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Hydrology and Earth System Sciences Discussions

# Historical modelling of changes in Lake Erken thermal conditions

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**Abstract.** The thermal structure of lakes is strictly related to climate and to the variability of thermal and mixing dynamics. In this study, a physical hydrodynamic model (GOTM) was used to reconstruct daily time-step water temperature of Lake Erken (Sweden) over the period 1961-2017, using seven climatic parameters as forcing data: wind speed (WS), air temperature (Air T), atmospheric pressure (Air P), relative humidity (RH), cloud cover (CC), precipitation (DP) and shortwave radiation (SWR). The model was calibrated against real water temperature data collected during the study interval, and the calibrated model revealed a good match between modelled and observed temperature (RMSE=1.112 °C). From the long-term simulations of water temperature, this study focused on detecting possible trends in water temperature over the entire study interval 1961-2017 and in the sub-intervals 1961-1987 and 1988-2017. The analysis of the simulated temperature showed that epilimnetic temperature has increased on average by +0.43°C/decade and +0.809 °C/decade in spring and autumn in the sub-interval 1988-2017. Summer epilimnetic temperature has increased by +0.348 °C/decade over the entire interval 1961-2017. Hypolimnetic temperature has increased significantly in the sub-interval 1988-2016 by +0.827 °C/decade in autumn. Whole-lake temperature showed a significant increasing trend in the sub-interval 1988-2017 during spring (+0.378 °C/decade) and in autumn (+0.809 °C/decade). Moreover, this study showed that changes in the phenology of thermal stratification, have occurred over the 57-years period of study. Since 1961 the stability of stratification (Schmidt Stability) has increased by 5.535 $Jm^{-2}$/decade. The duration of thermal stratification has increased by 7.083 days/decade, correspondent with an earlier onset of stratification of ~ 16 days and to a delay of stratification termination of ~ 26 days. The average thermocline depth during stratification became shallower by ~1.242 m, and surface-bottom temperature difference increased over time by +0.249 °C/decade. The creation of daily-time step water temperature dataset not only provided evidence of changes in Erken thermal structure over the last decades, but it is also a valuable resource of information that can help in future research on the ecology of Lake Erken. The use of readily available meteorological data to reconstruct Lake Erken's past water temperature is shown to be a useful method to evaluate long-term changes in lake thermal structure, and it is a method that can be extended to other lakes.

## 1. Introduction

The variability of thermal stratification and the dynamics of mixing in lakes and reservoirs is closely coupled to several atmospheric factors such as solar radiation, air temperature and wind speed, highlighting the fact that changes in water thermal conditions are strongly related to changes in climatic conditions (Samal et al. 2012). As a consequence of a warmer climate on

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a global scale, several studies have shown that lake water temperature is strongly affected (Adrian et al. 2009), causing shorter ice cover-periods (Blenckner et al. 2002, Butcher et al. 2015, Kainz et al. 2017), increased water temperature (Arhonditsis et al. 2004) and stronger summer stratification (Jankowski et al. 2006). Since climatic conditions have changed markedly in the last century and they are expected to change considerably in the next decades (IPCC, 2013), the importance of predicting how freshwater bodies will be affected by such changes becomes evident. Several studies have used modelling tools to assess how lake water temperature and more generally the entire lake ecosystem will respond under different future scenarios (Stefan et al. 1998, Taner et al. 2011, Winslow et al. 2017). However, future predictions on how lakes will respond to climate change are less credible without model validation based on comparison with historical water temperature data. A long record of historical data provides more background information and allows better documentation of the changes that have already taken place and leads to more accurate predictions of lake thermal condition in future decades. One of the best arguments to counter climate change sceptics is well documented long-term records of the ongoing effects of climate change.

For these reasons, we aimed to create a daily time-step dataset of historical water temperature data for Lake Erken (Sweden) using a hydrodynamic model. Lake Erken has been studied extensively over the past 70 years (Pettersson 2012) and automated hourly measurements of water temperature and meteorological data have been collected from the lake since October 1988. Before 1988, water temperature measurements were taken manually only during periodic sampling campaigns. As a consequence, information about the thermal state of the lake before 1988 was missing or patchy for most of the time, and even after 1988 there are significant gaps in the measured temperature data. The aim of this study is to use a hydrodynamic model to extend records of lake water temperature further back in time until 1961, in order to provide a longer and more consistent picture of the changes that have occurred in Lake Erken over the last five decades. The model is driven by meteorological data collected from Uppsala University's field station at Lake Erken (http://www.ieg.uu.se/erken-laboratory/) and from nearby stations to create daily time-step water temperature profiles for the entire period 1961-2017. This work aims to (1) demonstrate the validity of using modelled temperature to reconstruct past water temperature of Lake Erken for the period 1961-2017, providing a valuable method that can be extended to other lakes and (2), to evaluate how water temperature and other metrics of lake stratification have changed over the study period. Finally, the creation of a reliable consistent and complete 57-year dataset of daily water temperature profiles will be a valuable source of information for future research on Lake Erken that will help to better our understanding of many ecological processes that can be affected by changes in thermal conditions.

## 2. Methods

### 2.1 The lake

The lake investigated in this study was Lake Erken (59.4166 N, 18.2500 E) a mesotrophic lake located ~60 km North-East from Stockholm (Sweden) at an altitude of 10 m above the sea level and it covers an area of about 24 km$^2$. Lake Erken's mean

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depth is 9 m and its maximum depth is 21 m. The retention time of the lake is around 7 years. The lake is ice-covered during winter until March-early May (Blenckner et al. 2002).

### 2.2 The model

The model used in this work is GOTM (General Ocean Turbulence Model). It is a 1-dimensional physical model built to simulate water temperature and other physical parameters using meteorological parameters as driving factors. Detailed information about GOTM can be found in Burchard (2002) and on the website www.gotm.net. In this study, seven climatic parameters were used as input to the GOTM model over the study period (January 1st, 1961 - October 31st, 2017): wind speed (WS; m/s), air temperature (Air T: °C), relative humidity (RH; %), atmospheric pressure (Air P; hPa), cloud cover (CC; dimensionless value between 0-1), shortwave radiation (SWR; W/m$^2$) and precipitation (DP; mm/day). To run the model, hourly datasets were created for six climatic parameters over the considered study period (WS, Air T, Air P, RH, CC, SWR), while DP dataset was based on daily values. For the purpose of this study the lake was considered to have a fixed water level equal to the long-term mean. This assumption was justified given the lakes long retention time and that the mean annual variation in lake level is only 48 cm.

