RESEARCH PAPER

LAKE PHYSICS IN CHANGING CLIMATE: CASE STUDY OF KOSINO LAKES (MOSCOW, RUSSIA) IN 1984-2023

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ABSTRACT. The one-dimensional lake model GLM was used to simulate the ice and stratification dynamics of two small lakes within Moscow City, Russia – lakes Beloe and Svyatoe of the Kosino Lake group. The model was calibrated on observation data from 2021–2023, and the significant trends of the lakes' thermal and mixing regime were calculated based on the model run for the period of 1983–2023. Some of the most distinct changes are associated with ice phenology, as both lakes lose ice cover at 4.4–5.0 days/decade. The length of the stratified period does not significantly change, but the stability of stratification in dimictic Lake Beloe is increasing. Both lakes have experienced an increase in mean surface water temperature over the year between 0.22–0.26 °C/decade, which is two times lower than the observed trend in the local air temperature. In polymictic Lake Svyatoe, bottom water temperature also increases at a maximum of 0.65 °C/decade. The fastest changes in ice phenology, water temperature and stratification occurred before 2013, while in the last decade most parameters have stabilized, despite the growing intensity of climate warming. This might demonstrate how the lakes are compensating for some of the climate signal.

KEYWORDS: lake modeling, thermal stratification, Schmidt stability, lake ice, climate change

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INTRODUCTION

The physical aspects of lakes – their water temperature, density, and hydrodynamics – are the features that affect all the processes within their ecosystems. As lake hydrodynamics are closely interconnected with climate via changes in water and energy budget, lakes often act as good indicators of climate change (Williamson et al. 2008; Adrian et al. 2009), rapidly reacting to shifts in solar radiation, air temperature, available wind energy, precipitation, and other climate-related factors (Woolway et al. 2020).

Some of the most widely observed changes in lakes attributed to climate change include reduced ice cover (Sharma et al. 2021), rising water temperature in surface layers (O'Reilly et al. 2015; Dokulil et al. 2021), and some shifts in the water balance (Zhang et al. 2020; Yao et al. 2023). Prolonged ice-free periods with higher water temperatures can lead to an increase in biological productivity and the occurrence of harmful algal blooms (Ho et al. 2019; Woolway et al. 2021), the accumulation of nutrients and organic matter in the bottom layer (Schwefel et al. 2019), a worsening of the oxygen regime (Schwefel et al. 2016), and a restructuring of trophic webs (Jeppesen et al. 2014). Other changes are less detectable but can also pose a threat to the stability of lake ecosystems. Hypolimnetic water temperature is shown to have both decreasing and increasing trends in various lakes around the world (Oleksy and Richardson 2021; Winslow et al. 2015), which can affect lake metabolism. Uneven heating at different depths and changing weather conditions during spring and fall can also cause the intensification of stratification (Magee and Wu 2017).

Many lake-specific characteristics, such as lake morphometry, water clarity, the structure of external water balance, and the surrounding landscape, significantly influence the thermal and mixing regime of lakes. Individual features of lakes can cause high variation in stratification and ice phenology even between lakes in very similar climatic conditions (Read et al. 2014; Higgins et al. 2021). The biogeochemistry of a specific lake can provide reliable feedback to climate signals, as dissolved substances and microorganisms also play a part in a lake's mixing regime (Mesman et al. 2021; Pilla et al. 2018). Due to this, the observed changes in water temperature, stratification, and ice phenology vary in intensity – and sometimes direction – in lakes around the world, as some of them effectively compensate for effects of climate change (Woolway et al. 2020). That means that climate change mitigation and adaptation strategies in lake management have to be developed locally, taking into consideration the observed and expected changes in lake hydrodynamics and ecology. Studies on regional lakes are also necessary to assess the possible range of changes in a specific area.

