and May. Air temperature was measured at the Inari Nellim meteorological station (site C) (Fig. 1), the closest station to water sampling location – site A. Hereafter, we assume that each sampling site is representative of the entire lake.

2.4 Data analysis

In this study, we also investigated 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 summer mean Secchi depth, annual ice-off date, and the summer mean air temperature (July to September). Each of the predictor variables considered have previously been suggested to influence considerably the thermal response of lakes to climate change (Woolway et al., 2020). Lake water and surface air temperature anomalies were used with respect to their long-term mean values to explore the possible linear warming/cooling trends in the datasets. 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 in the SPSS environment. Mann-Kendall (Mann, 1945; Kendall, 1975) and Sen estimator (Sen, 1968) methods were applied to determine, respectively, statistically significant trends in air and water temperature anomalies, ice phenology, 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 estimator methods were ran 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 observations suggest a statistically significant increase in spring (0.37 °C decade^{-1}; *p*–value <0.01) and summer (0.27 °C decade^{-1}; *p*–value <0.01) air temperatures in Lake Inari, as well as rapid warming of air temperature during the cold-season (0.48 °C decade^{-1}; *p*–value <0.001). Within this period of long-term change, we also calculated corresponnding variations in ice phenology. Our observations suggest a long-term change in the date of ice-on (+1.2 days decade^{-1}, *p*–value >0.1), ice-off (–1.8 days decade^{-1}, *p*–value ≤0.01), and in the duration of the ice-free period (3.0 days decade^{-1}, *p*–value ≤0.05) (Fig. 3). In-line with observed changes in air temperature and lake ice conditions, our observations also suggested a significant warming of lake surface water temperature during the open-water season (Fig. 4). The observed increase in summer lake surface water temperature (0.25 °C decade^{-1}; *p*–value ≤0.05) is comparable to the magnitude of long-term change in summer air temperatures (0.27 °C decade^{-1}; *p*–value <0.05).

Below the water surface, our observations suggest a somewhat muted lake thermal responses to climate change, particularly compared to the near-surface temperatures. Most notably, our data suggests that the magnitude of long-term change in water temperature decreases with increasing depth (Figs. 4 and 5). Moreover, our data suggests that the statistical significance of water temperature trends decreases with increasing depth, with lake temperatures at 0, 5, 10, 15, and 20 m changing at statistically significant rates, and changes in deep-water temperature (30 and 40 m) being non-significant (*p*–value >0.1) (Fig. 4). In addition, our data suggests that the direction of change in deep-water temperature is opposite to that observed at the lake surface, and likewise in the atmosphere during summer. Interestingly, our data also suggests higher warming rates at depths of 5 m and 10 m, compared to the lake surface (Figs. 4 and 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 reversing mercury/digital thermometer data). A one-way ANOVA suggested that the difference between the warming rates calculated at the lake surface and at a depth of 5 m were statistically significant (*p*–value <0.05), whereas those at 10 m were not (*p*–value >0.05). Difference between the observed surface and bottom temperatures in Lake Inari are used in this study as a proxy for the strength of thermal stratification. Using these observations, our analysis suggests a substantial and statistically significant long-term change in lake thermal stability (Fig. 6a), which has increased at a rate of 0.286 °C decade^{-1} (*p*–value ≤0.05).

To offer insights about the dominant drivers of change in lake surface and bottom water temperature in Lake Inari, we investigated the influence of three predictor variables that we hypothesized might have an effect (Fig. 7). Our investigation showed that the most important driver of surface water temperature was the summer air temperature (SAT.Su) with a strong positive correlation coefficient of 76.9%. Also important was the date of ice-off (I.Of.D; correlation coefficient = –28.4%) (Fig. 7), with warmer summer water temperature often coinciding with an earlier break-up of ice cover. No statistically significant correlation was observed between the lake surface water temperature and the summer mean Secchi depth (*p*–value >0.1), which decreased during the study period at a rate of –0.192 m decade^{-1} (*p*–value ≤0.05) (Fig. 6b). With respect to deepwater temperatures, the only statistically significant driver, of the variables tested, was the date of ice-off (I.Of.D; correlation coefficient = –21.9%), with earlier ice break-up coinciding with warmer bottom temperatures. Our data also suggested no significant relationship between the summer deep-water temperature and summer air temperature (SAT.Su; *p*–value >0.1) (Fig. 7).