### 2.3 Data sources of driving parameters

Driving climatic parameters were primarily retrieved from the Erken laboratory meteorological station (Malma islet; 59.8391 N, 18.6296 E, fig. 1) and Svanberga station (59.8321 N, 18.6348 E, fig. 1), about 800 m from the Malma weather station. The Svanberga weather station is managed by SMHI (Swedish Meteorological and Hydrological Institute) and climatic data were

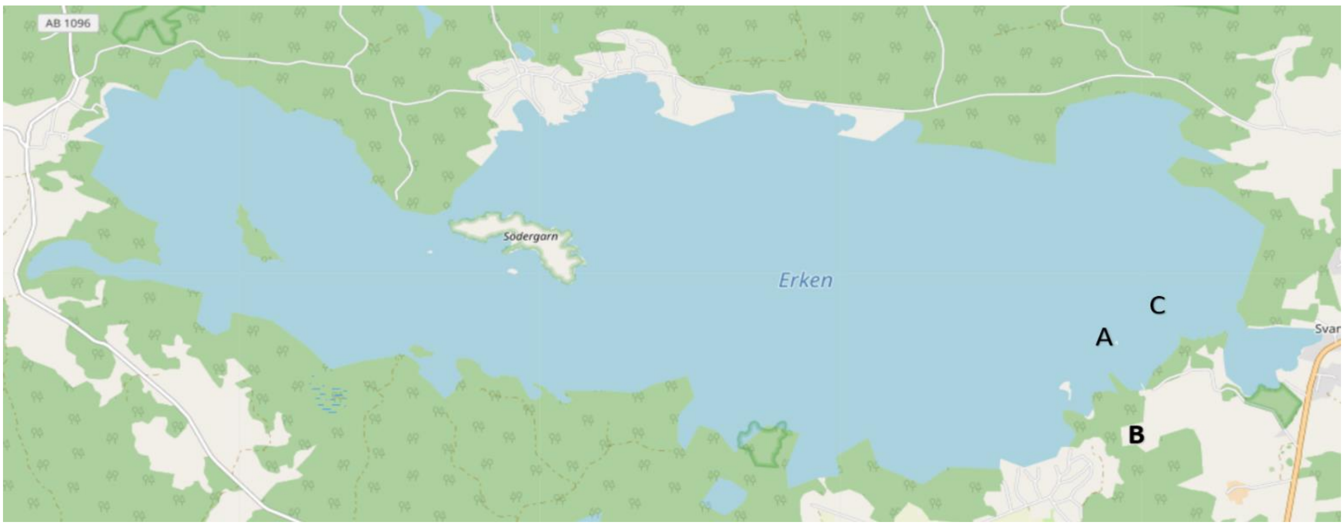


**Figure 1: Position of meteorological and floating stations within Lake Erken basin and catchment area. Letter A shows the position of Malma meteorological station (59.83909 N, 18.62956 E), letter B identifies Svanberga SMHI weather station (59.8321 N, 18.6348 E), letter C represents the position of the floating station that records water temperature data (map retrieved from OpenStreetMap: https://www.openstreetmap.org.**

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downloaded from SMHI website (http://opendata-download-metobs.smhi.se/explore/). Climatic data from neighboring stations were used when data from Erken or Svanberga were not available. A detailed description on the methodology used to retrieve these climatic data is available in supplementary material.

### 2.4 Missing data replacement and missing data estimation with Artificial Neural Network analysis

To simulate Lake Erken water temperature at daily time step using GOTM, a continuous hourly record of meteorological forcing data was created by merging the data sources described above. In the case of DP missing data were replaced by taking data from the closest station to Lake Erken. For cloud cover that was only available from one station, missing data were replaced by linear interpolation. Similar methods were first used to estimate WS, Air T, Air P, RH and SWR. However, for these remaining meteorological variables that showed significant inter-station variability, we found that Artificial Neural Network (ANN) algorithms provided the best estimate of local Erken meteorological data as judged by comparison of modeled and observed water temperature. ANN function fitting analysis was used to predict missing data using the ANN fitting tool (nftool) in MATLAB version R2017b (MathWorks Inc. Natick, Massachusetts). Compared to other methods, ANN nftool also made maximum use of data from surrounding stations to predict missing meteorological data at Erken.

ANN algorithms were used to estimate each driving parameter during occasions when no local measurements were recorded at Malma (WS, Air T and SWR) and Svanberga (Air P and RH). Input data were those collected from the nearest (less than 60 km away) meteorological stations to Lake Erken and Svanberga. Input data were retrieved from SMHI database, except for SWR data that were retrieved from measurements made at the Swedish Agricultural University (SLU) near Uppsala. The choice of the climatic datasets to use as input data was based on two characteristics:

1. Offsite datasets that have recorded data when data from Lake Erken or Svanberga were not available.
2. Offsite and local datasets overlap for at least 8-10 years. We found that the ANN fitting tool requires this length of data overlap in order to obtain the best fit function that describes input-target relationship.

A detailed description of the Neural Network analysis is available in supplementary material.

### 2.3 Model Calibration

The model was calibrated using measured profiles of averaged daily water temperature collected between April and November when the lake was ice-free. Observed data in the period 1961-1988 were collected manually during occasional sampling campaigns, and from strip chart data recordings made at the island station. Most of the observed temperature data were measured at 0.5, 5, 10 and 20 m depth. A much greater number of observed data were available for the period 1989-2017 when an automated floating station (59.84297 N, 18.635433 E) was deployed to collect water temperature data during ice-free period. The floating station measured water temperature data every 0.5 meters, from 0.5 m to 15 m depth. Profiles were stored every 30 minutes and these were averaged to provide a daily mean profile. Also between 1989-2017 water temperature was digitally recorded in a manner similar to the old strip chart recordings. These measurements were made year-round from the 1, 3 and 15 m depths at the Malma island station, and used for calibration at times the floating system was not deployed.