A large number of European lakes are well monitored and thoroughly studied in terms of dynamics of water temperature, ice, and mixing regimes (Blenckner et al. 2007). However, a large part of Eastern Europe, including European Russia, remains relatively underinvestigated. At the same time, the effects of climate change are expected to be more dramatic in areas with a continental climate (Dokulil et al. 2010), making it possible to underestimate the possible consequences of climate change in more landlocked areas based on data from lakes located in milder climates.

The Kosino Lakes are three natural small lakes located on the eastern edge of Moscow City. In the first half of the 20th century, pioneering research on water physics, water chemistry, and hydrobiology was conducted at the Kosino biological station, although after 1941 only occasional short-term observations were made (Shirokova and Ozerova 2019). In 2021, a regular year-round monitoring campaign was started on the Kosino Lakes, and combined with a hydrodynamic lake model, this data allows us to describe their modern regime and emerging climate-related trends. These results can be used to make general assessments of the effects of climate change on small stratified and polymictic lakes in areas with continental European climates.

MATERIALS AND METHODS

Study sites

Lake Beloe is the largest of the three Kosino lakes, with a surface area of 0.3 km^2 and a maximum depth of 17 m (Fig. 1). A thin channel connects Lake Beloe to the smaller and shallower Lake Chernoe (maximum depth about 3 m). Occasional flow of water occurs between the two lakes through the channel; during winter and summer, the channel typically remains frozen or nearly dry, and during periods of higher water levels, its depth does not exceed 0.5 m. Lake Chernoe itself was not considered within the bounds of this study due to insufficient data on its thermal regime and its more complicated morphometry (the presence of a large shallow zone with limited water exchange with the deeper part). There is also a small drainage outlet located at the south-western shore of Lake Beloe, where free flow into the municipal drainage system occurs when the water level reaches the outlet. Lake Svyatoe is the smallest of the three lakes, with a surface area of only 0.08 km^2 and a maximum depth of ~3 m. It is mostly surrounded by a 70–200 m wide strip of peat bog and does not have significant water exchange with any other water bodies.

The Kosino lakes historically had poor water quality due to eutrophication caused by their old age and exacerbated by anthropogenic pressure. Lake Beloe is dimictic, has a Secchi depth of 0.5–1.7 m (based on data of 2021–2024), and all water below 3–5 m depths is anoxic almost year-round (except for spring and autumn mixing periods) and contains hydrogen sulphide. Lake Svyatoe has a Secchi depth of 0.35–2.3 m; it is polymictic and has a lower dissolved salt and nutrient content; therefore, its oxygen regime is more favorable, but anoxic conditions may still spread for up to 1.5 m from the bottom in the summertime and take up almost all of the water mass in winter.

According to year-round manual observations on staff gauges maintained on the shores of both lakes throughout 2020–2023, Lake Beloe has an annual water level variation of 0.3–0.6 m, and Lake Svyatoe – about 0.2–0.5 m. In both lakes, the maximum water level is observed after snowmelt and is followed by a generally stable decline throughout the ice-free period.

Data collection

The data on the water temperature of lakes Beloe and Svyatoe was collected during the period of July 2021–December 2023. Monthly manual measurements of water temperature were taken at their deepest points with 1 m vertical resolution using a YSI Pro30 water temperature and conductivity meter. Buoys were also set up at the deepest point of each lake in ice-free months, with a chain of several HOBO Pendant water temperature loggers attached. On Lake Beloe, the loggers functioned in July–November 2021 and May–October 2023 at 0.5, 2, 4, 6, 10 and 15 m depths. On Lake Svyatoe, a buoy functioned during the same periods, and additionally, we set temperature loggers at 0.5, 1 and 2.5 m depths in late April–August 2022.

