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Research Article

Keywords: Climate change, Limnology, Warming trend, Generalized additive model

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

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Abstract

Depth-resolved water temperature data on the thermal environment of lakes are often hindered by sparse temporal frequency, limited depth resolution, or short duration that create many challenges for long-term analysis. Where high frequency and depth-resolved data exist, they can provide a wealth of knowledge about how lakes are responding to a changing climate. In this study, we analyzed 302 profiles of summer mean water temperature (July to September), which includes 6756 unique observations, from Lake Konnevesi (Finland) and investigated changes in lake surface and deep-water temperature from 1984 to 2021. Statistical analysis of this dataset suggests a substantial warming of lake surface water temperature ($0.41\text{ }^{\circ}\text{C decade}^{-1}$) but no significant change in the deepest layer ($0.00\text{ }^{\circ}\text{C decade}^{-1}$). Our analysis also suggested the inter-annual variability in lake surface temperature correlated significantly with the upward trends of summer mean air temperature and solar radiation, but suggested no significant effect of observed changes in ice break-up dates or changes in near-surface wind speed. None of the investigated predictors correlated with the change in deep-water temperature. Due to the variable response of lake surface and bottom water temperature to climate change in this high-latitude lake, our data suggest a substantial increase in lake thermal stability. Our study supports the growing literature on lake thermal responses to climate change, and illustrates the unique contrast of climate change impacts at the surface and at depth in lake ecosystems, with deep waters acting as a potential thermal refuge to aquatic organisms within a warming world.

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

Introduction

Climate change has resulted in several impacts on the Earth system. Particularly, observations show a considerable warming of different components of the hydrological cycle, such as lakes, with notable implications for global biodiversity (Stachowicz et al. 2002; Cantin et al. 2010; O'Reilly et al. 2015; Behrenfeld et al. 2016; Woolway and Merchant 2019; Jane et al. 2021). The severity of warming in lake ecosystems during the 20th and 21st century is undeniable (O'Reilly et al. 2015; Anderson et al. 2021), and has resulted in several implications for the aquatic environment. Specifically, changes to a number of physical and biogeochemical processes in lakes, which are sensitive to temperature variations, have been widely reported due to climate change. These include changes in mixing and stratification patterns (Woolway and Merchant 2019; Stetler et al. 2021), an increased severity of algal blooms (Vilhena et al. 2010; Modabberi et al. 2020) and thus a deterioration of water quality, and the production of potent greenhouse gases in lake sediments (Adrian et al. 2009; Marotta et al. 2014; Kraemer et al. 2015) with knock-on impacts on the global carbon budget. Moreover, the warming observed at the lake surface can contribute to greater lake evaporation (Woolway et al. 2020), which when combined with other anthropogenic stressors (e.g., water abstraction for irrigation) can have dramatic consequences for the availability of surface freshwater (Gao et al. 2011; AghaKouchak et al. 2015; Ravilious 2016; Wurtsbaugh et al. 2017; Tal 2019).

A wide range of climatic drivers, including air temperature, solar radiation, and wind speed can influence lake water temperature (O'Reilly et al. 2015; Schmid and Köster 2016; Woolway et al. 2019; Noori et al. 2021). Among these climatic drivers, air temperature is often considered the most important. Air temperature is not only involved causally in the emission of long-wave radiation from the atmosphere and in the exchange of sensible and latent heat across

the lake surface, but is also strongly correlated with other meteorological variables that influence lake surface water temperature. Thus, as global air temperatures rise, lakes typically, but not always, follow the same direction (O'Reilly et al. 2015). Global air temperatures are warming most dramatically at high latitudes (Alexander et al. 2013). In turn, the surface temperature of lakes in this region are also warming at rapid rates, often in excess of the global average (O'Reilly et al. 2015; Woolway and Merchant 2017). However, lake water temperature is also influenced by a wide range of morphometric drivers (such as lake depth and surface area) as well as the timing of seasonal ice cover, resulting in the interaction between air and water temperature being considerably different across lakes. This could lead to a large variation in the magnitude and even the direction of change in lake temperature (Kraemer et al. 2015; O'Reilly et al. 2015; Pilla et al. 2020).

