ENVIRONMENTAL RESEARCH
COMMUNICATIONS

INCLUSIVE PUBLISHING
TRUSTED SCIENCE

Part of the
ENVIRONMENTAL RESEARCH
SERIES

PURPOSE-LED
PUBLISHING™

LETTER • **OPEN ACCESS**

Long-term water temperature changes in Seneca Lake and their nexus to climate change and human activities

To cite this article: Xin Lan *et al* 2023 *Environ. Res. Commun.* **5** 111003

View the article online for updates and enhancements.

You may also like

- Energy sector water use implications of a 2 °C climate policy
Oliver Fricko, Simon C Parkinson, Nils Johnson et al.

- Riverine ecosystem services and the thermoelectric sector: strategic issues facing the Northeastern United States
Ariel Miara, Charles J Vörösmarty, Robert J Stewart et al.

- Indications of a changing winter through the lens of lake mixing in Earth's largest freshwater system
Eric J Anderson, Brooke Tillotson and Craig A Stow

This content was downloaded from IP address 173.177.195.252 on 26/02/2026 at 21:15

Environmental Research Communications

LETTER

Long-term water temperature changes in Seneca Lake and their nexus to climate change and human activities

Xin Lan[1,2], **Lifeng Luo**[1,2,*], **Zhicheng Xu**[2,3], **Yuean Qiu**[1] and **Xiang Yu**[2,4]

[1] Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, MI 48824, United States of America
[2] Environmental Science and Policy Program, Michigan State University, East Lansing, MI 48824, United States of America
[3] School of Planning, Design, and Construction, Michigan State University, East Lansing, MI 48824, United States of America
[4] Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI 48824, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: lluo@msu.edu

Keywords: water temperature, climate change, temperature profile, human activity, water warming

Supplementary material for this article is available online

OPEN ACCESS

RECEIVED
20 June 2023

REVISED
5 September 2023

ACCEPTED FOR PUBLICATION
22 September 2023

PUBLISHED
9 November 2023

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Abstract

While many freshwater lakes have witnessed a rapid increase in surface water temperatures, the trends in subsurface water temperatures are not well-understood. This study explored the long-term subsurface water temperature change and its connection to climate change and human activities in Seneca Lake. Utilizing linear regression and the Theil-Sen estimator, the study identified a significant monotonic temperature trend in the subsurface water. Principal component and contribution analyses revealed that climate changes, particularly air warming, were more critical in explaining water temperature patterns, and human activities such as land cover change could exacerbate the impact of climate change. Using remotely sensed surface water temperature data, the study found a significant positive correlation between thermal pollution and water temperatures in the northern region of the lake, and after incorporating control variables, the regression analysis suggested that the adverse effects of thermal pollution are primarily confined to the area adjacent to the power plant. This research can offer fresh insights into lake ecology improvement and management strategies.

1. Introduction

Lakes are sentinels of climate change due to their sensitivity to environmental changes (Adrian *et al* 2009). There is a robust scientific consensus that the global mean air temperature has increased at an unprecedented rate over the last century (Winslow *et al* 2018). Consequently, *in situ* and satellite observations have shown that surface water temperatures rose rapidly in many freshwater lakes over the past several decades (Yang *et al* 2019, O'Reilly *et al* 2015, Yang *et al* 2020). What is less clear is how deep water temperatures have changed during the same period. The subsurface mixing determines the vertical distribution of heat within lakes, a process that can be affected by thermal stratification (Pilla *et al* 2020, Anderson *et al* 2021). Thus, deep water temperature in lakes may have changed at different rates from the lake's surface temperature. Due to limited direct observations of subsurface water temperatures, only a few studies have examined the deep water temperatures and vertical thermal structure of lakes, which were also limited to several largest lakes, such as Lake Michigan (Anderson *et al* 2021). While there are many more lakes with sizes smaller than the Great Lakes, our knowledge of how these smaller lakes respond to climate change is still lacking. Thus, the first objective of the study is to better understand how surface and subsurface temperatures have changed in smaller lakes.

Previous studies have suggested that climate change is a critical driver for the rapid increase of lake water temperatures (O'Reilly *et al* 2003, 2015, Anderson *et al* 2021). However, the significant impact of human activities on lake temperatures should not be ignored. For example, the expansion of impervious surfaces due to

© 2023 The Author(s). Published by IOP Publishing Ltd

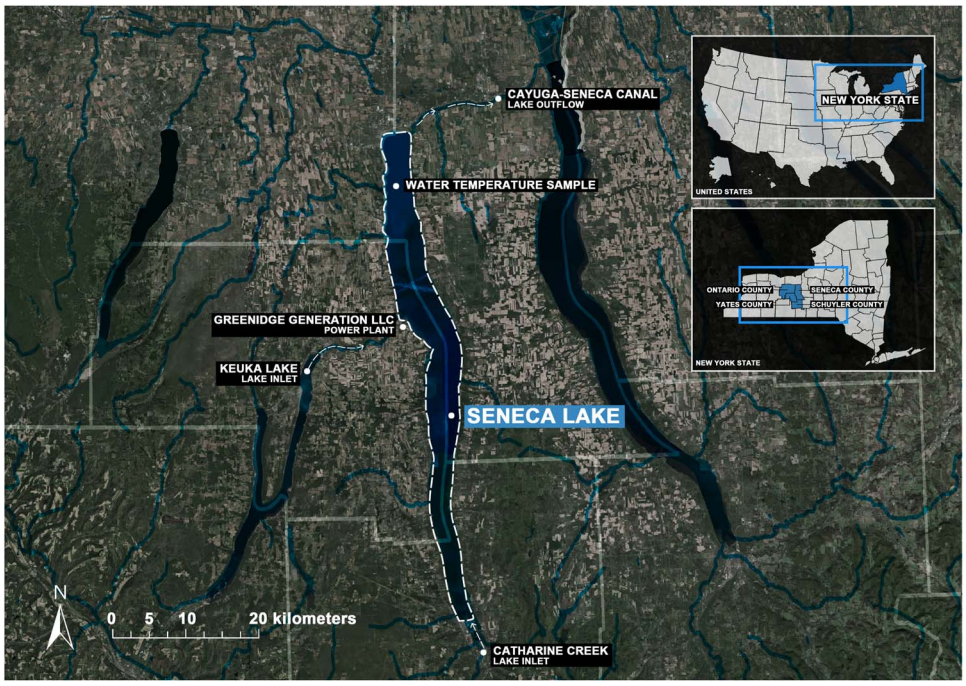

Figure 1. The geographical location of Seneca Lake.

urbanization can exponentially accelerate land surface temperature rise (Xu *et al* 2013), which has a warming effect on surface runoff and lake surface temperature (Yang *et al* 2019). Thermal pollution from a power plant's cooling water discharge may not only significantly affect the lake surface temperature but also seriously threaten the vertical stability of the water column and affect the water temperatures elsewhere in the lake (Kirillin *et al* 2013). But few studies have tried to quantitatively analyze the impact of human activities on the lake water temperatures besides climate change (Yang *et al* 2019), and most of them focused on the impact on lake surface temperature. It is less clear how human activities may have affected the vertical thermal structure of lakes and the temperature changes in deep water. Therefore, the second objective of the study is to attribute changes in deep water temperature to various environmental factors associated with climate change and human activities.