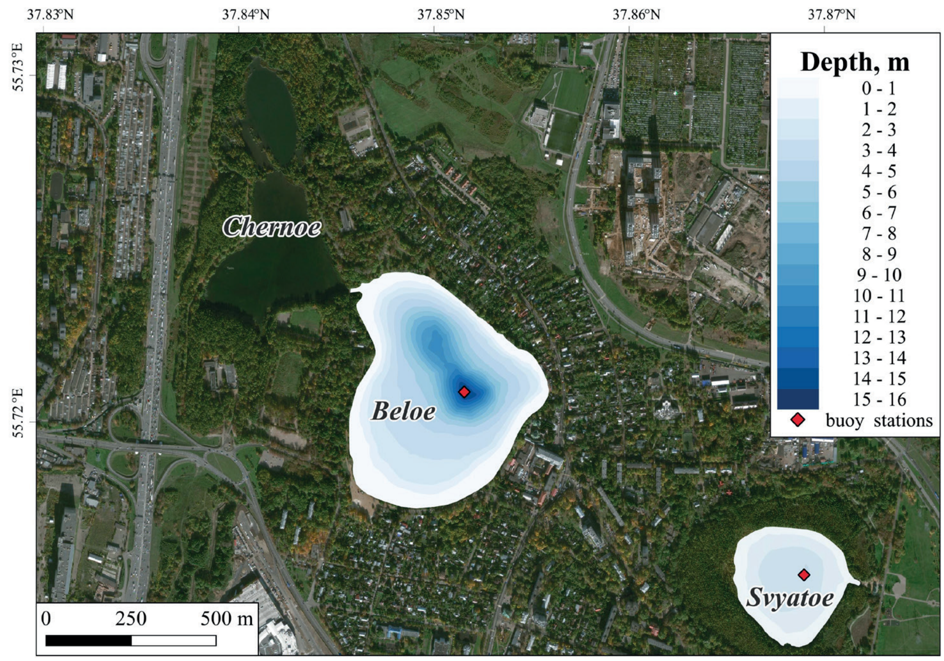

Fig. 1. Location and bathymetry of the Kosino Lakes

For lake bathymetry, a depth-area curve was approximated for each lake from the data of depth sounding made in the summer of 2020. As meteorological forcing, time series from ERA5 global reanalysis were used (Hersbach et al. 2020), and linearly interpolated to the lakes' coordinates between the nearest grid points.

There was no reliable data on surface and groundwater runoff for the lakes. Moreover, a large portion of the surrounding area drains into the municipal storm sewage system, and the high degree of urbanization in their watersheds limits the ability to model runoff. For the purpose of this study, the water balance of the lakes was only represented by surface mass fluxes (precipitation and evaporation) as calculated in the model based on meteorological data.

Model description and setup

The General Lake Model (GLM) is a one-dimensional model used for simulating lake hydrodynamics on seasonal and annual timescales. It utilizes a Lagrangian layer structure to simulate a lake's external water balance, heat budget, vertical mixing, and ice formation on a daily time step. External water balance includes surface mass fluxes, inflows, and outflows. The heat budget of the surface layer consists of shortwave and longwave radiation fluxes and sensible and latent heat fluxes. Mixing is simulated based on the balance of potential (PE) (Eq. 2) and available kinetic (TKE) energy (Eq. 1):

$$TKE = \left\{0.5C_K w_*^3 \Delta t\right\}_{conv} + \left\{0.5C_K C_w u_*^3 \Delta t\right\}_{wind} + \left\{0.5C_S\left(u_b^2 + \frac{u_b^2}{6}\frac{d\xi}{dz_{sml}} + \frac{u_b \xi}{3}\frac{du_b}{dz_{sml}}\right)\right\}_{shear} \Delta z_{k-1} \quad (1)$$

$$PE = \left[\left\{0.5C_T\left(w_*^3 + C_w u_*^3\right)^{2/3}\right\}_{accel} + \left\{\frac{\Delta p}{\rho_0} g z_{sml}\right\}_{lift} + \left\{\frac{g\xi^2}{24\rho_0}\frac{d(\Delta\rho)}{dz_{sml}} + \frac{g\xi\Delta\rho}{12\rho_0}\frac{d\xi}{dz_{sml}}\right\}_{K-H}\right]\Delta z_{k-1} \quad (2)$$