In this study, we investigate the observed changes in summer water temperature in a boreal lake (Lake Konnevesi) using 38 years of water temperature profiles. In addition, we perform a multivariate statistical analysis to better understand the impact of atmospheric (i.e., air temperature, solar radiation, wind speed) and lake-specific drivers (i.e., ice break-up date) on observed changes in lake surface and deep-water temperatures. Our observations suggest a strong warming at the lake surface, whilst the water temperature at depth remained unchanged, which could have implications for the thermal structure and ecosystem functioning of the lake.

Materials and Methods

Study area

Lake Konnevesi is a dimictic (i.e., mixes vertically twice per year) lake situated in central Finland (62° 38' N and 26° 24' E) at a surface elevation of 95 m above sea level (Fig. 1). This medium-

sized lake has a surface area of 187 km², and an average and maximum depth of 57 m and 11 m, respectively.

Place [Figure 1](#) Here

Konnevesi experiences direct and inverse thermal stratification during the warm and cold months, respectively, with an upper mixed layer that commonly reaches up to 20 m below the lake surface during summer. Mean summer water color at the surface of Lake Konnevesi is typically low (about 6 mg/L Pt). Given mean summer chlorophyll-*a* and total phosphorus about 4.2 µg/L and 6 µg/L at uppermost 1 m layer, the trophic state in this lake varies from mainly oligotrophic to sometimes mesotrophic (Kuha et al. [2016](#)).

In-situ lake observations

Water temperature profiles in Lake Konnevesi have been routinely measured since 1984 using a digital thermometer by the Finnish Environment Institute at sampling location A shown in [Fig. 1](#). Water temperature is sampled consistently with a vertical interval of 1 m from the near-surface to a depth of 20 m and thereafter at 2 m intervals to the lake bottom. In this study, we used water temperature profiles measured at the lake surface to a depth of 40 m (hereafter referred to as deep-water) from 1984 to 2021. As Lake Konnevesi is typically ice-covered from late-autumn to mid-spring, we investigated water temperature profiles only during the open-water summer season (July-September) i.e., when the lake is ice-free. Our dataset consists of 302 profiles of water temperature measured during summer, and includes 6756 unique observations. Change in ice break-up dates measured at site B ([Fig. 1](#)) is also explored in this study from 1984 to 2021. The

ice break-up date is consistently reported as the date when ice is no longer observed from the observation site.

Meteorological data

In our study, the changes in spring and summer mean air temperature and summer mean solar radiation and near-surface wind speed were investigated. The spring mean air temperature was investigated and compared to changes in the ice break-up date. We also investigated the influence of summer mean air temperature on summer water temperatures during the study period. As no meteorological observations with long-term data is available near the lake, here we investigated air temperatures (1984-2021) measured at the Vesanto kirkonkylä meteorological station (Point C; [Fig. 1](#)), situated approximately 30 km from the lake, as a proxy for over-lake atmospheric conditions. We also investigated the influence of other meteorological variables, including summer mean solar radiation and near-surface wind speed on the observed change in lake temperature. Time series data of these two variables were obtained from the ERA5-Land reanalysis product (9 km² resolution) at the location of Lake Konnevesi from 1984 to 2021 ([Muñoz Sabater 2019](#)).

Data analysis

In this study, we explored the potential influence of four predictor variables on the inter-annual variability in summer mean water temperature in Lake Konnevesi, using a generalized additive model (GAM). The predictor variables tested include the summer mean air temperature (SAT), solar radiation (SR), near-surface wind speed (WS), and the ice break-up date (IBD), which have all been hypothesized previously to influence the thermal response of lakes to climate change ([Woolway et al. 2020](#)). Here, the GAM ([Eq. 1](#)) was performed using the “mgcv” package in *R* with a gamma-error distribution and the logarithm-link function f :

$$\tau_i = f(\mu_i)^{-1} = f(\varepsilon_0 + g_1(\text{SAT}_i) + g_2(\text{SR}_i) + g_3(\text{WS}_i) + g_4(\text{IBD}_i))^{-1} \quad (1)$$

where, τ_i = the expectation of response variable (here, the summer mean water temperature at the lake surface and bottom) for the i^{th} data, μ_i = the linear predictor consists of ε_0 (a constant term) and smooth functions g_l ($l = 1$ to 4).