In this study, we take advantage of the *in situ* observations of the water temperature profile at Seneca Lake in New York state to explore the long-term surface and subsurface water temperature changes and their connection to climate change and human activities. Interestingly, a natural gas power plant was built on the western shore of Seneca Lake. The power plant utilizes a once-through cooling system that extracts water from the lake and discharges cooling water back to the lake, potentially raising the water temperature and resulting in further harm to aquatic life (Van Vliet *et al* 2012, Madden *et al* 2013, Kirillin *et al* 2013, Van Vliet *et al* 2013, Coffel and Mankin 2021). This also gives us the opportunity to assess the impact of thermal pollution on lake water changes.

Since deep water temperatures are an essential factor in lake ecological environments, our study could offer new insights by providing a reference for environmental impact assessment, improving the lake ecology, and supporting sustainable lake management (Zhu *et al* 2020).

2. Data and methods

2.1. Study area

Seneca Lake is at the heart of the Finger Lakes region of western New York state (figure 1). Eleven lakes in the Finger Lakes region formed over 2 million years ago, and all lakes, including Seneca Lake, are glacier lakes that are the dominant lake type in North America (Anderson *et al* 1997, Mašín *et al* 2012). Seneca Lake is the largest by volume in the region (Hunkins and Fliegel 1973), with a total volume of 15.9 km^3. The maximum water depth of the lake is 186 m, and the mean water depth is 88 m (Hunkins and Fliegel 1973). Herdendorf (1982) considered natural lakes with a surface area greater than 500 km^2 as large lakes and only identified 253 such large lakes in the world, such as Lake Michigan. But compared to Lake Michigan, Seneca Lake, with an area of 175 km^2, is a much smaller but more typical-size lake in the U.S. Seneca Lake is a warm monomictic lake (i.e. it circulates only during the winter and stratifies during the summer) (Anderson *et al* 1997, Hambright *et al* 1994).

When present, the thermocline (a steep temperature gradient in a body of water) of Seneca Lake is usually approximately 20m but may oscillate vertically (Ahrnsbrak 1975). Catharine Creek at the southern end and the Keuka Lake Outlet on the central western shore provide most of the water flowing into the lake, and Seneca Lake water releases into the Seneca River or Cayuga-Seneca Canal at the northern end.

Near Keuka Lake Outlet is the Greenidge Generation Plant. Originally established in 1937, the plant had to be shut down in 2011 due to financial insolvency. However, it resumed operations in 2017 to cater to the region's power needs and eventually commenced the production of electricity specifically for cryptocurrency mining in 2019. The plant utilizes water from Keuka Lake Outlet for cooling and discharges the cooled water directly into Seneca Lake. The initiation of cryptocurrency mining at the power plant has resulted in a substantial surge in power production, stirring up a contentious issue concerning the impact of water pollution on the Seneca Lake watershed. The dispute regarding the potential thermal pollution in the lake water still remains unresolved and inconclusive.

2.2. Data Source

***In-situ* water temperatures:** Lake water temperatures were observed at the mid-lake water quality monitoring buoy (42.82°N, 76.96°W), which is managed by the Finger Lakes Institute. The water depth at this sampling location is around 60 m. We obtained water temperature records at multiple depths, from the lake surface to 55 m near the lake bottom, between 2006 and 2022, with the exception of 2020. This study focused on long-term temperature change during summertime when the lake develops thermal stratification. Due to the missing data in other summer months, we only used temperature data in August during the 16-year period to minimize uncertainties of the long-term changes at various depths. To exclude the influence of diurnal variations of lake water temperature (Woolway *et al* 2016, Wan *et al* 2017), only water temperature records at noon of each day were used, and they were averaged to obtain monthly mean water temperatures at each depth before the trend analysis.

Remotely sensed water temperature: To investigate the impact of thermal pollution from the power plant on the lake temperature, we relied on remotely sensed water temperature instead of *in situ* data. The Landsat Level 2 Land Surface Temperature (LST) products covering the period of 2017 to 2021, which were derived from Landsat 8 OLI/TIRS, were acquired using Google Earth Engine (GEE). As the spatial resolution of the thermal bands from Landsat 8 is 100 m, the images were resampled to 30 m using the cubic convolution resampling method (Sekertekin and Bonafoni 2020). Subsequently, we removed pixels that were contaminated by clouds, cloud shadows, and snow. Finally, the monthly surface lake water temperatures of each pixel were derived from the average LST of the available images for each given month, and linear interpolation was used to fill in the missing months.

Environmental data: The daily air temperature, wind speed, shortwave radiation, longwave radiation, and precipitation were from the North American Land Data Assimilation System (NLDAS) (Cosgrove *et al* 2003, Xia *et al* 2012), averaged over all 1/8 degree NLDAS grids covering Seneca Lake. The mean daily streamflow data for the Keuka Lake Outlet and Cayuga-Seneca Canal, which are primary inlets and outlets of Seneca Lake, were obtained from the National Water Information System (NWIS) of the United States Geological Survey (USGS) and then averaged to obtain monthly streamflow data.

Human factor data: We extracted the land cover information from the National Land Cover Database (NLCD) for the Seneca Lake watershed to examine the land cover change in this watershed. The land cover data in NLCD contain snapshots of land cover in time, including 2006, 2008, 2011, 2013, 2016, and 2019 records. We applied linear interpolation to estimate the percentage change in the land cover during those missing years. In this study, we used changes in low-, medium-, and high-intensity developed areas, and the areas of cultivated crops, based on NLCD categories, as a proxy for human activities. The monthly average intake water temperatures, average discharge water temperatures, and cooling water volumes between April 2017 and December 2021 were obtained from and fully validated by the United States Energy Information Administration (EIA). Furthermore, we can estimate the heat discharge from the power plant using the given equation (1).

$$H = \frac{(T_d - T_i) \times V \times \rho \times C}{D \times 24 \times 60 \times 60 \times 10^6} \tag{1}$$

where H denotes the heat discharge in megawatts (MW), T_d/T_i denotes the monthly average discharge/intake water temperatures in degree Celsius ($^\circ C$), V denotes the monthly cooling water volumes in cubic meters (m^3), ρ denotes the liquid water density, set at 1000 kilograms per cubic meter (kg/m^3), C denotes the water heat capacity, set at 4184 joules per kilogram-degree Celsius ($J/kg^\circ C$), and finally, D denotes the number of days in a specific month.