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 (Tuomenvirta, 2004; Räisänen, 2019; Ruosteenoja and Räisänen, 2021) with a maximum warming during the cold-season (Tuomenvirta, 2004). However, warming rate in mean surface air temperature in spring is a bit less than that of in summer. This is resulted by the June's hiatus condition in the air temperature reported in Finland (Ruosteenoja and Räisänen, 2021). We further calculated the change in monthly mean air temperature in June and found a nonsignificant neglegible change around 0.05 (*p*–value >0.1), veryfing the state of June's hiatus in the location of Lake Inari duirng the last decades. In response to the rapid warming of near-surface air temperature, 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 (Korhonen, 2006; Benson et al., 2012; Sharma et al., 2019; Sharma et al., 2021). For example, the warming rate observed in air temperature near Lake Inari very likely contributed to the later onset (+1.2 days decade^{-1}) and earlier break-up of of ice cover (-1.8 days decade^{-1}), as well as an increase in the number of annual ice-free days (+3.0 days decade^{-1}). However, our analysis suggested no statistically significant trend in the timing of ice formation (*p*–value >0.1). This could be due to regional-scale changes in other climatic variables that contribute to the lake surface energy budget (e.g., wind speed, solar radiation), which can have a considerable influence on ice phenology. For example, changes in near-surface wind speed can act to delay or accelerate ice formation in many lakes, depending on its directional change (Kirillin et al., 2012; Magee and Wu, 2017). While we did not have observational data to investigate the influence of wind speed on the timing of ice formation in Lake Inari, we hypothesise that a decline in wind speed during winter could have contributed to the somewhat muted long-term trend in ice-on (Magee and Wu, 2017).

Our analysis of summer water temperatures in Lake Inari suggested that the lake surface has warmed at a rate of 0.25 °C decade^{-1} (*p*–value ≤0.01) from 1961 to 2020. This rate of change is comparable to that observed in local summer air temperature during the same period (0.27 °C; *p*–value <0.01). 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 variables remain unchanged (Schmid et al., 2014). Our observations also align with 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. In the deeper regions of Lake Inari, our analysis suggested that water temperatures are cooling at a rate of –0.03 °C decade^{-1} (*p*–value >0.1). A cooling at depth in Lake Inari is opposite to that suggested for many other lakes at local to regional scales, which have primarily reported a warming trend (Ambrosetti and Barbanti, 1999; Vollmer et al., 2005; Anderson et al., 2021). 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 observation of a contrasting directional change in surface and bottom water temperature, 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 increased at a rate 0.29 °C decade^{-1} during the study period. A strengthening of summer stratification is an expected lake thermal response to climate change (Butcher et al., 2015; Kraemer et al., 2015; Oleksy and 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. Our results suggested that the most important drivers of change in lake surface temperature was the mean summer air temperature followed by the date of ice-off, which is in agreement with previous studies that have investigated lake thermal responses to climate change (Austin and Colman, 2007; O'Reilly et al., 2015). Regarding the change in bottom water temperature, our analysis suggested that the date of ice break-up was the only statistically significant driver. An earlier break-up of ice cover results in a lengthening of the open-water season and, in turn, the period of time in which surface heating takes place, and ultimately leading to a rapid increase of summer lake surface temperature. Water clarity was suggested to have a minimal influence on surface and bottom water temperatures, despite experiencing a long-term change.

Our observations suggested that rate of lake warming at a depth of 5 m exceeded that observed at the lake surface (i.e., at 0 m). Given a 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 ocean (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 explain a greater rate of warming at this depth. However, the question of a deepening of the upper mixed layer in both the oceans and lakes is debated, with some modeling-based studies suggesting that the upper mixed layer should become shallower with climatic warming (Behrenfeld et al., 2006; Polovina et al., 2008; Boyce et al., 2010). Other factors that can explain more warming rate in the depth of 5 m than the lake surface is the increase in wind speed and inflows, resulting in deeper mixed layer (Zhang et al., 2014; Woolway et al., 2017), but were not explored in this study due to the lack of available long-term observational data.