We used the penalized cubic regression spline to optimize the smooth functions g_l since it decreases computational costs and prevents overfitting in the model (Wood and Augustin 2002). The sequence of the analysis was guided by the protocol of Zuur et al. (2009). The residuals from each GAM were first checked for any breach of assumptions. Detailed information on the method used are given by Wood and Augustin (2002) and Wood (2013).

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

Results and Discussion

Our data suggests a substantial warming of spring ($0.47 \text{ }^\circ\text{C}$, decade^{-1}) and summer ($0.60 \text{ }^\circ\text{C}$, decade^{-1}) air temperatures in the region of Lake Konnevesi from 1984 to 2021 (Figs. 2a and 2b). These trends are consistent with previous studies that have reported a significant increase in surface air temperature in Finland in recent decades (Tuomenvirta 2004; Räisänen 2019; Ruosteenoja and Räisänen 2021). An increasing trend is also calculated in summer average solar radiation ($3.1 \text{ W m}^{-2} \text{ decade}^{-1}$) whilst the wind speed approximately remains unchanged ($0.01 \text{ m s}^{-1} \text{ decade}^{-1}$) (Figs. 2c and 2d). As a result of a significant increase in spring and summer air temperature, an earlier

ice departure date is observed in Lake Konnevesi with a statistically significant negative rate of -3.5 days decade⁻¹ (Fig. 3a). This finding is in-line with our understanding about the rapid change in ice phenology of boreal lakes as reported by others (Korhonen 2006; Benson et al. 2012; Sharma et al. 2019; Sharma et al. 2021).

Place Figure 2 Here

As a result of the observed increase in summer air temperature and solar radiation, as well as an earlier ice departure date, the surface water temperature of Lake Konnevesi has warmed rapidly in recent decades, at a rate of 0.41 °C decade⁻¹ (Fig. 3b). This rate of change is greater than the global average summer lake surface temperature increase of 0.34 °C decade⁻¹ (1985-2009) reported by O'Reilly et al. (2015). In fact, an earlier ice departure date can increase the number of ice-free days in a given year, which can subsequently influence surface water temperature trends in lakes, due primarily to a lengthening of the warming season. Our observations suggest that the rate of change in lake surface water temperature is approximately 0.87 times the increase in local air temperature. The observed change in surface water temperature thus agrees with our expectations, particularly according to previous predictions which suggest that lake surface temperatures should warm by 75–90% of the increase in air temperature (Schmid et al. 2014). Our observations also align with the results of Woolway et al. (2017) which investigated the increase in lake surface temperature of central European lakes in recent decades.

Our statistical analysis using a GAM suggests that the most important predictors of the long-term change in summer surface water temperature was the summer mean air temperature (SAT) with the largest effective degrees of freedom (EDF) (i.e., 1.32) and F -statistic (i.e., 23.2)

values (Table 1; p -value <0.000), followed by summer mean solar radiation (SR) with the EDF = 1.16 and F -statistic = 8.3 (Table 1; p -value <0.006). The impact of summer mean air temperature on the lake surface water temperature ($R = 0.74$) is shown in Fig. 4a. The ice break-up date (Table 1; p -value <0.2) and the summer mean wind speed (WS) (Table 1; p -value <0.2) did not have a statistically significant influence the lake surface temperature according to our analysis. These findings are in-line with the dominant drivers on the surface temperature in the Lake Zurich, where around 60% and 40% of the summer lake surface warming were induced by air temperature and solar radiation, respectively (Schmid and Köster 2016). The dominant impact of air temperature and solar radiation on the lake surface warming have also reported in local, regional, and global scales (Fink 2014; O'Reilly et al. 2015; Schmid and Köster 2016; Woolway et al. 2020; Shinohara et al. 2021a).