2.3. Methods

Trend analysis: To determine the long-term trends of summertime lake temperatures, we used two approaches to estimate the trends and the associated statistical significance. A simple linear regression was applied to the August mean water temperature time series at each depth, and the slope is an estimate of the warming rate while the *p*-value/standard error represents the significance and uncertainty of this warming trend. Furthermore, the Mann-Kendall and Sen's Slope estimator test, a non-parametric method, was also employed for determining long-term monotonic trends alongside the linear regression because of their robustness to outliers and the skew and heteroscedastic data (Kaushal *et al* 2010, Yang *et al* 2020).

Contribution analysis: The contribution analysis is to determine the relative contributions of climate change and human activities to the warming trends in Seneca Lake. In the analysis, multiple linear regression models are used to quantify the association between a set of predictors and the response variable. For a specific predictor x_i, we calculate the R^2 values of two linear regression models: one that excludes x_i but includes all other predictors and the other that includes all predictors (Brereton 2019, Yang *et al* 2020). The difference between the two R^2 values represents the relative contribution of x_i on explaining the response variable, which describes the proportional impact of predictor x_i on R^2 (Johnson 2000). Since all predictors within the linear regression models must be orthogonal (Brereton 2019), we performed the principal component analysis (PCA) on all climate and human activity variables, which helps to remove redundant information and form orthogonal components (Daffertshofer *et al* 2004). We also performed a varimax rotation of all predictors to make our principal components (PCs) more interpretable.

Correlation analysis: Pearson's correlation coefficient, as a measure of linear association, was calculated to describe the relationships between the remotely sensed surface water temperature and heat discharge from the power plant (Yang *et al* 2020, van den Heuvel and Zhan 2022). To account for the possibility of the inaccurate linear association, we utilized Kendall's tau rank correlation coefficients as an alternative method to estimate non-linear monotonic relationships (van den Heuvel and Zhan 2022).

Regression analysis: We performed the multiple linear regression at each pixel within Seneca Lake to assess how thermal pollution from the power plant, which is the variable of interest, affects the lake's surface temperature. Control variables that are known to have an influence on water temperatures, including air temperatures, wind speed, and streamflow for the Keuka Lake Outlet, were included in the analysis to isolate the effect of thermal pollution on the lake water temperatures (Makni *et al* 2009). Before conducting the linear regression tests, we assessed the predictor variables for potential collinearity.

3. Results and discussion

3.1. Long-term trends in vertical temperature profiles

Similar to many middle-latitude lakes, thermal stratification occurs in Seneca Lake during the summertime. Thermal stratification means that water can be divided into three layers based on the temperature profile (Haddout *et al* 2020), namely, epilimnion, metalimnion, and hypolimnion. To capture the vertical temperature profiles with greater details, we discretized the profile into 2-m layers here, while for the rest of the analysis, we used 5-m layers. The climatological mean of August temperatures for each 2-m layer from 2006 to 2022 is depicted in figure 2(a). It is evident that the well-mixed epilimnion layer between 0m and 10 m has relatively uniform temperatures (Berger *et al* 2010, Haddout *et al* 2020). The metalimnion layer is between 10 m and 20 m where lake water temperatures change rapidly with depth (usually 0.5–4.5 °C/m) (Haddout *et al* 2020, Yankova *et al* 2016). At the bottom, between 20 m and 50 m, is the relatively undisturbed hypolimnion layer where temperatures are relatively uniform but cooler.

We divided the top 50-m water column into ten 5-m layers and calculated the annual rate of change for the lake water temperature in August with the two approaches. As shown in figure 2(b) and table S1, we observed an increasing trend in summertime lake water temperature throughout the entire water column. The rates of change reported in both approaches are very similar for all 10 layers, both in magnitude and statistical significance.

From 2006 through 2022, Seneca Lake's surface water temperature rose at an average rate of approximately 0.9 °C per decade based on the linear regression and TheilSen estimator analysis. This warming trend is stronger than the global summertime average warming for lake surface water temperatures, which was about 0.34 °C per decade between 1985 and 2009 (O'Reilly *et al* 2015). O'Reilly *et al* (2015) also suggested that the warming rates of water temperatures, dependent upon the combination of climate and local characteristics, were much higher in the northeast United States than the global level (O'Reilly *et al* 2015), which was consistent with our results here. The higher warming rate found in this study may also be related to the fact that our study period is more recent than what was reported in O'Reilly *et al* (2015).

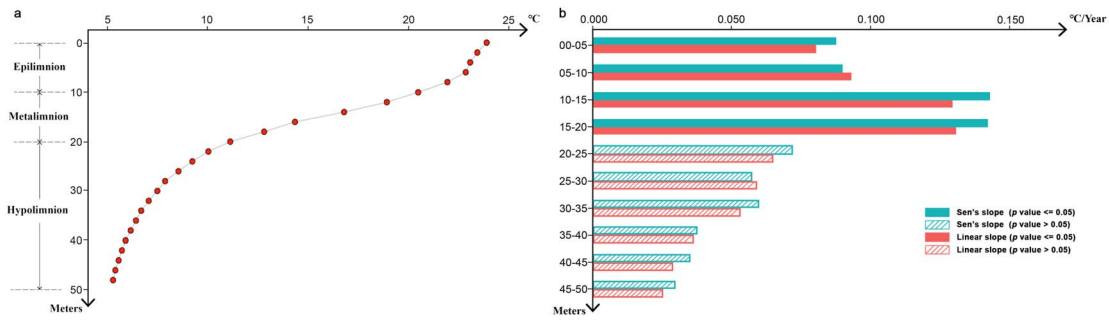

Figure 2. Vertical water temperature profile and long-term changes in Seneca Lake during Augusts of 2006 to 2022. (a) Climatological mean of lake temperatures for each 2-m layer for all Augusts between 2006 and 2022. (b) Trends of long-term temperature changes in August for every 5-m layer.