The contrasting thermal response of surface and bottom water temperature in Lake Inari resulted in a strengthening of summer stratification. A strengthening of thermal stratification can result in, among other things, a depletion of dissolved oxygen in the hypolimnion resulting in hypoxic conditions (Noori et al., 2018 and 2021), with implications for aquatic organisms and biogeochemical processes in the lake. These implications can also include greater greenhouse gas production in lake sediments, notably the potent greenhouse gas methane, and internal cycling of nutrients. 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; O'Beirne et al., 2017).

5 Conclusion

Northern Europe is known as a hotspot with respect to climate change and its consequence on lake water temperature. 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 warming and marginally cooling rates, respectively, in the lake surface and bottom waters that both impacted by the date of ice-off during the study period. The strength of thermal stratification that largely induced by divergent between the warming and cooling rates observed in the lake surface and deepwater, respectively, can result in profound implications for the lake water chemistry and shift in the lake's biota and health. Although this study improves our understanding about the impact of climate change on the arctic lakes, it also opens an important question about the impact of warming environment on deepening or shoaling upper mix layer in arctic lakes.

Competing Interest Statement

The authors report that they have no conflicts of interest.

Author Contributions

R.N.: Data management, methodology, interpretation, formal analysis, software, visualization, and writing-original draft. **R.I.W.**: Supervision, methodology, interpretation, writing-review and editing. **M.S.**: Visualization and writing-review and editing. **P.M.**: Data preparation, interpretation and writing-review and editing. **B.K.**: Funding acquisition and writing-review and editing.

Data Availability

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

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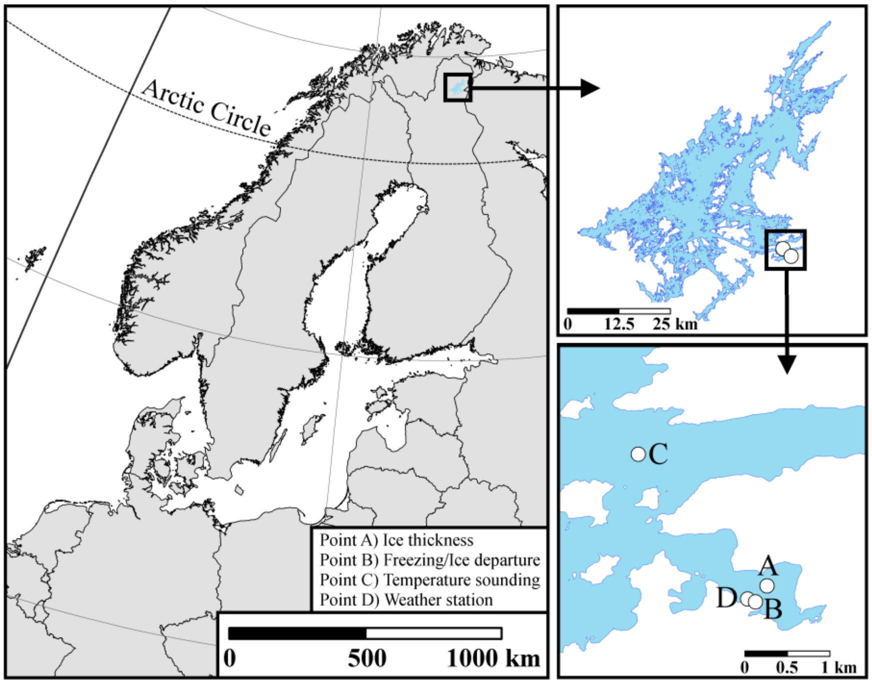