In model equations, TKE is made up of surface wind stress (*wind*), convective mixing (*conv*), shear production between layers, and Kelvin-Helmholtz billowing (*shear*). PE, on the other hand, is the amount of energy needed to lift water at the bottom of the mixed layer (*lift*), speed it up to the speed of the mixed layer (*accel*), and consume the energy that comes from making waves inside the layer (*K-H*). Internal heat balance also accounts for deep mixing based on constant or variable turbulent diffusivity in hypolimnion. A detailed description of model parameterization of hydrodynamic processes is provided in (Hipsey et al. 2019). A number of multi-lake studies (Read et al. 2014; Bruce et al. 2018; Prats et al. 2018) and cross-model comparisons (Golub et al. 2022; Ishikawa et al. 2022; Man et al. 2021) show that GLM is very good at simulating of the thermal regime of natural and man-made lakes in many places around the world.

In this study, we used GLM version 3.0.5 executed via the R package *GLM3r* and processed the output data with functions from the package *glmtools*. The required meteorological input data include daily shortwave and longwave radiation, air temperature, relative humidity, wind speed, and precipitation.

Model calibration was conducted via the random search function from the *FME* R package. It included adjusting model parameters to reach the minimal RMSE of water temperature, as well as a good representation of the water level and the timing of freezing and thawing of lakes. The model was calibrated on data from 2022–2023 and then its performance was validated based on data from 2021; data for a period of over two years of continuous water temperature measurements is considered sufficient in multi-model intercomparison studies, e.g., in works supporting the ISIMIP protocol (Mesman et al., 2020; Golub et al., 2022). The final values of the model parameters as well as the resulting model errors are presented in Table 1. Final RMSE values for the validation period were 1.45 °C for Lake Beloe and 1.19 °C for Lake Svyatoe.

The non-parametric Mann-Kendall trend test (Kendall 1975) as implemented in the *Kendall* R package was used to assess the statistical significance of the simulated trends on ice-on and ice-off dates and the parameters of summer stratification.

RESULTS

Freeze-up and ice-break dates

Lakes Beloe and Svyatoe show a high variation in freezing dates (Fig. 2). In the period from 1984–2023 the earliest ice-on date on Lake Beloe was November 10th, 1988, and the latest – December 26th, 2006. In 18 out of 40 simulated winters, the lake froze in the last ten days of November.

Table 1. Calibrated model parameters and model errors for calibration, validation, and whole simulation period

Parameter name	Parameter meaning	Lake Beloe	Lake Svyatoe
Kw	Light extinction coefficient	0.76	1.66
coef_wind_stir	Mixing efficiency – wind stirring	0.43	0.10
wind_factor	Scaling factor for wind speed	0.75	0.98
lw_factor	Scaling factor for longwave radiation	0.96	1.02
at_factor	Scaling factor for air temperature	1.02	0.98
snow_albedo_factor	Scaling factor for snow albedo	0.35	0.45
RMSE	– calibration (2022–2023)	0.90 (n=1026)	1.15 (n=809)
	– validation (2021)	1.45 (n=500)	1.19 (n=230)
	– whole period (2021–2023)	1.10 (n=1526)	1.55 (n=1039)

Lake Svyatoe, on average, freezes 2 days earlier than Lake Beloe and generally has the same long-term pattern of freeze-up dates with overall variation between November 4th and December 25th. In 1987, 1995 and 2021 ice cover on Lake Svyatoe appeared 10–16 days before Lake Beloe, but in all other cases, the difference between ice-on dates of the two lakes did not exceed one week. Although generally Lake Svyatoe freezes earlier, in 9 out of 40 simulated winters it froze 1–7 days later than Lake Beloe. This occurred in years where, following a fall cold period with negative air temperatures, as both lakes approached the freezing point, the daily air temperature rose by several degrees. In those years, the mean air temperature over the 10 days before freezing of Lake Beloe was on average –1.6 °C (–1.9 – +0.8 °C), while in other years it averaged –4.0 °C (–9.0 – –0.1 °C). While both lakes likely accumulated heat, the smaller Lake Svyatoe apparently heated more efficiently, which might also be aided by its lower transparency (light extinction coefficient of 1.66 versus 0.76 in Lake Beloe).