The temperature trend in the top 10 m was approximately 0.8 °C–0.9 °C per decade, which is nearly equivalent to the rate of warming at the surface. Warming trends can be identified at depths of 10-20 m, and these trends increased to approximately 1.3 °C–1.4 °C per decade. These trends were all statistically significant at the 0.05 significance level. Water temperature change rates at 20–50 m depths were still non-negative and between 0.3 °C and 0.7 °C per decade but statistically insignificant in both approaches. And the warming rates tended to diminish with the increase in depth. The slower warming in the hypolimnion layer could be attributed to the weaker coupling of deep water with air temperature due to lake stratification (Niedrist *et al* 2018, Read *et al* 2011). Our results indicate that surface water temperatures alone are not sufficient to obtain a full picture of the warming in freshwater systems. This is particularly important as most *in situ* observations currently only account for surface water temperatures.

It is interesting to note that as shown in figure 2(b), the rate of temperature increase in the metalimnion layer was notably higher than that in the epilimnion layer. The temperatures of the epilimnion layer are strongly correlated with air temperature and are directly affected by climate warming (Haddout *et al* 2018). But the heightened vertical mixing occurring within the epilimnion and metalimnion layers due to warming (Wahl and Peeters 2014) can push the thermocline slightly downward, causing faster warming at the metalimnion layer. Additionally, the wind's cooling effect through enhanced evaporation on the epilimnion layer might also be a contributing factor to the notably elevated warming rate observed in the metalimnion layer (Yang *et al* 2020).

The warming rate of Seneca Lake is significantly higher than that of Lake Michigan, despite their similar latitudes. Smaller lakes, such as Seneca Lake, with smaller volumes and lower heat storage capacities, are more sensitive to the increase in air temperature and radiation, which leads to faster warming (Mooij *et al* 2008, Anderson *et al* 2021). Additionally, significant warming trends exist in the top 100 meters in Lake Michigan and in the top 20 meters in Seneca Lake, which are about 36% and 11% of their respective maximum depth. Warming trends usually exist in much shallower water in smaller lakes than in larger ones because stronger wind-sheltering reduces water mixing in smaller lakes (Winslow *et al* 2015).

3.2. Driving factors in long-term water warming trends

We performed the contribution analysis to explore the contributions of different driving factors to long-term water warming in Seneca Lake. We applied PCA to our exploratory variables to ensure our driving factors are orthogonal. There are four PCs, and the correlations between the PCs and the original exploratory variable are shown in table S2. The first PC strongly correlates with the lake inflows, outflows, and precipitation. These three variables are related to water supplies in Seneca Lake, and we labeled the first PC as the Flow factor. The change in the developed area was found to have a correlation of 0.91 with the second PC, while the change in agricultural land was found to have a correlation of 0.95 with this component. Thus, the second PC is associated with human activities in the watershed, and we labeled it as the Human factor. The third PC has strong correlations with net radiation and air temperature. Because the net radiation is the sum of the longwave and shortwave radiation, which can heat up the soil and air (An *et al* 2017), we labeled the third PC as the Heat factor. The fourth PC was labeled as the Wind factor because it exhibits a strong correlation with wind speed.

Our analysis examined how the four factors contribute to warming trends in the epilimnion, metalimnion, and hypolimnion layers, as well as the entire water column. As shown in figure 3, the environmental factors (Flow, Heat, and Wind) were the dominant driving factors. The Heat factor had the largest contribution throughout the water column. A high correlation between the net solar radiation and the air temperature suggests that the increased net solar radiation is strongly associated with air warming, and lake temperature can increase following rapid air warming (Webb and Nobilis 2007, Kaushal *et al* 2010, Yang *et al* 2019, 2020).