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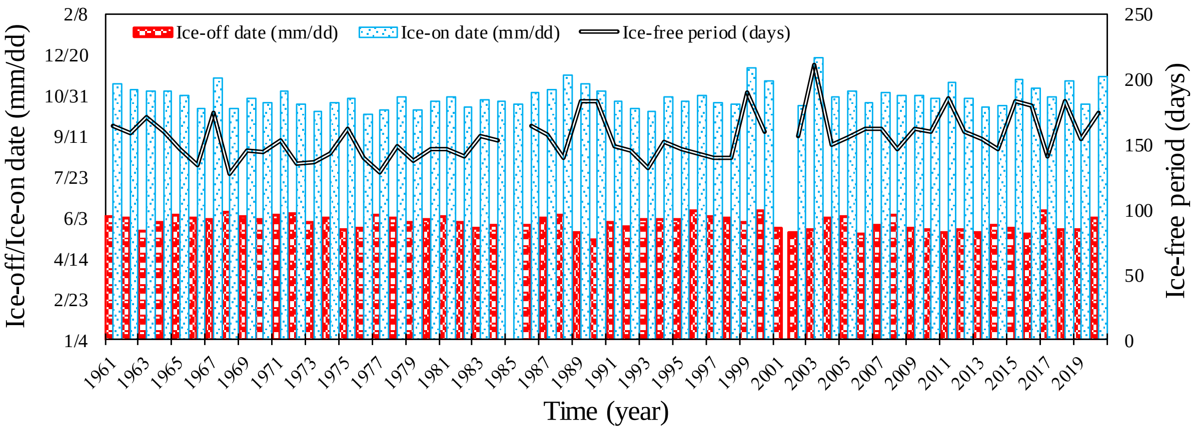

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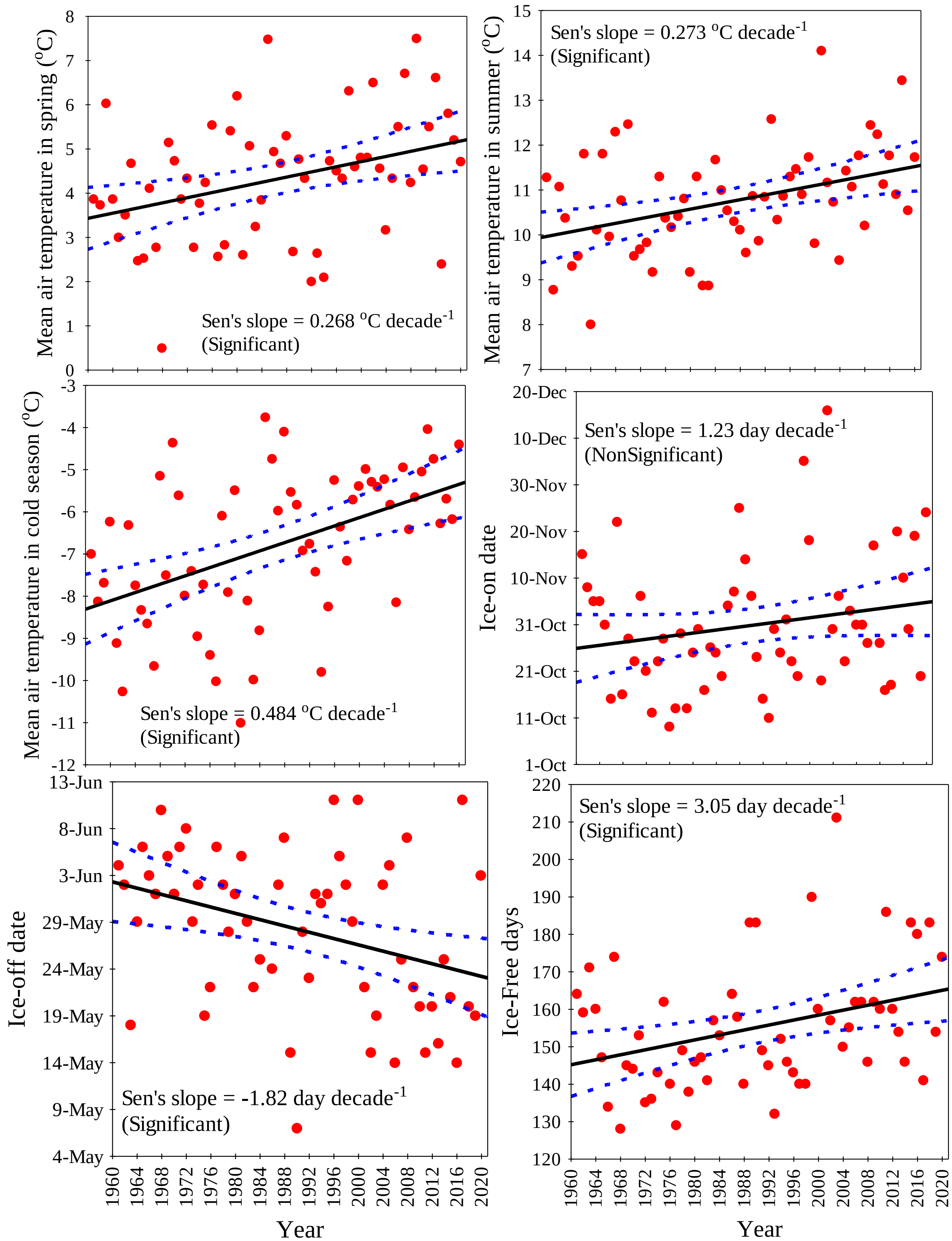