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The program ACPy (Auto Calibration Python) was used to calibrate the model (webpage: www.bolding-bruggeman.com/portfolio/acpy/). A set of model parameters was calibrated and adjusted within their feasible range (see table 1) in order to minimize the difference between the simulated and measured water temperature. A 1-year simulation spin-up was used to minimize errors in the calibration by allowing the initial state of the model to better reflect typical lake conditions. To make full use of the input data when spinning up the model a copy of the 1961 data was appended to the beginning of the input data and this year was used as the spin up. In this way, 1961 data were both used as spin-up year and discarded from calibration, and then reused in the proceeding calibration.

In ACPy, a Differential Evolution algorithm (Storn and Price 1997) is used to calculate a log likelihood function which compares the modelled water temperature to the observed temperature.

The likelihood Λ is defined in Eq. (1):

$$\Lambda = - \sum_i \frac{(x_{obs,i} - x_{mod,i})^2}{var_x} \quad (1)$$

where $x_{obs,i}$ is the observed temperature, $x_{mod,i}$ is the modeled temperature and $var_x$ is the variance between the modelled and observed temperature. Following the calibration, model fit was judged based on estimates of bias, mean absolute error (MAE), and the root mean squared error defined in Eq. (2), Eq. (3) and Eq. (4) respectively:

$$bias = \sum_{i=1}^{N} \frac{(x_{mod,i} - x_{obs,i})}{N} \quad (2)$$

$$MAE = \frac{\sum_{i=1}^{N} |x_{obs,i} - x_{mod,i}|}{N} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (x_{obs,i} - x_{mod,i})^2}{N}} \quad (4)$$

Since the purpose of this study was to reconstruct the lake water temperature over a pre-defined period (1961-2017), we used the entire record of measured temperature over this period to judge the validity of the calibration. This ensured that the greatest range of environmental conditions would be represented, and that our simulations within the calibration period would have the greatest degree of accuracy. The best set of parameters calculated from the ACPy calibration (table 1) were then used for the final simulation which produced the data analyzed in the remainder of this paper. The error distribution between the modelled and the observed water temperature after calibration is shown in figure 2, while the comparison between modelled and observed temperature at different depths is shown in figures 3-4.

## 2.4 Statistical analysis

The Lake Analyzer R package (Read et al. 2011) was used to retrieve several metrics describing lake thermal structure at a daily time step for the entire study period from the modelled water temperature profiles. Lake Analyzer calculates volumetrically averaged epilimnetic, hypolimnetic and whole lake temperature (°C), Schmidt stability (J m$^{-2}$, Schmidt 1928,

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Idso 1973), thermocline depth (m) and difference between surface and bottom temperature (ΔT, °C). In addition, we calculated the length of the growing season for each year, which is defined as the number of days in which epilimnetic temperature exceeds 9 °C (Håkanson and Boulion, 2001).

In this study, the lake was considered stratified when the difference between surface temperature and bottom temperature (ΔT) was greater than 1 °C (Woolway et al. 2014). The onset of stratification was considered to be the first day of the first period of 4 or more consecutive days in which ΔT > 1 °C (Yang et al. 2016). Thus, stratification events shorter than 4 days were not considered in the analysis of stratification duration.

To assess if water temperature trends vary with seasons, the seasonal averages of the simulated water temperature were analyzed using the non-parametric Mann-Kendall test (Mann 1945, Kendall 1975). This test assesses whether a statistically significant monotonic increase or decrease over time is occurring. The values of such trends were estimated using the non-parametric Sen's slope (Sen 1968), which is the median of all pairwise slopes of the considered data. For autocorrelated data, the modified version of Mann-Kendall test proposed by Hamed and Rao (1998) was used instead of the traditional Mann-Kendall test, which does not account for autocorrelation. Since the simulation stops in October 2017, autumn water temperature of that year were not taken into consideration in the data analysis. In addition, since Lake Erken is always ice-covered during winter and the GOTM model does not contain an ice-cover module, the simulated winter lake temperature might have been underestimated, especially in the bottom layers, where GOTM might have not simulated the effect of heat flux from the sediment into the water. For this reason, trends in winter lake temperature were not analyzed in this study. The Mann-Kendall, modified Mann-Kendall test and Sen's slope were also used to evaluate trends in average Schmidt stability during thermal stratification, thermocline depth, stratification duration, onset and termination of stratification and growing season length. We used the Pettitt's test (Pettitt 1979) to assess whether an abrupt change in annual mean air temperature occurred during the study period. The entire statistical analysis was carried out using R Studio version 3.4.1 (R Studio Team 2016).

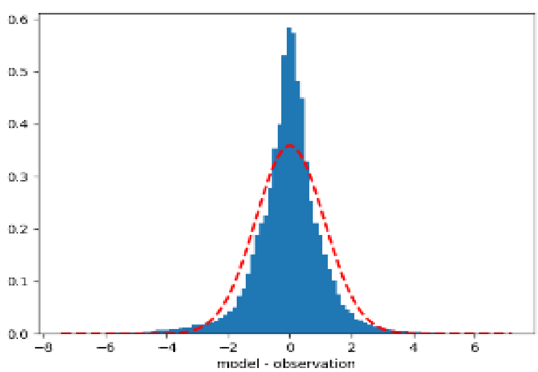


**Figure 2: Error distribution between modelled water temperature and observed water temperature (Model-Observation) retrieved from ACPy calibration.**