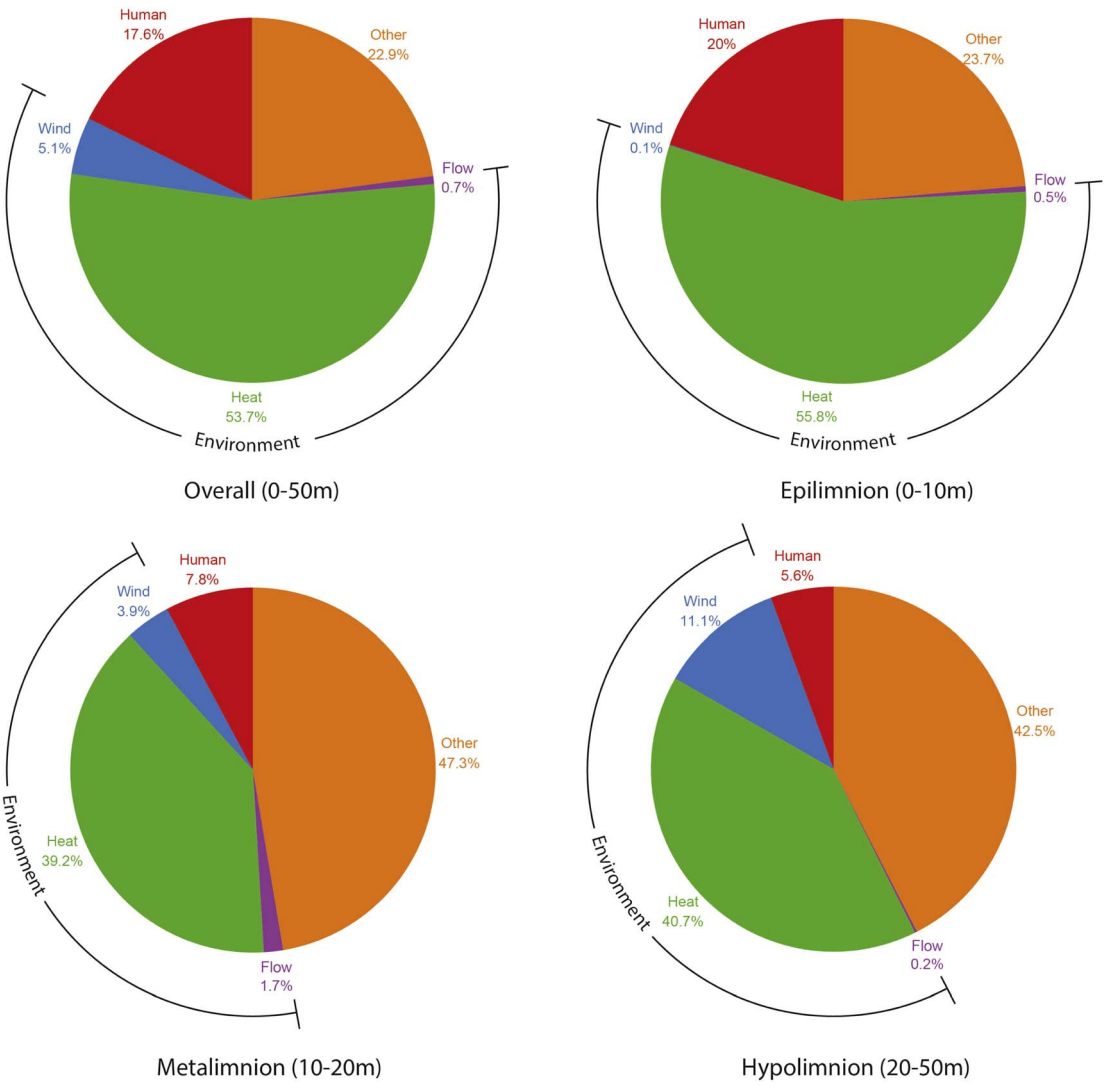

Figure 3. Relative contribution of four driving factors as determined in the PCA.

Furthermore, our analysis revealed that the impact of wind speed was particularly notable for the metalimnion and hypolimnion layers. Wind effects on lake heat distribution can usually be categorized into thermal (enhanced cooling due to evaporation) and dynamic (enhanced vertical mixing) effects. As the depth increases, the role of direct solar heating in determining lake water temperatures diminishes (Jassby and Powell 1975), and the importance of heat exchange associated with vertical mixing becomes increasingly pronounced (Mesman *et al* 2021). Considering the crucial role of wind speed in influencing thermal stratification, vertical mixing, and ultimately heat transfer (Oleksy and Richardson 2021), the relative importance of the impact of wind on the water temperatures of deeper layers is observed to increase. Finally, the Flow factor does not seem to show a noticeable impact on water temperatures, whose contribution is less than 2% throughout the water column.

Our analysis also showed that the Human factor contributed 20% and 17.6% to the warming in the epilimnion layer and the entire water column, while its contributions are weaker for the metalimnion and hypolimnion layers. As suggested by Kaushal *et al* (2010), the land cover might be one of the critical factors in determining water warming. Our results confirmed this as the Human factor in our study was mainly related to land cover changes (developed area and agricultural land change). Urbanization represented by the expansion of developed areas usually means increasing impervious surfaces, which can increase the air temperature due to the urban heat island effect (Kaushal *et al* 2010) and accelerate land surface temperature rise (Xu *et al* 2013), resulting in warming in streams and freshwater bodies. The expansion of agricultural land has been accompanied by the shrinking of forests. And agricultural land expansion, which is strongly correlated with the Human factor, is often the primary driver of deforestation (Macedo *et al* 2013). The headwater in the forest usually stays at a low temperature due to the shade and shelter, and deforestation directly exposes steams to solar radiation (Evans *et al* 1998, Macedo *et al* 2013), thus contributing to water warming.

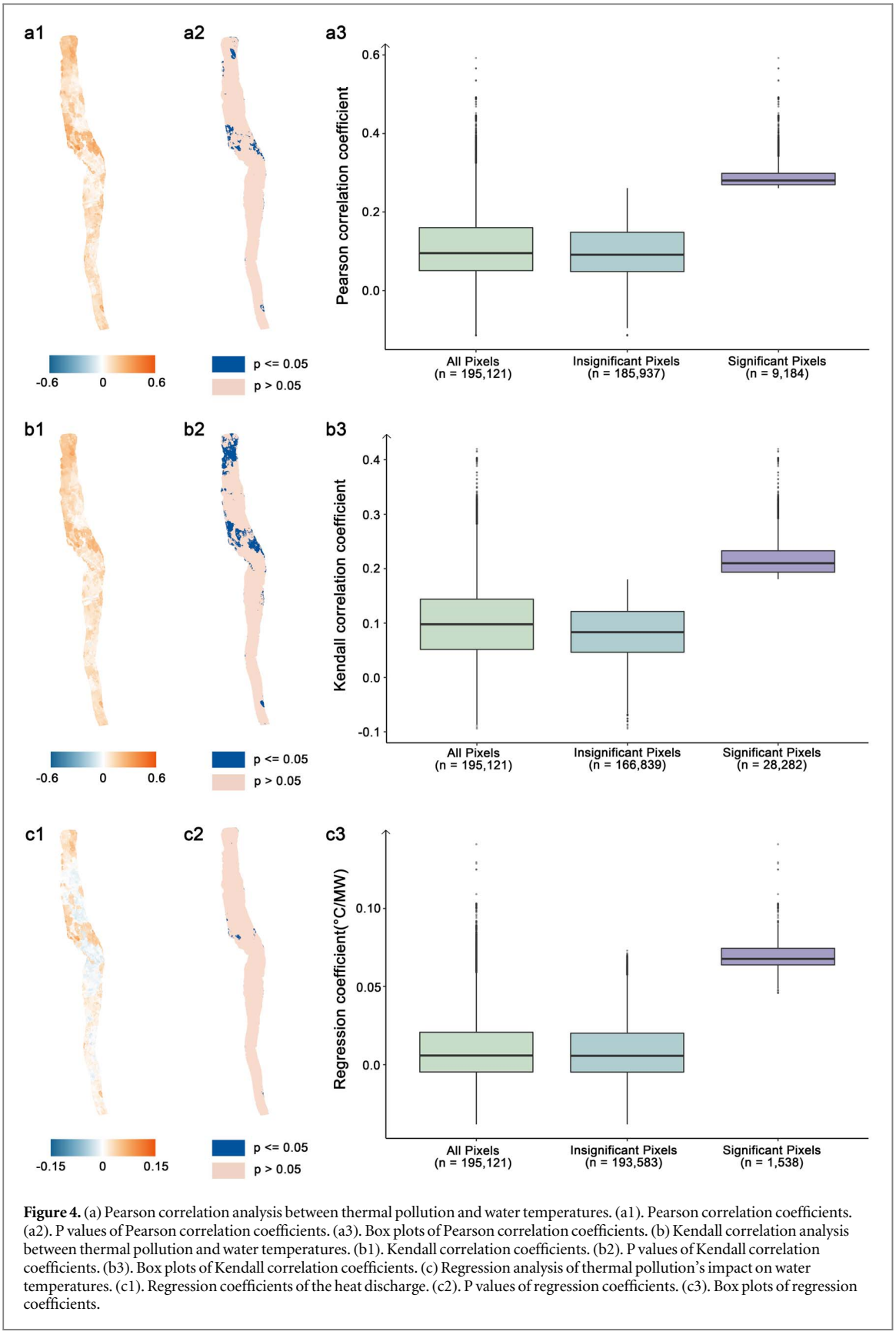

Figure 4. (a) Pearson correlation analysis between thermal pollution and water temperatures. (a1). Pearson correlation coefficients. (a2). P values of Pearson correlation coefficients. (a3). Box plots of Pearson correlation coefficients. (b) Kendall correlation analysis between thermal pollution and water temperatures. (b1). Kendall correlation coefficients. (b2). P values of Kendall correlation coefficients. (b3). Box plots of Kendall correlation coefficients. (c) Regression analysis of thermal pollution's impact on water temperatures. (c1). Regression coefficients of the heat discharge. (c2). P values of regression coefficients. (c3). Box plots of regression coefficients.