Place Table 1 and Figure 3 Here

With respect to deep-water temperatures in Lake Konnevesi, our observations suggest minimal change from 1984 to 2021 ($0.00\text{ }^{\circ}\text{C}$, decade^{-1} ; p -value >0.1), notwithstanding considerable inter-annual variability (Fig. 3c). Whilst some previous studies have reported significant changes in bottom water temperature, including a warming and cooling trend across lake regions (Vollmer et al. 2005; Richardson et al. 2017), our observations largely align with global studies which have suggested that deep-water temperatures have experienced little seasonal-average change in recent decades (Pilla et al. 2020). Our statistical analysis suggests that deep-water temperature in Lake Konnevesi is not significantly impacted by the drivers investigated in our study (Table 1; p -value >0.1). Regardless the significance level of the statistical analysis, the

ice break-up date (IDB) is the most important driver of the lake deep-water temperature (LDWT) (Table 1). The IDB relates to the LDWT with a correlation coefficient of -0.21 as shown in Fig. 4b. The earlier ice break-up date, the warmer deep-water temperatures. However, our results suggest no changes in the lake deep-water temperature although the lake has experienced a significant change in ice break-up date. This could be explained by the impact of non-climatic drivers (e.g., water clarity and lake morphology) on the lake deep-water temperature. Although we did not investigate the impact of non-climatic drivers on the lake water temperature, no trend in the lake deep-water temperature suggests the net impact of climate and non-climatic drivers on the deep-water temperature trend is negligible in Lake Konnevesi.

Place [Figure 4](#) Here

The difference in observed warming between the surface and bottom waters of Lake Konnevesi, has resulted in a strengthening of thermal stratification (Fig. 3d). Indeed, our long-term time series suggests that the strength of thermal stratification has increased at a rate of 0.41 °C decade⁻¹. A strengthening of thermal stratification will have implications for lake ecology (Noori et al. 2018; Hampton et al. 2008; O’Beirne et al. 2017; Pilla et al. 2020). For example, it reduces the severity of mixing in lakes and limits transformation of nutrients and dissolved oxygen between surface and deep layers. This mechanism could impact the water quality, aquatic species populations, and food webs in global lakes (Woodward et al. 2010), especially in (sub)arctic lakes. Reduced dissolved oxygen in lake bottom further induces the emission of greenhouse gases (Woszczyk and Schubert 2021) and can increase nutrient release from lake sediments (Noori et al. 2021) that can likely result in eutrophication during the fall overturn (Shinohara et al. 2021b).

Conclusions

As air temperature in (sub)arctic regions are increasing at alarming rates, high-latitude lakes are also expected to experience substantial warming with considerable implications for lake ecosystems. However, the interaction between air temperature and lake water temperature may differ across (sub)arctic lakes. Using a long-term water temperature data, we investigated the changes in water temperature in Lake Konnevesi, a boreal lake in Finland. We found a progressive deviation between the lake surface and bottom temperatures from 1984-2021, resulted by a strong warming rate in the lake surface impacted by the air temperature and solar radiation, and a null rate in deep-water temperature. Given the projected warming trends in air temperature over Finland, further separation of the bottom and surface layers in Lake Konnevesi during summer is expected. This could strengthen lake thermal stratification, leading to numerous consequences for the aquatic life (e.g., change in species, communities, and food webs) and positive functions of the lake (e.g., fishery and recreational activities) in the future.

Author Contributions

Conceptualization, R.N.; methodology, R.N., R.I.W.; software, R.N., C.J., S.M.B.; validation, R.N., R.I.W., and P.M.; formal analysis, R.N.; investigation, R.N. and R.I.W.; resources, R.N.; data curation, R.N.; writing—original draft preparation, R.N.; writing—review and editing, R.I.W., M.M., and P.M.; visualization, R.N., M.M., and C.J.; supervision, R.I.W.; project administration, R.N. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Water temperature data are publicly available through <https://wwwp2.ymparisto.fi/scripts/kirjaudu.asp>. Surface air temperature data are publicly

available through <https://en.ilmatieteenlaitos.fi>. The MAKESENS 1.0 software is available through <https://en.ilmatieteenlaitos.fi/makesens>.