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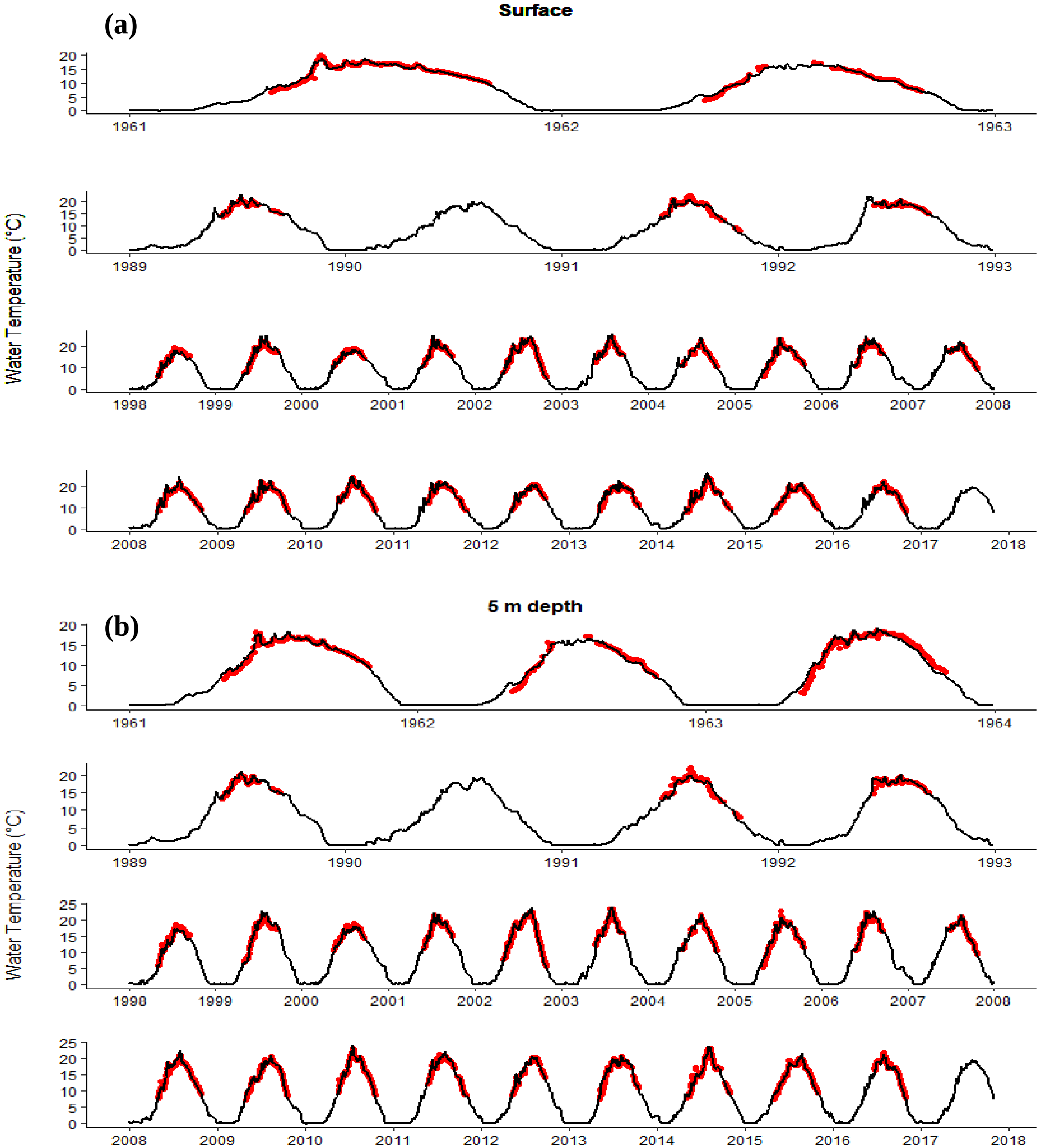


**Figure 3: Comparison between Erken modeled (black) and observed daily temperature (red) at surface (a), and 5m (b) depth. For better visualization of the results, years in which observed data were scarce are omitted.**

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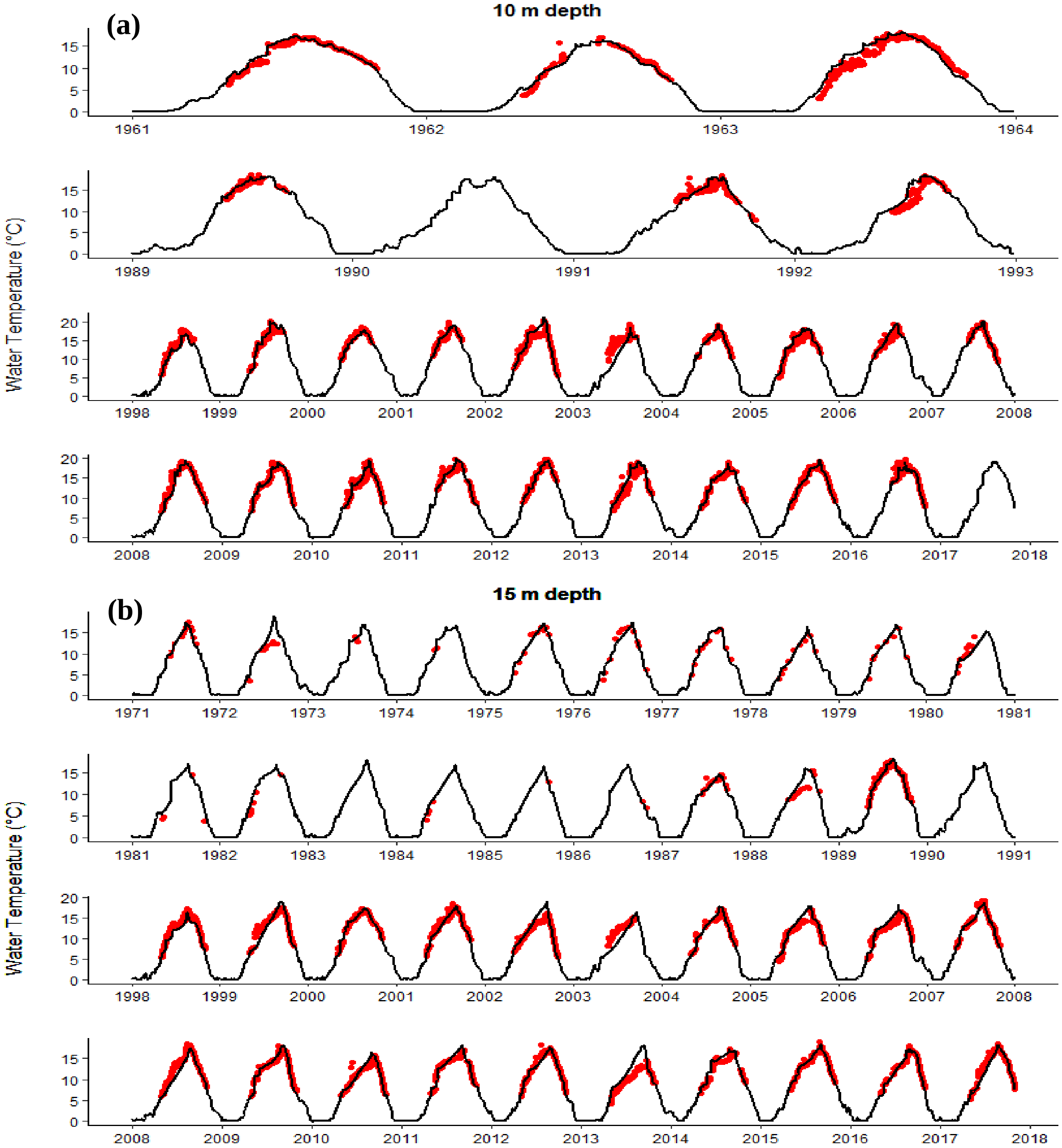