Our analysis lumped factors other than those being represented into Other component, and these factors can play an important role in influencing temperatures in metalimnion and hypolimnion layers. The interaction with groundwater is a part of this other component. Saline groundwater intrusion into Seneca Lake has been observed (Wing *et al* 1995), ultimately leading to groundwater recharge. In addition, the groundwater recharge often generates concave-upward thermal profiles and intensifies the thermal stratification within Seneca Lake

(Dong *et al* 2018). As depth increases, the importance of heat exchange becomes more pronounced (Mesman *et al* 2021). Consequently, the impact of groundwater, which can affect thermal profiles and heat transfer, becomes increasingly noticeable within the metalimnion and hypolimnion layers.

3.3. Impact of the power plant on water temperatures

The controversy surrounding the impact of thermal pollution on the lake environment after the reopening of the power plant in 2017 received substantial public attention. We examined the influence of thermal pollution on lake surface water temperature between April 2017 and December 2021, using correlation analysis to assess the relationship between heat discharge and lake surface water temperature, as well as linear regression that incorporated air temperature, wind speed, and streamflow as control variables. As shown in figure 4, both Pearson and Kendall correlation analyses show significant positive correlation coefficients at the 5% level, primarily in the upper part of Seneca Lake. However, after accounting for the impacts of environmental factors, the significant positive regression coefficients at a 5% significance level were confined to the lake area adjacent to the power plant. Significant regression coefficients near the lake's edge may be attributed to the typically low accuracy of remote sensing data at the water-land boundary, potentially leading to an absolute error of up to 5 °C (Schaeffer *et al* 2018). Conversely, no significant regression coefficients, either positive or negative, were detected in the rest areas of Seneca Lake. In summary, the lake areas influenced by thermal pollution were relatively small.

However, it would be imprudent to overlook the potential adverse impact of that thermal pollution on the lake's ecosystem. In our study, the strong negative correlation between wind and air temperatures suggested collinearity in the linear regression, based on the guideline that collinearity exists when the absolute value of the Pearson correlation coefficient nears 0.8 (Shrestha 2020). However, collinearity was only detected among the control variables, not between the independent and control variables (Shrestha 2020), the coefficient for the thermal pollution in the regression was still interpretable and meaningful (Johnston *et al* 2018). For the lake region with significant regression, figure 4 indicates that a heat discharge of one megawatt (MW) from the power station typically resulted in a median surface water temperature increase of about 0.07 °C. Starting in February 2020, the power plant's heat emission surged, with monthly heat discharge typically ranging between 40 and 95 MW, potentially leading to a rise of 3 to 7 °C estimated based on the regression results. Usually, an increase of 5 °C or above in water temperatures can substantially impact the aquatic biodiversity and ecosystems (Madden *et al* 2013). Therefore, thermal pollution should be recognized as an issue for aquatic environments near this power station.

Considering the average margin of error of 1.34 °C in remotely sensed water temperature data (Schaeffer *et al* 2018), detecting subtle effects of thermal pollution becomes quite challenging. A past case study has shown that while the local warming effect of thermal pollution can reach up to 3.4 °C, the average effect across the entire lake system drops to 0.3 °C (Råman Vinnå *et al* 2017). Less precise remote sensing data may explain why our regression only showed a significant association in the vicinity of the power plant but missed the more subtle effects of thermal pollution in the wider area of Seneca Lake. Thus, more precise year-round *in situ* monitoring or regular monitoring coupled with numerical model simulations of the lake environment is indispensable to better assess the power plant's impacts on water temperatures and their subsequent influence on lake ecosystems and biodiversity.

4. Conclusion

By taking advantage of *in situ* observations at multiple depths, we found that surface and sub-surface water temperatures gradually warmed in Seneca Lake between 2006 and 2022. Long-term warming trends, significant at 5% level, exist in the top 20 m with an average rate of approximately 0.8 °C–0.9 °C per decade above 10 m and around 1.3 °C–1.4 °C per decade between 10 m and 20 m. While many earlier studies observed pervasive and rapid surface water warming around the world (O'Reilly *et al* 2015, Yang *et al* 2019, 2020), our results showed that the warming could extend downward a few dozen meters, and it is not necessarily the surface layer that warms the most due to changes in the lake dynamics. Our study highlights the need for more *in situ* observations at multiple depths to better assess and understand the changes in freshwater systems and their impact on aquatic ecosystems. Furthermore, understanding the changes in Seneca Lake, a more typical-sized lake in the US and the world, can help to better understand how other freshwater systems may behave under climate change.

Previous research has indicated that climate warming plays a pivotal role in the rapid increase of lake water temperatures (O'Reilly *et al* 2003, 2015, Anderson *et al* 2021). However, our study reveals that human activities, such as urbanization and thermal pollution, can further exacerbate these changes. Despite the allocation of substantial resources by governments in recent years to address ecological issues in lakes, there has been limited observable progress in improving the lake environments (Jia *et al* 2022). In this context, our study provides valuable insights into the role of human activities, enabling governments to identify the underlying causes of

environmental and ecological issues in specific lakes. Such understanding is essential for effective lake water quality management. By acknowledging the contribution of human activities to lake water warming and taking appropriate measures to mitigate our environmental impact, we can contribute to a sustainable future for our planet and its inhabitants.