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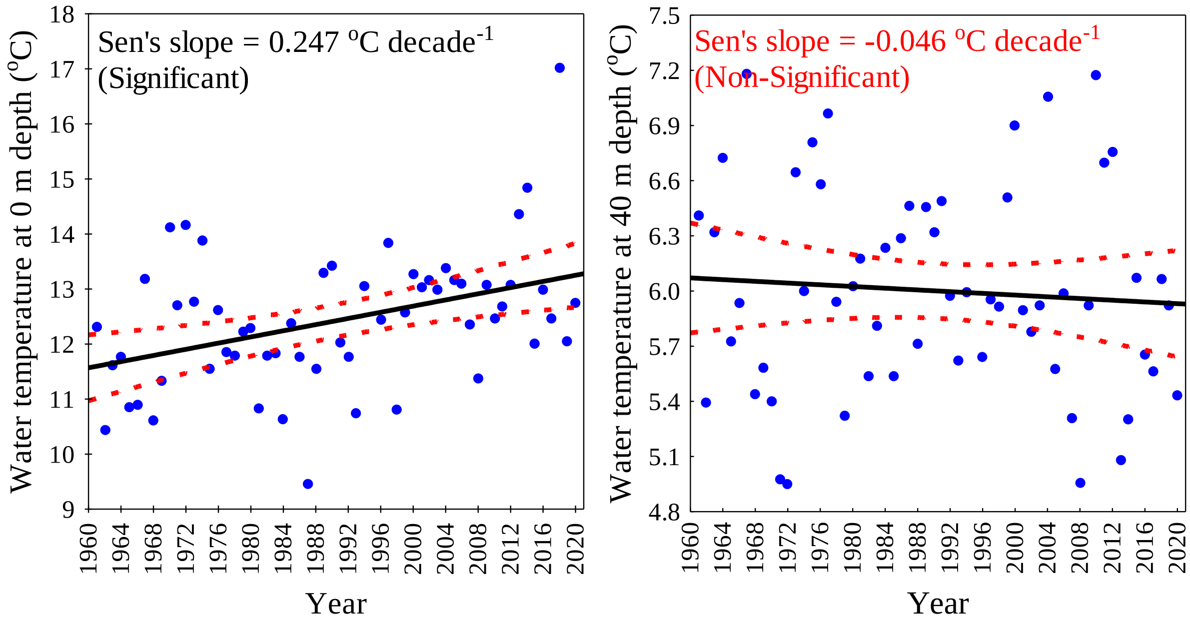