**Figure 4: Comparison between Erken modeled (black) and observed daily temperature (red) 10m (a) and 15m (b) depth. For better visualization of the results, years in which observed data were scarce are omitted.**

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## 3. Results

The Pettitt's test showed that a significant abrupt change in annual mean air temperature occurred in 1988 ($p < 0.001$). Therefore, in addition to checking for trend in lake thermal structure over the entire simulation period we also evaluated the possibility of trends occur over the period starting in 1988. The results suggest that Lake Erken did indeed change more rapidly since 1988. The Mann-Kendall test showed that during summer (June-August) a significant increase in epilimnetic temperature of +0.348 °C/decade (p-value < 0.001, fig. 5b) occurred over the entire study period (1961-2017). However, no other significant trends were detected over the entire simulation period or over the sub-interval 1961-1987. In contrast, significant positive trends were detected from 1988 onwards during both the spring and autumn. Since 1988, spring (April – May) whole-lake temperature showed an average increasing trend of +0.378 °C/decade (p-value < 0.05, fig. 5a) and epilimnetic temperature an average increasing trend of +0.43 °C/decade (p-value < 0.05, fig. 5b). The same pattern is showed during autumn months (September-November) with no trends detected in the sub-interval 1961-1987, while significant increasing trends were detected in the sub-interval 1988-2016 for whole-lake (+0.809 °C/decade, p-value < 0.001, fig. 5a) epilimnetic (+0.809 °C/decade, p-value <0.001, fig. 5b). Also during the autumn hypolimnetic temperature showed an increasing trend of +0.827 °C/decade (p-value < 0.001, fig. 5c). Other metrics of thermal statification showed long-term trends that were significant over

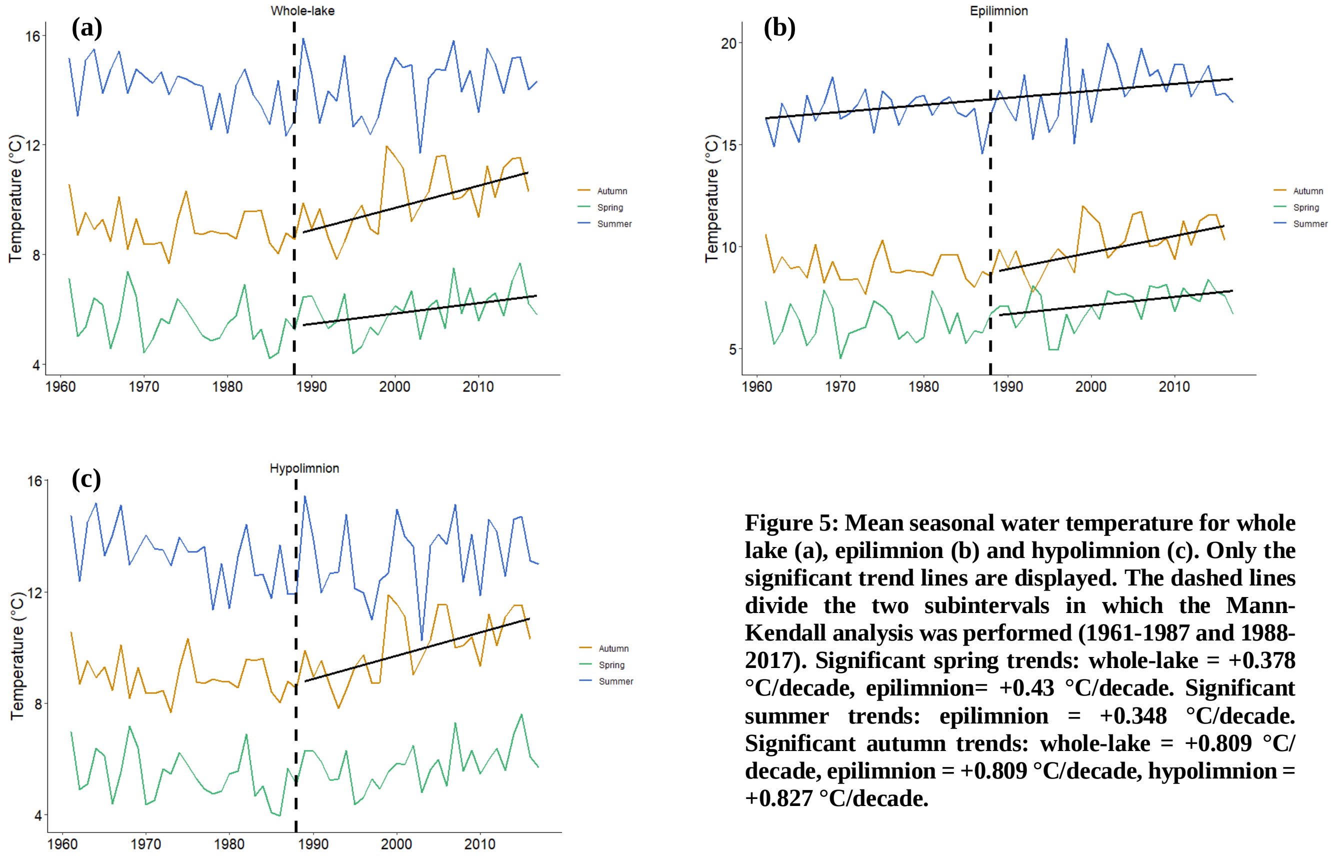


**Figure 5: Mean seasonal water temperature for whole lake (a), epilimnion (b) and hypolimnion (c). Only the significant trend lines are displayed. The dashed lines divide the two subintervals in which the Mann-Kendall analysis was performed (1961-1987 and 1988-2017). Significant spring trends: whole-lake = +0.378 °C/decade, epilimnion= +0.43 °C/decade. Significant summer trends: epilimnion = +0.348 °C/decade. Significant autumn trends: whole-lake = +0.809 °C/decade, epilimnion = +0.809 °C/decade, hypolimnion = +0.827 °C/decade.**

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the entire simulation period. The length of the growing season showed a positive significant increase, which, on average was of +3.684 days/decade (p-value < 0.001, fig. 6) in the interval 1961-2017. With regards of thermal stability, the trend analysis of Schmidt stability revealed that more energy is required to mix the lake during stratified conditions in recent years if compared to the first years of the study period (+5.535 $Jm^{-2}$/decade, p-value < 0.01, fig. 7). This greater stability also corresponded with a longer duration of stratification. From 1961, the duration of lake stratification increased, on average, by 7.083 days/decade (p-value < 0.001, fig. 8a).