Lastly, the debate over the thermal pollution from the power plant near Seneca Lake underscores the need to revisit state and federal environmental guidelines concerning water temperature, ensuring they are grounded in solid scientific research. Our findings emphasize the adverse effects of thermal pollution in the vicinity of the power plant, but more precise data and additional research are needed to understand the mechanisms of how the thermal pollution dissipates from the lake and finally to gauge the extent of these impacts. Therefore, it is imperative to conduct frequent and extensive *in situ* monitoring of surface and subsurface waters near the power plant and throughout the entire lake to provide a comprehensive assessment of the impact of thermal discharge. Additionally, given the essential need for electricity to support domestic and industrial activities, we must recognize the inevitability of thermal pollution from power plants, even when the electricity is not used for cryptocurrency mining. Hence, it's imperative to conduct more research to identify the best areas and depths for thermal waste release to reduce its ecological impact, such as, possibly employing a multi-point discharge system to spread heat more broadly and reduce local warming rates.

Acknowledgments

This work was supported by the Environmental Science and Policy Program and the Department of Geography, Environment, and Spatial Sciences at Michigan State University, as well as by the US National Science Foundation through grant IIS-2006633. We thank Dr John Halfman and his associates at the Finger Lakes Institute for supplying the vertical water temperature data, and Dr Pang-NIng Tan for constructive discussions. We also wish to express our appreciation to two anonymous reviewers whose insightful feedback significantly enhanced the quality of the manuscript.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Data availability statement

Vertical water temperatures are from the Seneca Lake Instrument Network (http://fli-data.hws.edu/buoy/seneca/). The remotely sensed surface temperature data is acquired from the Landsat Level 2 LST products via Google Earth Engine (GEE) (https://developers.google.com/earth-engine/datasets/catalog/landsat). The daily air temperature, wind speed, shortwave radiation, longwave radiation, and precipitation were from NLDAS (Cosgrove *et al* 2003, Xia *et al* 2012, 2012). USGS (https://waterdata.usgs.gov/nwis/sw) offers access to the daily streamflow data for both the Keuka Lake Outlet and the Cayuga-Seneca Canal. The land cover information can be obtained from NLCD (https://www.usgs.gov/centers/eros/science/national-land-cover-database) using the Seneca Lake watershed shapefile. The monthly average intake water temperature, average discharge water temperature, and cooling water volume data are obtained from EIA (https://www.eia.gov/electricity/data/eia923/).

ORCID iDs

Xin Lan https://orcid.org/0000-0002-0607-2270
Lifeng Luo https://orcid.org/0000-0002-2829-7104
Zhicheng Xu https://orcid.org/0000-0002-6832-8964
Yuean Qiu https://orcid.org/0000-0002-3167-2294
Xiang Yu https://orcid.org/0009-0004-0095-9980

References

Adrian R *et al* 2009 Lakes as sentinels of climate change *Limnol. Oceanogr.* **54** 2283–97
Ahrnsbrak W F 1975 A saline intrusion into Seneca Lake, New York *Limnol. Oceanogr.* **20** 275–8
An N, Hemmati S and Cui Y J 2017 Assessment of the methods for determining net radiation at different time-scales of meteorological variables *Journal of Rock Mechanics and Geotechnical Engineering* **9** 239–46