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Conflicts of Interest

The authors declare no conflict of interest.

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Table 1. Summary output from the fitted generalized additive model (GAM), as shown in Eq. (1). Summary of the GAM used to describe the impact of summer mean air temperature (SAT), summer mean solar radiation (SR), summer mean near-surface wind speed (WS), and ice break-up date (IBD) on the summer mean lake surface and deep-water temperatures in the Lake Konnevesi (1984-2021). RDF is the reference degrees of freedom.

Dependent variable	Smooth function (g_i)	RDF	F -statistic	p -value
Lake surface water temperature	SAT	1.32	23.20	<0.000
	SR	1.16	8.30	<0.006
	WS	1.00	1.79	<0.190
	IBD	1.00	1.71	<0.201
Lake deep-water temperature	SAT	1.00	0.34	<0.564
	SR	1.00	0.15	<0.697
	WS	1.00	0.11	<0.747
	IBD	1.00	2.06	<0.160

Figure Captions

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

Figure 2. Magnitude and direction of change in (a) spring mean air temperature ($^{\circ}\text{C}$), (b) summer mean air temperature ($^{\circ}\text{C}$), (c) anomalies of summer mean solar radiation (W m^{-2}), and (d) near-surface wind speed (m s^{-1}) in Lake Konnevesi from 1984 to 2021.

Figure 3. Magnitude and direction of change in (a) ice break-up date (IBD) (dd-mm), (b) summer mean water temperature ($^{\circ}\text{C}$) at the surface layer, (c) summer mean water temperature ($^{\circ}\text{C}$) at the bottom layer, and (d) the difference in observed warming between the surface and bottom waters in Lake Konnevesi from 1984 to 2021.

Figure 4. Relationship between (a) the lake surface water temperature (LSWT) and summer mean air temperature (SAT), and (the lake deep-water temperature (LDWT) and the ice break-up date (IBD) in the Lake Konnevesi (1984-2021).