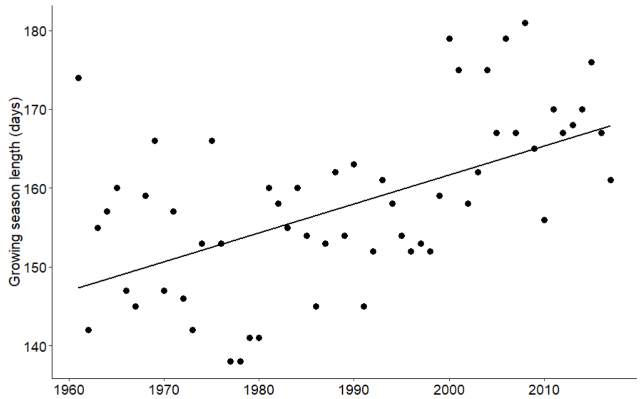


**Figure 6: Growing season length calculated from simulated water temperature between 1961-2017 (Sen's slope: +3.684 days/decade, p < 0.001).**

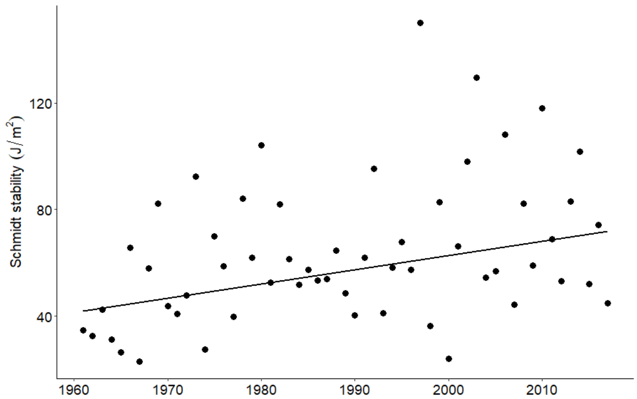


**Figure 7: Schmidt stability calculated from simulated water temperature between 1961-2017 (Sen's slope: +5.535 Jm-2/decade, p < 0.01).**

The longer period of stratification is the result of both an earlier onset of thermal stratification, which now occurs on average ~16 days earlier since 1961 (-2.841 days/decade, p-value < 0.01, fig. 8b) and a later loss of thermal stratification that now is on average delayed by ~26 days (+4.545 days/decade, p-value < 0.001, fig. 8c). The difference between surface and bottom temperature is often used as a simple indicator of thermal stratification. Its mean annual value during the stratified period increased significantly over time, increasing, on average, by +0.249 °C/ decade (p-value < 0.05, fig. 9). Mean annual thermocline depth during lake stratification period shows a significant decrease over the entire study period, with an average decrease of ~1.242m since 1961 (-0.218 °C/decade, p-value < 0.01, fig. 10).

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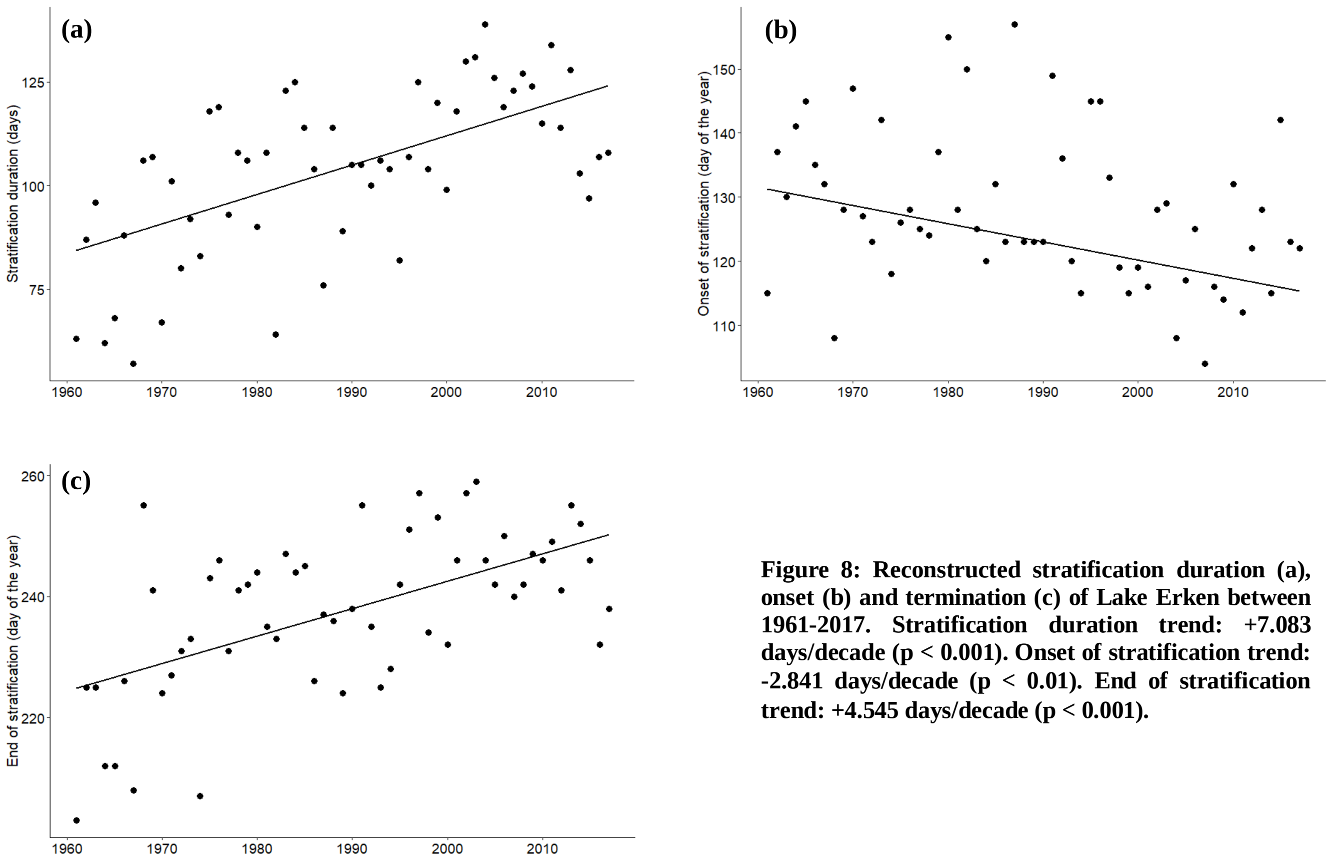