The ice-off dates of the two lakes showed much less variation: on Lake Beloe, break of ice cover occurred between March 28th and April 23rd; on Lake Svyatoe – between March 19th and April 19th. For Lake Beloe, in 29 out of 40 years, the ice-off occurred in the second ten days of April. For Lake Svyatoe, in 20 of the years it occurred in the first ten days of April, and for 19 of the years – in the second ten days of April. Lake Svyatoe lost ice cover 1–10 days before Lake Beloe (average 5 days).

For ice-on dates, despite the high variation, statistically significant (at $p<0.05$) trends of +2.4 and +3.1 days/decade were detected for lakes Beloe and Svyatoe. However, only Lake Beloe showed a significant trend of -1.5 days/decade for ice-off dates. Between 1982–2002 and 2003–2023, the total duration of ice cover decreased from 122–160 days to 99–151 days on Lake Beloe and from 118–157 days to 95–153 days on Lake Svyatoe. The mean trend of ice cover loss was –4.4 days/decade for Lake Beloe and –5.0 days/decade for Lake Svyatoe ($p<0.05$ in both cases). Changes in ice cover are also reflected in reduced ice thickness: while for the whole period maximum ice thickness varied between 23 and 67 cm, it is found to be declining at approximately 2 cm/decade, but these trends are not statistically significant.

Stratification duration

In this study, we classified a lake as stratified if the difference between the surface and bottom temperatures exceeded 1 °C, and defined the start of the stratified period as the date when this difference persisted for a minimum of 7 consecutive days. Over the simulation period, the stratified period on Lake Beloe began 1–22 days after ice melt – between April 11th (2008) and May 8th (1986). On Lake Svyatoe, periods of stratification over a week long did not occur before late April–May, or as late as 80 days after the ice-off date. The earliest onset of stratification on Lake Svyatoe was on March 31st (2007) and the latest – on June 13th (2021). On average, stratified period on Lake Beloe starts 7 days after ice melt, and on Lake Svyatoe – 22 days after ice melt.

Stratification on dimictic Lake Beloe remained unbroken for several months after its onset (Fig. 3), with fall mixing occurring normally from middle to late October. The earliest disruption of summer stratification occurred on September 28th in 1986, and the latest occurred on November 2nd in 2019. The uninterrupted stratified period lasted 143–198 days (183 days on average). It was followed by a mixing period of 18 to 65 days that ends with the formation of ice cover.

Lake Svyatoe is polymictic, and in 1983–2023 was characterized by 3 to 14 separate events of stratification onset and break per year (including periods when the lake became stratified for less than 7 days). The longest periods of uninterrupted stratification lasted for almost as long as on Lake Beloe: in various years they were 16 to 132 days long. Only in 5 out of 41 years did the longest period of stratification on Lake Svyatoe not reach 30 days; in most of the years, one stratified period of 50–90 days or two periods of 30–50 days occurred. Mixing between stratified periods lasted between 1 and 20 days. In total, Lake Svyatoe remained stratified for 66 to 143 days each year. After August, only shorter periods of stratification occurred (<20 days long), and in October they only lasted for up to 5 days. For the remaining 32 to 118 days in fall until the freezing of the lake, it remained in a nearly mixed state as it cooled off.