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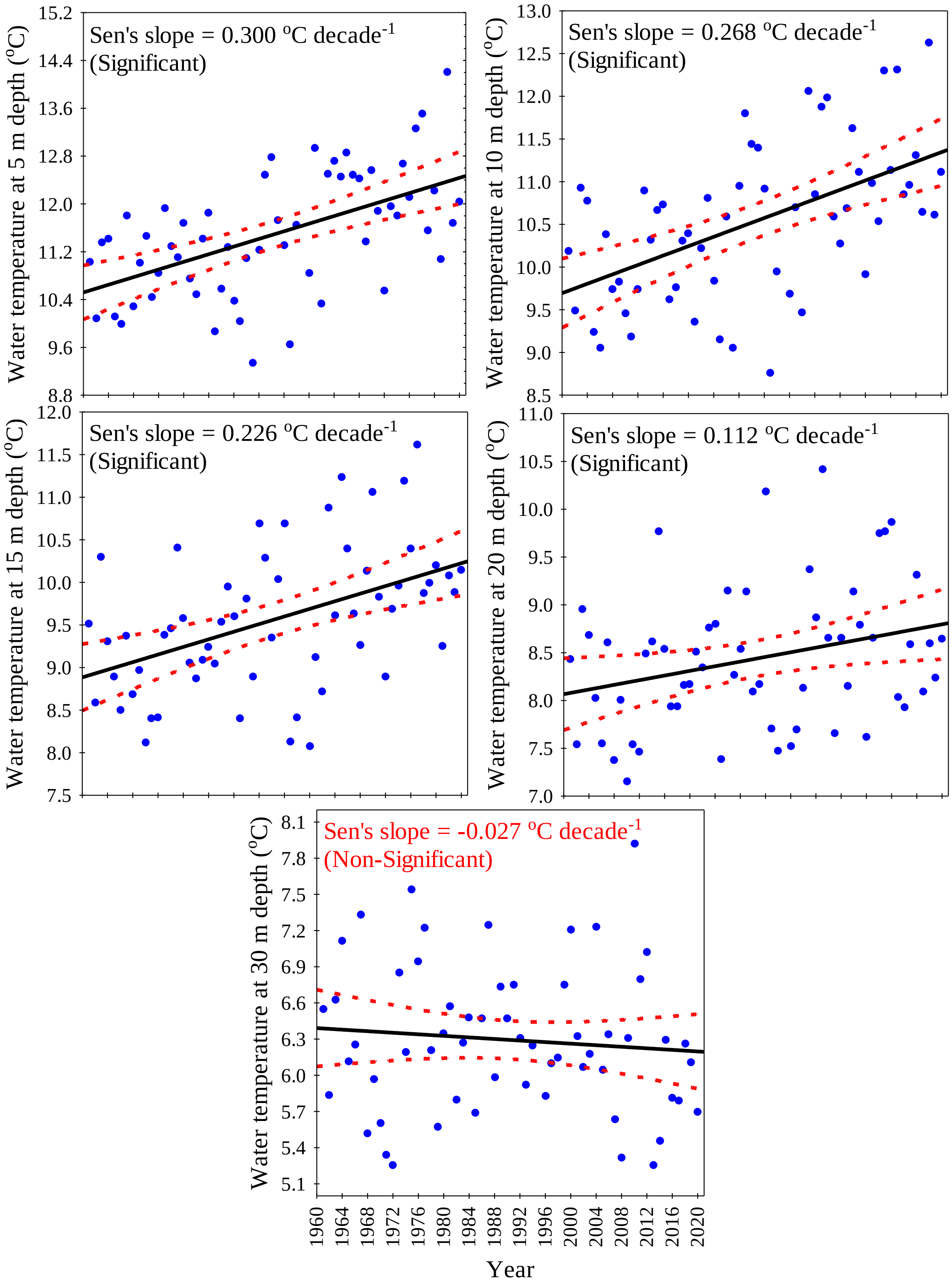