**Figure 8: Reconstructed stratification duration (a), onset (b) and termination (c) of Lake Erken between 1961-2017. Stratification duration trend: +7.083 days/decade ($p < 0.001$). Onset of stratification trend: -2.841 days/decade ($p < 0.01$). End of stratification trend: +4.545 days/decade ($p < 0.001$).**

## 4. Discussion

The model used in this study revealed a good match between observed and simulated water temperature during the entire study period 1961-2017. In particular, the GOTM model was able to reproduce past water temperature with a high level of accuracy not only when meteorological driving data were available from the Erken field station (1988-2017), but also during the period 1961-1988, when most of the meteorological data were estimated using Artificial Neural Network Analysis. Indeed, the model was able to well describe summer water temperature during the three-year period 1961-1963, when it was possible to compare frequent water temperature measurements recorded from several depths by strip chart recorders.

Moreover, the Pettitt's test showed that an abrupt change in air temperature occurred in 1988, consistent with the results of Temnerud and Weyhenmeyer (2008), who detected that most of the abrupt changes in air temperature (interval 1961-2005) across different sites in Sweden occurred in 1988 and 1989. The similarity of these findings with the present work demonstrates the reliability of air temperature data used to drive GOTM model, and also supports our finding that trends in water temperature were strongest during this period, which found that the 1988-2017 interval plays an important role in defining the trends water

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temperature warming. The majority of the increasing trends were detected only in this sub-interval, suggesting that most of the increase in Erken water temperature has occurred during the last three decades rather than during the entire study period. Overall, autumn is the season that showed the highest increase in water temperature between 1988-2017 (epilimnion: +0.809

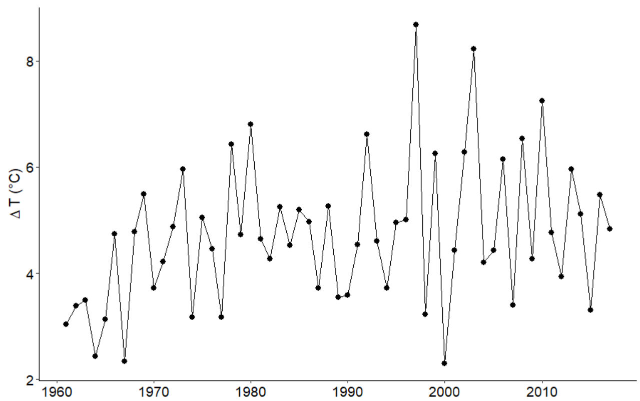


**Figure 9: Surface-Bottom modeled temperature difference (ΔT) during stratification between 1961-2017. ΔT increasing rate +0.249 °C/ decade ($p < 0.05$).**

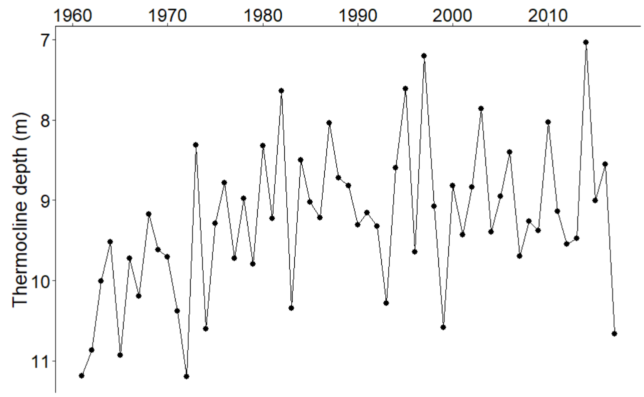


**Figure 10: Mean annual thermocline depth between 1961-2017. Average thermocline depth decrease since 1961: 1.6 m ($p < 0.001$).**

°C/decade, hypolimnion: +0.827 °C/decade, whole-lake: +0.809 °C/decade). A lesser trend was detected during spring between 1988-2017 for epilimnetic and whole-lake temperature (+0.43 °C/decade, and +0.378 °C/decade respectively).Only summer epilimentic temperature showed a constantly increasing trend throughout the entire study period, with a significant increase since 1961, but no significant increase in the sub-intervals, suggesting that the first and most persistent effects of global warming have occurred during summer, while the more recent and more significant trends are most apparent in spring and autumn. These results also show that while epilimnetic temperature increased in each season, hypolimnetic temperature showed a significant increase only in autumn between 1988-2017. This probably results from the fact that hypolimnetic temperature is less affected by meteorological variability than epilimnetic temperature (Adrian et al. 2009).

A large-scale study carried out by O'Reilly et al. (2015), compared trends in summer surface water temperature from 235 lakes located in different climatic regions between 1985-2009. A global mean trend of increasing summer surface water temperature (+0.34 °C/decade) was detected, with trends from individual lakes ranging from -0.7 - +1.3 °C /decade. The study reports a surface water temperature trend for Lake Erken derived from measured data of +0.61 °C/decade (see O'Reilly et al. 2015, supporting information), while in the present work the trend of the surface summer modelled temperature (0.5 m depth) calculated over the same time period (1985-2009) is somewhat greater +1.115 °C/decade.