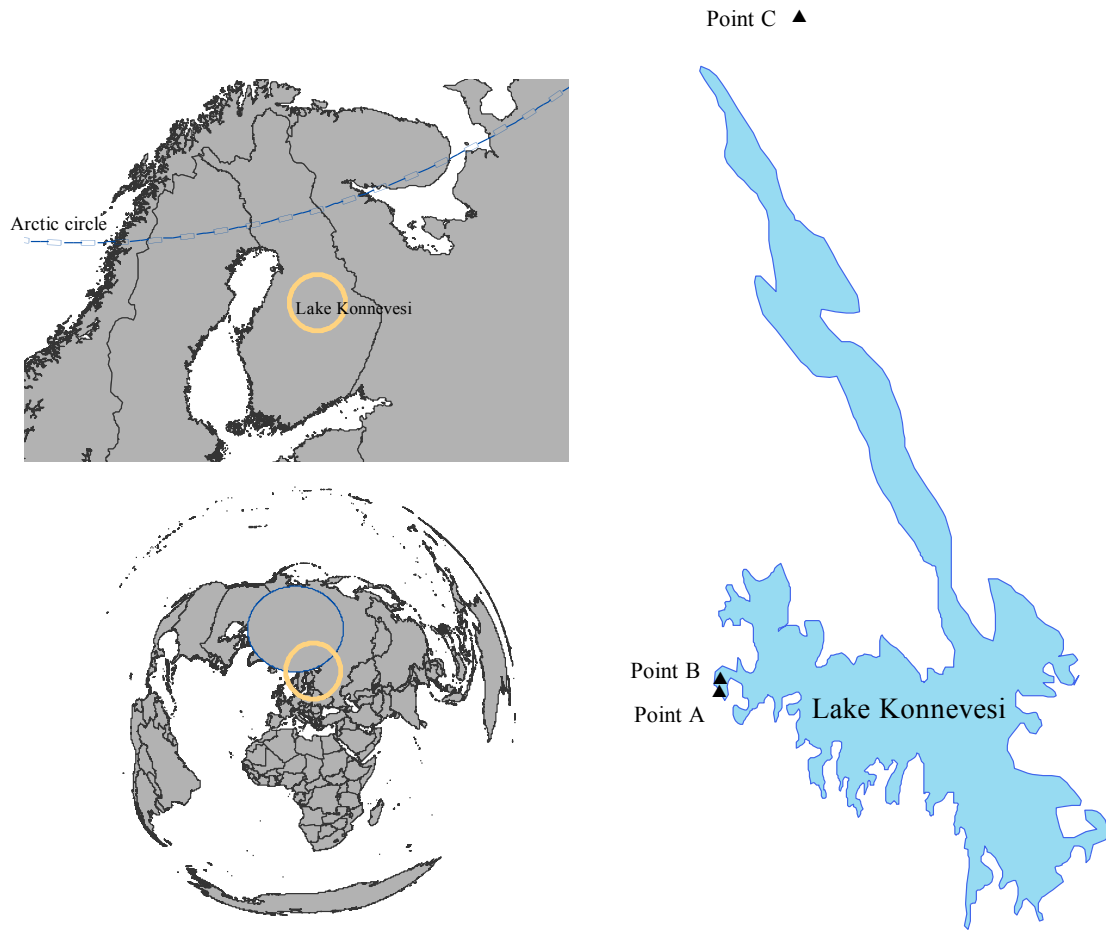


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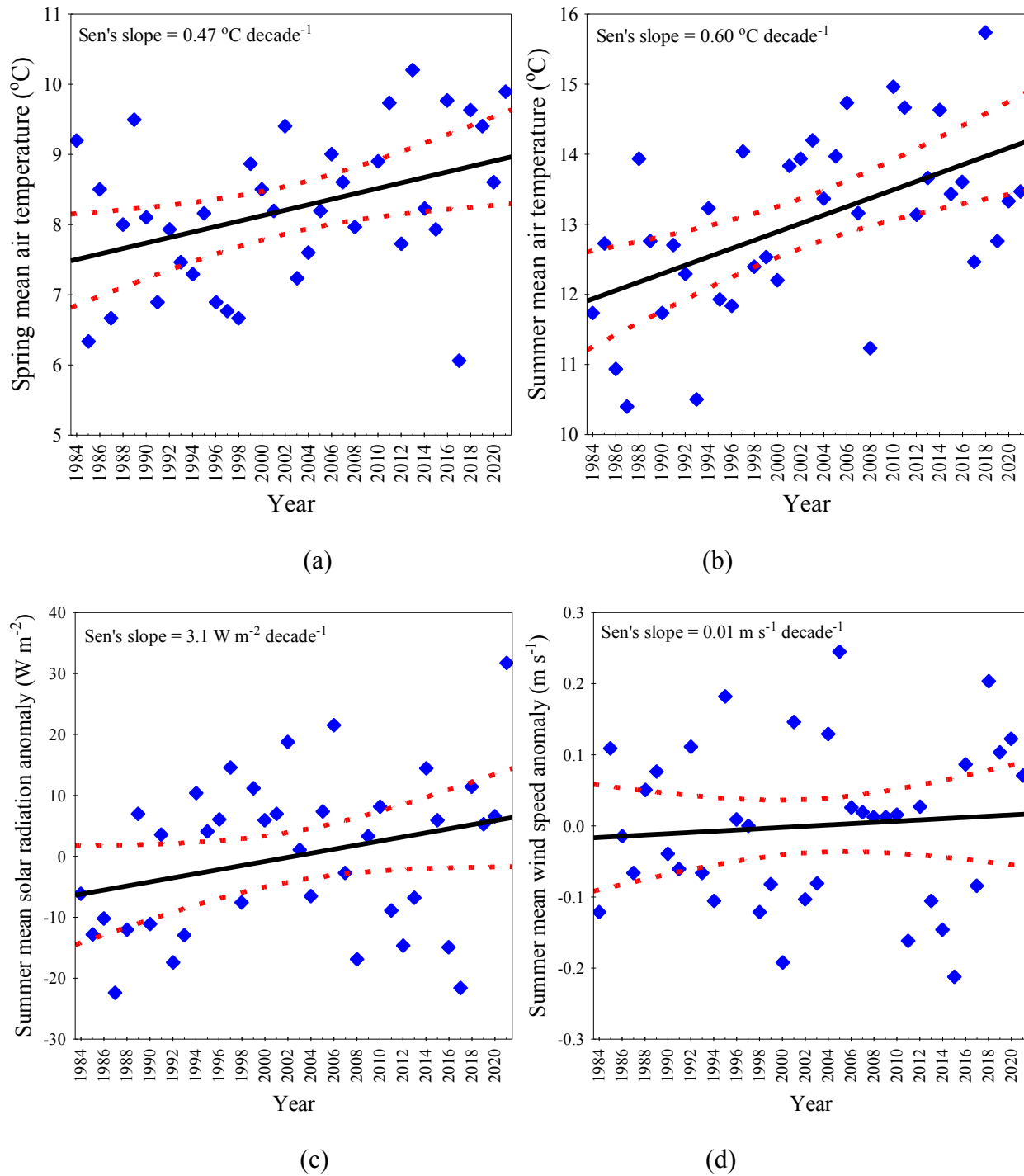