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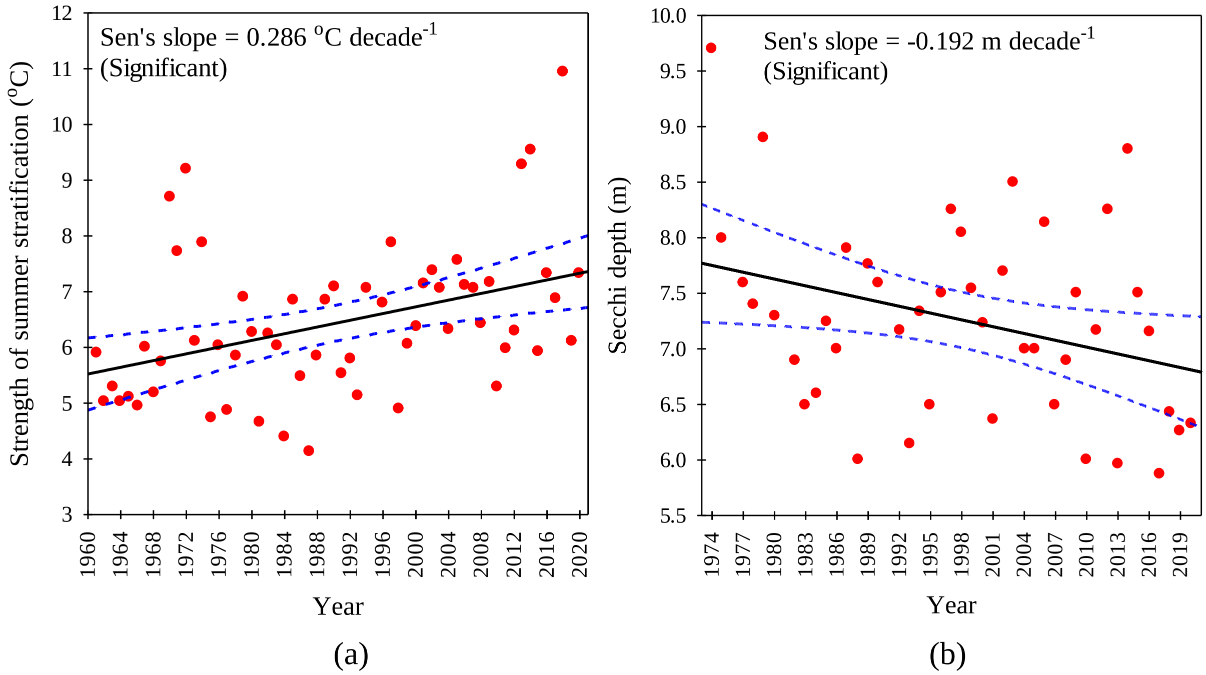

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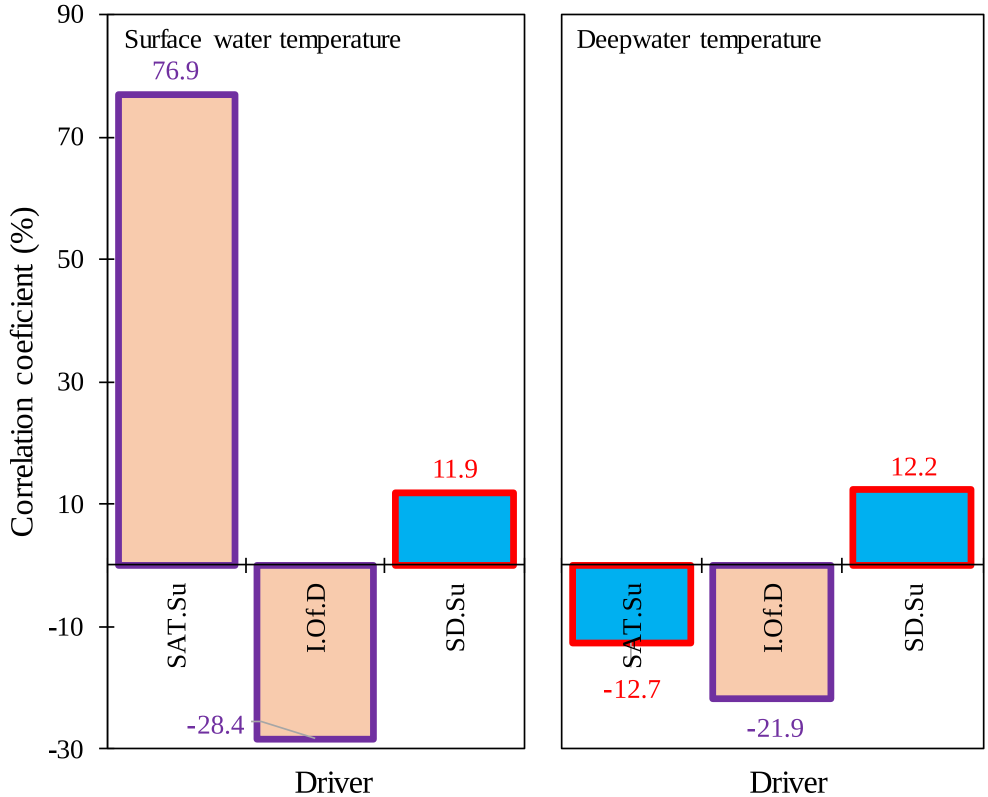

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