The trend detected by O'Reilly et al. (2015) is calculated using a dataset with temporal gaps in summer water temperature record (14 years with recorded data between 1985-2009), while in the present work the trend was calculated using a complete long-term dataset of simulated summer surface water temperatures. Furthermore, the same article suggests that water temperature trends detected for lakes with data gaps might have been underestimated, suggesting that the trend detected in the present study for Lake Erken could be more accurate. This illustrates the value of using more complete and consistent modelled

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data to calculate trends, and also indicates that the lake is warming at a rate near the global maximum. The rapid rated of warming estimated from our work is also consistent with the conclusions of O'Reilly et al. (2015) that lakes located in Northern Europe are warming more rapidly than the global average, and also of Kraemer et al. (2017) that lakes at greater latitudes are warming faster than tropical lakes. Temperature trends obtained in the present study are consistent with these findings.

A prolonged duration of high surface water temperature and an increase of epilimnetic temperature can have impacts on lake mixing dynamics leading to a higher thermal stability (Jankowski et al. 2006, Butcher et al. 2015). Such increases in water temperature can explain why Schmidt stability has also increased over the period 1961-2017 (5.353 $Jm^{-2}$/decade) and why the duration of stratification has also increased by about 40 days since 1961, shifting both the onset and the end of the stratification. Compared to 1961, the present onset of thermal stratification occurs on average 16 days earlier. However, the higher thermal stability has even a greater effect on the loss of stratification. From the simulated temperature, the end of the stratification now occurs on average 26 days later if compared with the 1960s. Very similar results were reported by Arvola et al. (2009) who used less frequently measured temperature data to estimate that the loss of stratification in Lake Erken was delayed by almost one month since the 1960, further verifying the reliability of the model based approach used in this study for detecting such variation. However, Arvola et al. (2009) did not detect the trends in the onset and duration of stratification or lake warming that were detected here. That these trends are now detected shows the value of using model simulations to provide long-term consistent temperature records that are more amenable to trend analysis.

Higher surface temperature has also increased the difference between surface and bottom temperature over the period 1961-2017 (figure 9) inducing a greater steepness of the thermocline, and that mean thermocline depth (figure 10) have decreased over time. This could be due to a lower wind speed in recent times. Trend analysis of mean annual wind speed have revealed that there is a significant decreasing trend in wind speed over the study period. Since 1961, the wind speed has decreased on average by 0.775 m/s (Sen's slope = -0.136 ms-1/decade, $p < 0.001$). Another possible explanation to a shallower thermocline could be related to a reduction of heat fluxes from water to air, which might have weakened the convective mixing of the upper layers (Monismith and MacIntyre 2009). However, heat fluxes have not been analyzed in this study, and further research is needed to better understand the causes behind reductions in thermocline depth.

Changes in lake water temperature and stratification patterns can have a broad influence on many aspects of lake ecosystems, both biotic and abiotic. For example, a longer duration of thermal stratification could lead to a depletion in hypolimnetic oxygen (Jankovski et al. 2006, Butcher et al. 2015), potentially reducing the natural range of lacustrine fish (Jones et al. 2008) or otherwise influence the vertical distribution of living organisms (Woolway et al. 2014). Moreover, an earlier onset of thermal stratification and warmer lake temperature could change the seasonal dynamics of phytoplankton species (Thackeray et al. 2008). A previous model simulation conducted by Blenckner et al. (2002) on the ecology of Lake Erken concluded that warmer water temperature and changes in mixing dynamics due to climate change are likely to boost nutrient concentration and phytoplankton production, with consequences for the entire lake ecosystem in the coming decades. Moreover, the relative long retention time of lake Erken (7 years) could enhance the importance of internal phosphorus loading due to warmer temperature, making the lake more susceptible to climate change than other Swedish lakes with shorter retention time (Malmeus et al. 2005).

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Another related issue could be an increase of carbon emission from the lake, since a recent study has revealed that an increase in nutrient concentration coupled with a rise in water temperature can have a positive and synergistic effect on methane ebullition (Davidson et al. 2018). In a warmer world not only methane, but also $CO_2$ emissions from boreal lakes are likely to increase (Weyhenmeyer et al. 2015). Finally, a general indicator of the effects of warmer conditions on the biological dynamics of Lake Erken is the growing season indicator of Håkanson and Boulion (2001). Our simulations showed a significant increase in the number of days in which epilimnetic temperature was greater than the suggested 9 ° C threshold during the 1961-2017 study period (+3.684 days/decade).

The present study has shown that the GOTM model accurately reconstructed the past 57-years of thermal conditions in Lake Erken, and the use of modelled data was a valuable tool for detecting changes in its thermal structure. This work also pointed shows that water temperature has been rising faster in the last three decades compared to the previous decades both in the epilimnion and hypolimnion and that other metrics describing thermal stratification have changed over the entire 57-year study period.

In conclusion, it is likely that increasing water temperature will cause many secondary effects with serious and to some extent unpredictable repercussions on lake ecosystems. This work can be seen as a baseline for future research on Lake Erken that involve climate-related investigations. A further step towards a better understanding of how the lake ecosystems will respond to climate change is to couple a biogeochemical model with the physical model GOTM using FABM - Framework for Aquatic Biogeochemical Models (Bruggemann and Bolding 2014). Then parameters such as chlorophyll, nutrient and dissolved organic carbon concentrations can be simulated and analyzed. The coupling of physical and biogeochemical models could, therefore, be a valuable tool to facilitate the mitigation of detrimental effects of a warmer world on lake ecosystems.

## Data and code availability

The model configuration, the input data used to run the GOTM model, the output data and the water temperature used to calibrate the model are available on Hydroshare (doi: 10.4211/hs.7e5ec8c0e2b245199ab13cc9ae08b841). Matlab codes, R codes and all the datasets produced during this study are available upon request from the corresponding author.

## Competing interests

The authors declare no competing interests.

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## Tables

**Table 1: Best parameter set and model statistics from ACPy calibration**

| Model parameter | Calibrated factor | Feasible range | Model statistics | Value |
|---|---|---|---|---|
| Heat-flux factor | 0.877031 | 0.5-1.5 | ln Likelihood | -57082.876 |
| Short- wave radiation factor | 0.981184 | 0.8-1.2 | Bias (°C) | -0.05194 |
| Wind factor | 1.28391 | 0.5-2.0 | MAE (°C) | 0.7693 |
| Minimum turbulent kinetic energy | $1.65975e^{-6}$ | $1.4e^{-7}$-$1.0e^{-5}$ | RMSE (°C) | 1.112 |
| e-folding depth for visible fraction | 2.64707 | 0.5-3.5 | Correlation | 0.9568 |