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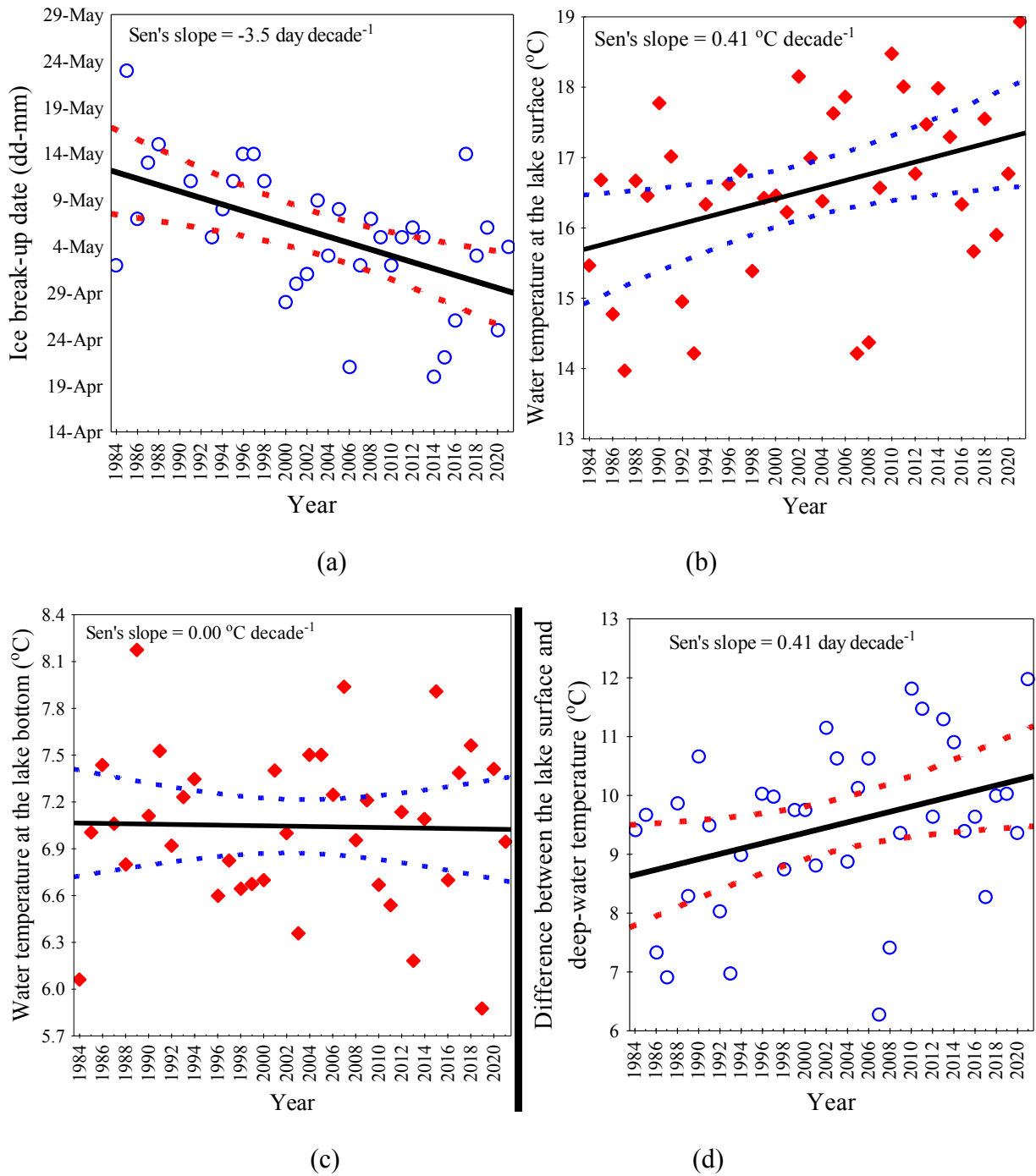