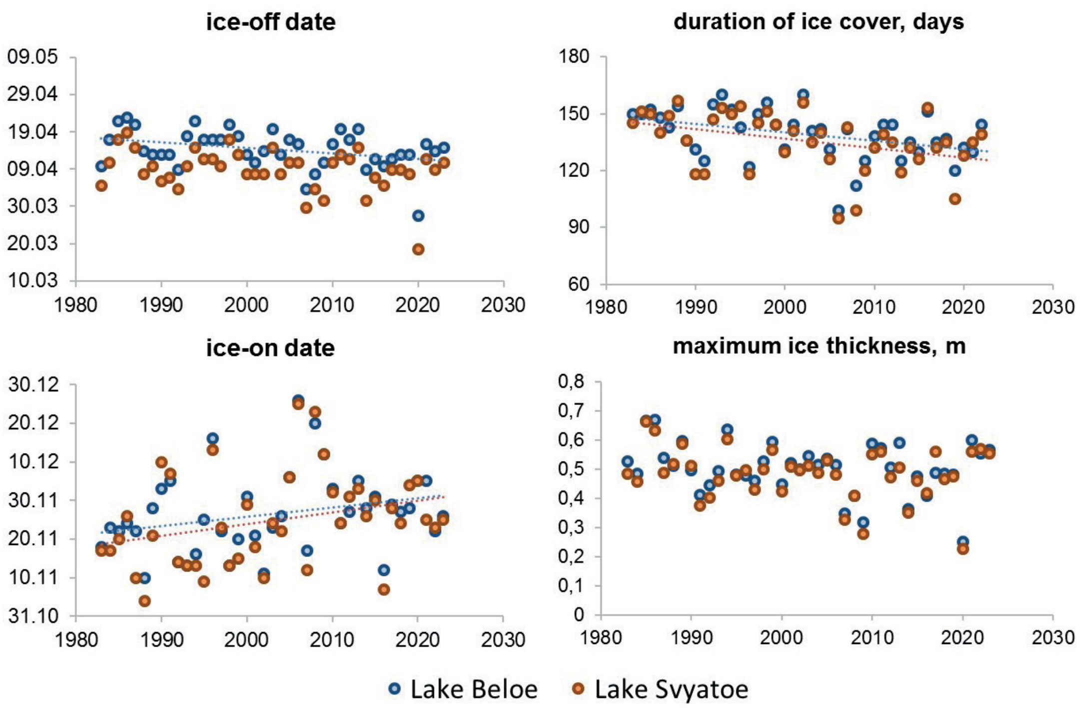

Fig. 2. Ice-off and ice-on dates, duration of ice cover, and maximum ice thickness on lakes Beloe and Svyatoe in 1983-2023. Dotted lines show statistically significant trends in time series