Anderson E J, Stow C A, Gronewold A D, Mason L A, McCormick M J, Qian S S and Hawley N 2021 Seasonal overturn and stratification changes drive deep-water warming in one of Earth's largest lakes *Nat. Commun.* **12** 1–9
Anderson W T, Mullins H T and Ito E 1997 Stable isotope record from Seneca Lake, New York: evidence for a cold paleoclimate following the younger dryas *Geology* **25** 135–8
Berger S A, Diehl S, Stibor H, Trommer G and Ruhenstroth M 2010 Water temperature and stratification depth independently shift cardinal events during plankton spring succession *Global Change Biol.* **16** 1954–65
Brereton R G 2019 Determining the significance of individual factors for orthogonal designs *J. Chemom.* **33** e3124
Coffel E D and Mankin J S 2021 Thermal power generation is disadvantaged in a warming world *Environmental Research Letters.* **16** 024043
Cosgrove B A *et al* 2003 Real-time and retrospective forcing in the North American Land Data Assimilation System (NLDAS) project *Journal of Geophysical Research: Atmospheres.* **108**
Daffertshofer A, Lamoth C J, Meijer O G and Beek P J 2004 PCA in studying coordination and variability: a tutorial *Clin. Biomech.* **19** 415–28
Dong L, Fu C, Liu J and Wang Y 2018 Disturbances of temperature-depth profiles by surface warming and groundwater flow convection in Kumamoto Plain, Japan *Geofluids* **2018**
Evans E, McGregor G R and Petts G E 1998 River energy budgets with special reference to river bed processes *Hydrol. Processes* **12** 575–95
Haddout S, Priya K and Boko M 2018 Thermal response of Moroccan lakes to climatic warming: first results *Annales de Limnologie-International Journal of Limnology* **54** 15
Haddout S, Qanza H, Guennoun M A, Azidane H, Karra R and Essaidi A 2020 Epilimnion and metalimnion thermal water temperature variables in Moroccan's Lakes using a one-dimensional fresh-water lake model *International Journal of River Basin Management* **18** 321–33
Hambright K D, Gophen M and Serruya S 1994 Influence of long-term climatic changes on the stratification of a subtropical, warm monomictic lake *Limnol. Oceanogr.* **39** 1233–42
Herdendorf C E 1982 Large lakes of the world *J. Great Lakes Res.* **8** 379–412
Hunkins K and Fliegel M 1973 Internal undular surges in Seneca Lake: a natural occurrence of solitons *J. Geophys. Res.* **78** 539–48
Jassby A and Powell T 1975 Vertical patterns of eddy diffusion during stratification in Castle Lake, California *Limnol. Oceanogr.* **20** 530–43
Jia T, Yang K, Peng Z, Tang L, Duan H and Luo Y 2022 Review on the change trend, attribution analysis, retrieval, simulation, and prediction of lake surface water temperature *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **15** 6324–55
Johnson J W 2000 A heuristic method for estimating the relative weight of predictor variables in multiple regression *Multivariate Behavioral Research* **35** 1–19
Johnston R, Jones K and Manley D 2018 Confounding and collinearity in regression analysis: a cautionary tale and an alternative procedure, illustrated by studies of British voting behaviour *Quality & Quantity* **52** 1957–76
Kaushal S S, Likens G E, Jaworski N A, Pace M L, Sides A M, Seekell D and Wingate R L 2010 Rising stream and river temperatures in the United States *Frontiers in Ecology and the Environment* **8** 461–6
Kirillin G, Shatwell T and Kasprzak P 2013 Consequences of thermal pollution from a nuclear plant on lake temperature and mixing regime *J. Hydrol.* **496** 47–56
Macedo M N, Coe M T, DeFries R, Uriarte M, Brando P M, Neill C and Walker W S 2013 Land-use-driven stream warming in southeastern Amazonia *Philosophical Transactions of the Royal Society B: Biological Sciences* **368** 20120153
Madden N, Lewis A and Davis M 2013 Thermal effluent from the power sector: an analysis of once-through cooling system impacts on surface water temperature *Environ. Res. Lett.* **8** 035006
Makni R, Francoeur C and Bellavance F 2009 Causality between corporate social performance and financial performance: evidence from Canadian firms *Journal of Business Ethics* **89** 409–22
Mašín M, Čuperová Z Z, Hojerová E, Salka I and Grossart Hans-Peter K M 2012 Distribution of aerobic anoxygenic phototrophic bacteria in glacial lakes of northern Europe *Aquat. Microb. Ecol.* **66** 77–86
Mesman J P, Stelzer J A, Dakos V, Goyette S, Jones I D, Kasparian J and Ibelings B W 2021 The role of internal feedbacks in shifting deep lake mixing regimes under a warming climate *Freshwater Biology* **66** 1021–35
Mooij W, Domis L D S and Hülsmann S 2008 The impact of climate warming on water temperature, timing of hatching and young-of-the-year growth of fish in shallow lakes in the Netherlands *Journal of Sea Research.* **60** 32–43
Niedrist G, Psenner R and Sommaruga R 2018 Climate warming increases vertical and seasonal water temperature differences and inter-annual variability in a mountain lake *Clim. Change* **151** 473–90
Oleksy I A and Richardson D C 2021 Climate change and teleconnections amplify lake stratification with differential local controls of surface water warming and deep water cooling *Geophys. Res. Lett.* **48** e2020GL090959
O'Reilly C M, Alin S R, Plisnier P D, Cohen A S and McKee B A 2003 Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa *Nature* **424** 766–8
O'Reilly C M *et al* 2015 Rapid and highly variable warming of lake surface waters around the globe *Geophys. Res. Lett.* **42** 10–773
Pilla R M *et al* 2020 Deeper waters are changing less consistently than surface waters in a global analysis of 102 lakes *Sci. Rep.* **10** 20514
Råman Vinnå L, Wüest A and Bouffard D 2017 Physical effects of thermal pollution in lakes *Water Resour. Res.* **53** 3968–87
Read J S, Hamilton D P, Jones I D, Muraoka K, Winslow L A, Kroiss R and Gaiser E 2011 Derivation of lake mixing and stratification indices from high-resolution lake buoy data *Environ. Modelling Softw.* **26** 1325–36
Schaeffer B A, Iiames J, Dwyer J, Urquhart E, Salls W, Rover J and Seegers B 2018 An initial validation of Landsat 5 and 7 derived surface water temperature for U.S. lakes, reservoirs, and estuaries *International Journal of Remote Sensing.* **39** 7789–805
Sekertekin A and Bonafoni S 2020 Land surface temperature retrieval from Landsat 5, 7, and 8 over rural areas: assessment of different retrieval algorithms and emissivity models and toolbox implementation *Remote Sensing* **12** 294
Shrestha N 2020 Detecting multicollinearity in regression analysis *American Journal of Applied Mathematics and Statistics* **8** 39–42
van den Heuvel E and Zhan Z 2022 Myths about linear and monotonic associations: pearson'sr, spearman's ρ, and kendall's τ *The American Statistician* **76** 44–52
Van Vliet M T, Vögele S and Rübbelke D 2013 Water constraints on European power supply under climate change: impacts on electricity prices *Environ. Res. Lett.* **8** 035010
Van Vliet M T, Yearsley J R, Ludwig F, Vögele S, Lettenmaier D P and Kabat P 2012 Vulnerability of US and European electricity supply to climate change *Nat. Clim. Change* **2** 676–81
Wahl B and Peeters F 2014 Effect of climatic changes on stratification and deep-water renewal in Lake Constance assessed by sensitivity studies with a 3d hydrodynamic model *Limnol. Oceanogr.* **59** 1035–52
Wan W *et al* 2017 A comprehensive data set of lake surface water temperature over the Tibetan Plateau derived from MODIS LST products 2001-2015 *Scientific Data* **4** 1–10

Webb B W and Nobilis F 2007 Long-term changes in river temperature and the influence of climatic and hydrological factors *Hydrol. Sci. J.* **52** 74–85
Wing M R, Preston A, Acquisto N and Ahrnsbrak W F 1995 Intrusion of saline groundwater into Seneca and Cayuga Lakes, New York *Limnol. Oceanogr.* **40** 791–801
Winslow L A, Leach T H and Rose K C 2018 Global lake response to the recent warming hiatus *Environ. Res. Lett.* **13** 054005
Winslow L A, Read J S, Hansen G J and Hanson P C 2015 Small lakes show muted climate change signal in deepwater temperatures *Geophys. Res. Lett.* **42** 355–61
Woolway R I *et al* 2016 Diel surface temperature range scales with lake size *PLoS One* **11** e0152466
Xia Y *et al* 2012 Continental-scale water and energy flux analysis and validation for the North American Land Data Assimilation system project phase 2 (NLDAS-2): 1. intercomparison and application of model products *Journal of Geophysical Research: Atmospheres* **117**
Xia Y *et al* 2012 Continental-scale water and energy flux analysis and validation for North American Land Data Assimilation system project phase 2 (NLDAS-2): 2. validation of model-simulated streamflow *Journal of Geophysical Research: Atmospheres* **117**
Xu H, Lin D and Tang F 2013 The impact of impervious surface development on land surface temperature in a subtropical city: Xiamen, China *Int. J. Climatol.* **33** 1873–83
Yang K, Yu Z and Luo Y 2020 Analysis on driving factors of lake surface water temperature for major lakes in Yunnan-Guizhou Plateau *Water Res.* **184** 116018
Yang K, Yu Z, Luo Y, Zhou X and Shang C 2019 Spatial-temporal variation of lake surface water temperature and its driving factors in Yunnan-Guizhou Plateau *Water Resour. Res.* **55** 4688–703
Yankova Y, Villiger J, Pernthaler J, Schanz F and Posch T 2016 Prolongation, deepening and warming of the metalimnion change habitat conditions of the harmful filamentous cyanobacterium Planktothrix rubescens in a prealpine lake *Hydrobiologia* **776** 125–38
Zhu S, Ptak M, Yaseen Z M, Dai J and Sivakumar B 2020 Forecasting surface water temperature in lakes: a comparison of approaches *J. Hydrol.* **585** 124809