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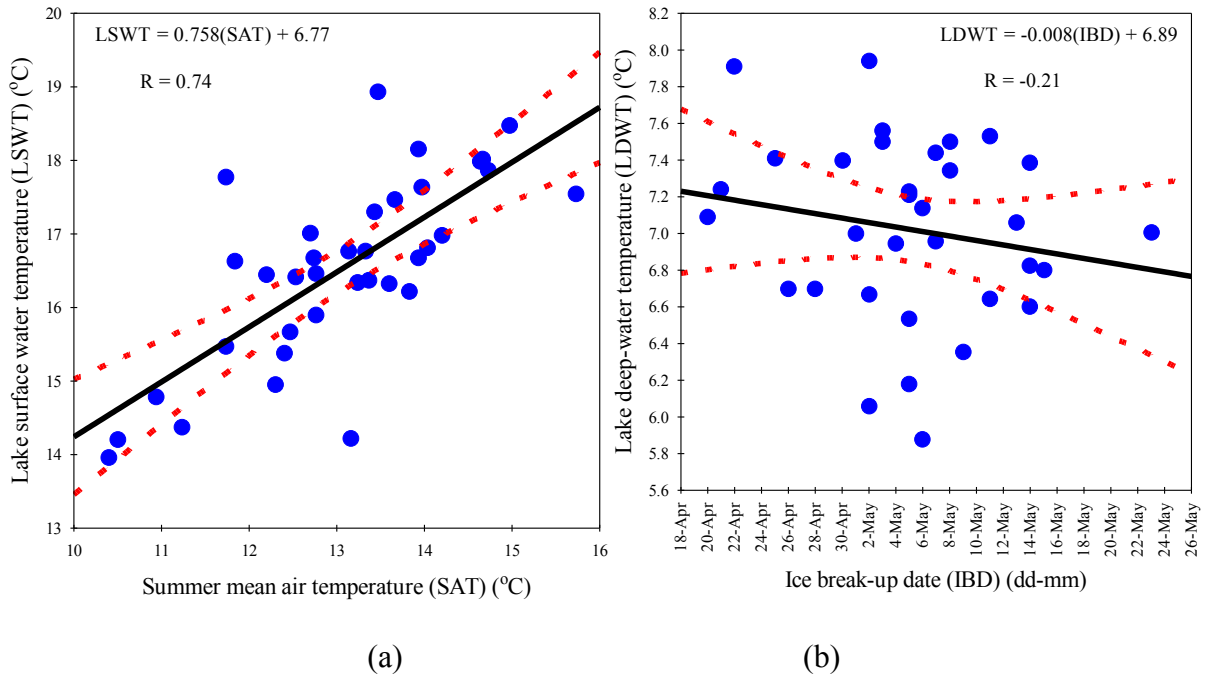


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