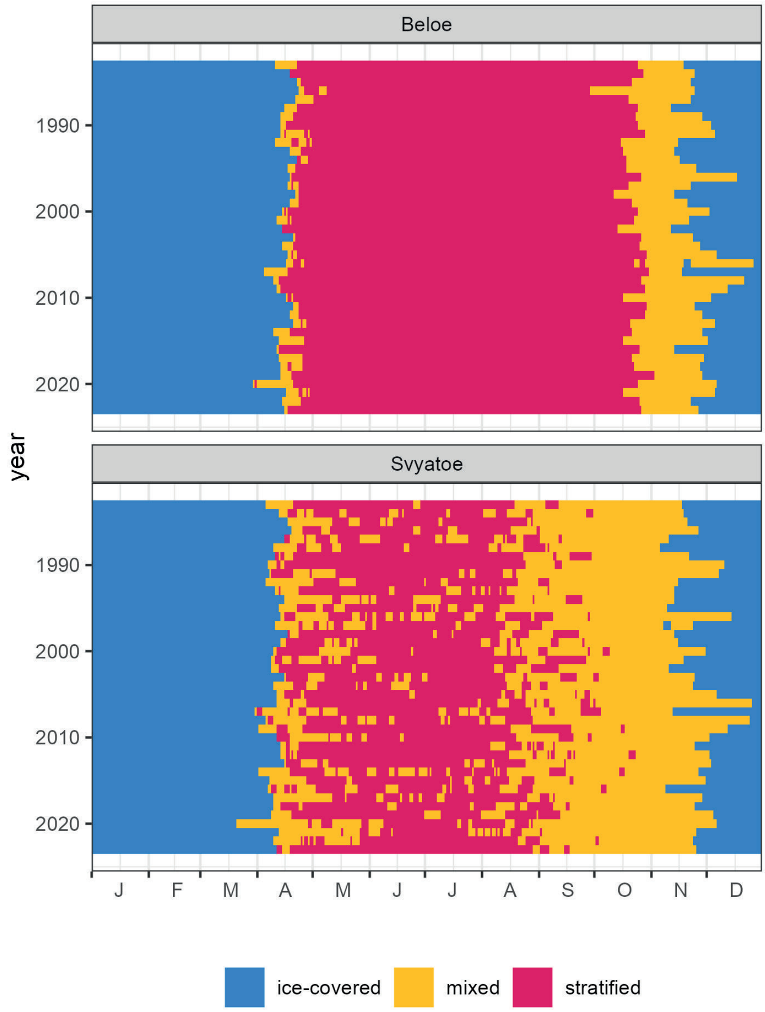

Fig. 3. Duration of ice-covered, mixed and stratified periods on lakes Beloe and Svyatoe based on simulations for 1983-2023

No statistically significant trends were detected for stratification onset, break, or duration for either of the lakes.

Water temperature

At the moment of stratification onset, the bottom temperature of Lake Beloe (at 0.5 m above lake bottom at the deepest point) varied between 4.2 and 7.9 °C. In general, higher bottom temperatures correspond to later stratification onset dates, but even in years with relatively fast stratification onset, the bottom layer can be relatively warm depending on wind conditions. For example, in 2008 the ice-off occurred on April 7th, but over the next 5 days, average air temperature of 12.8 °C and wind speed of 4.5 m/s caused the water temperature to reach 7.1 °C in the entire water column before the density gradient was enough to resist wind stirring. In most of the years, the bottom water temperature in Lake Beloe remained nearly constant (within 0.3 °C from starting temperature) during the whole period of summer stratification. There was a significant heat transfer into bottom layers only in 1997, 2009, 2017, and 2020. This was likely because heat moved slowly through the thermocline and into deeper layers during very warm times with little wind. This happened when the water temperature at the surface was high, which increased the vertical temperature gradient and, in turn, the vertical heat diffusion coefficient (Hondzo et al. 1991). Heating from the bottom sediments of the littoral zone or heat transport with dissipation of internal waves can also act as mechanisms of hypolimnion warming throughout the summer (Nishri et al. 2015). During the fall mixing, bottom water temperature rose by 1–3 °C from summer value; the maximum water temperature at the bottom of the lake at fall overturn reached 5.1–8.2 °C. The mean value of the bottom temperature for the stratified period was 7.2–7.7 °C.

In Lake Svyatoe, the bottom temperature during the summer is much more variable and follows the dynamics of air temperature and temperature of the surface layer more closely than in seasonally stratified Lake Beloe. At the first occurrence of prolonged (>7 days) summer stratification, the bottom water temperature of the lake varied between 4.3 and 19.3 °C, on average equaling 10.1 °C. At the moment of maximum heat storage, which normally occurred in August, the bottom water temperature reached 16.9–25.9 °C, and mean values for the summer period of intermittent stratification varied between 11.8 and 21.2 °C.

The surface temperatures of both lakes have been found to be almost synchronous (fig. 4). Maximum surface temperature mostly occurred in the second half of July and was within 22.8–31.9 °C for Lake Beloe and 24.3–33.6 °C for Lake Svyatoe. Mean surface water temperatures over the stratified period were 15.6–19.9 °C and 18.0–26.1 °C, respectively.

No statistically significant trends were detected for the start and mean bottom water temperature over the stratified period, but the maximum bottom temperature of Lake Svyatoe increased by 0.65 °C/decade. The mean summer surface temperature of Lake Beloe increased by 0.27 °C/decade, and the yearly mean water temperature increased by 0.26 and 0.22 °C/decade for lakes Beloe and Svyatoe, which corresponds to an increase of the mean annual heat storage by 1.21 and 0.17 J/m^2 per decade.

Simulated parameters of ice phenology, stratification, and thermal regime of both lakes in a more detailed form are presented in supplementary materials.

DISCUSSION

Ice-on and ice-off dates, as well as the water temperature of the Kosino Lakes, changed significantly between 1922–1929 (as published in reports of the Kosino biological station) and 2021–2023 (as observed during field work for this study). Our results and calculated trends allow to explore those changes in the recent decades in more detail. Based on our simulations, we calculated linear trend values for ice phenology, thermal regime, and stratification intensity for both lakes over different time periods (table 2). The obtained trends in surface water temperature over the first 20 years of simulation are close to the world average lake surface water warming rate of +0.34 °C/decade between 1985–2009 as summarized by O'Reilly et al. (2015) and mean warming rate of Central European lakes of +0.25 °C/decade (Dokulil et al. 2010). The increase in maximum surface water temperature at +0.42–0.44 °C/decade is also coherent with the average trend for European lakes of +0.58 °C/decade (Dokulil et al. 2021). The changes in water temperature are non-linear: the sharpest increase in water temperature occurred before 2013, which coincided with the steepest trend in air temperature over the summer period, while in the last decade the intensity of those changes decreased. Our data does not show a significant slowdown of water temperature rise in response to the "warming hiatus" of 1998–2012 as was found for many lakes of the Northern hemisphere (Winslow et al. 2018), but shows similar correlation between air and water warming rate at different aggregation periods and proves the necessity of using multiple decades of data for evaluating the intensity of climate change in lakes.

Both lakes are warming significantly slower than the ambient air: over the period of 1983–2023 the average air temperature warming trend was +0.53 °C/decade, while the surface water temperature of lakes only increased by 0.22–0.26 °C/decade. At the same time, a positive relationship between mean surface water temperatures over the whole year and the stratified period with air temperature is maintained with determination coefficients (r^2) of up to 0.40–0.81. On average, lakes of the world are warming faster than the air, but this varies regionally, and cases such as the Kosino Lakes are not rare (O'Reilly et al. 2015, Dokulil et al. 2021). Reduced intensity of lake surface warming can be caused by various feedback mechanisms, such as increased evaporation contributing to larger heat loss (Woolway et al. 2020). Adding wind speed to the regression model insignificantly enhances its predictive ability, as evidenced by an increase in r^2 of less than 0.05. This suggests that wind plays a minor role in the lakes' thermal regime during the current period.

Maximum bottom water temperature over the summer period has changed insignificantly for Lake Beloe, but for Lake Svyatoe it is increasing at a faster pace than mean surface temperature. Deep lakes around the world can show increasing or decreasing trends in bottom water temperature (Gerten and Adrian 2001), and for shallow polymictic lakes, the direction of its change depends on whether or not a lake is shifting into a dimictic regime. Lake Svyatoe does not show a statistically significant increase in duration or intensity of stratification, and its main tendency is currently towards a rise in bottom water temperature, which may negatively affect its water chemistry and biota.

The shift in ice phenology is one of the most prominent features of ongoing changes in temperate and high-latitude lakes (Sharma et al. 2021). Like many of the researched European and North American lakes, the Kosino Lakes experience a gradual decrease in ice cover period length at –4.4–5.0 days/decade, as well as increasingly frequent years with extreme ice phenology, such as multiple freezing and thawing events. For the Kosino Lakes and many other mesotrophic and eutrophic lakes in European Russia, the mixing regime and duration of ice cover are a defining trait for the entire ecological state. A decrease in the duration of the ice-covered period may have a positive impact on their

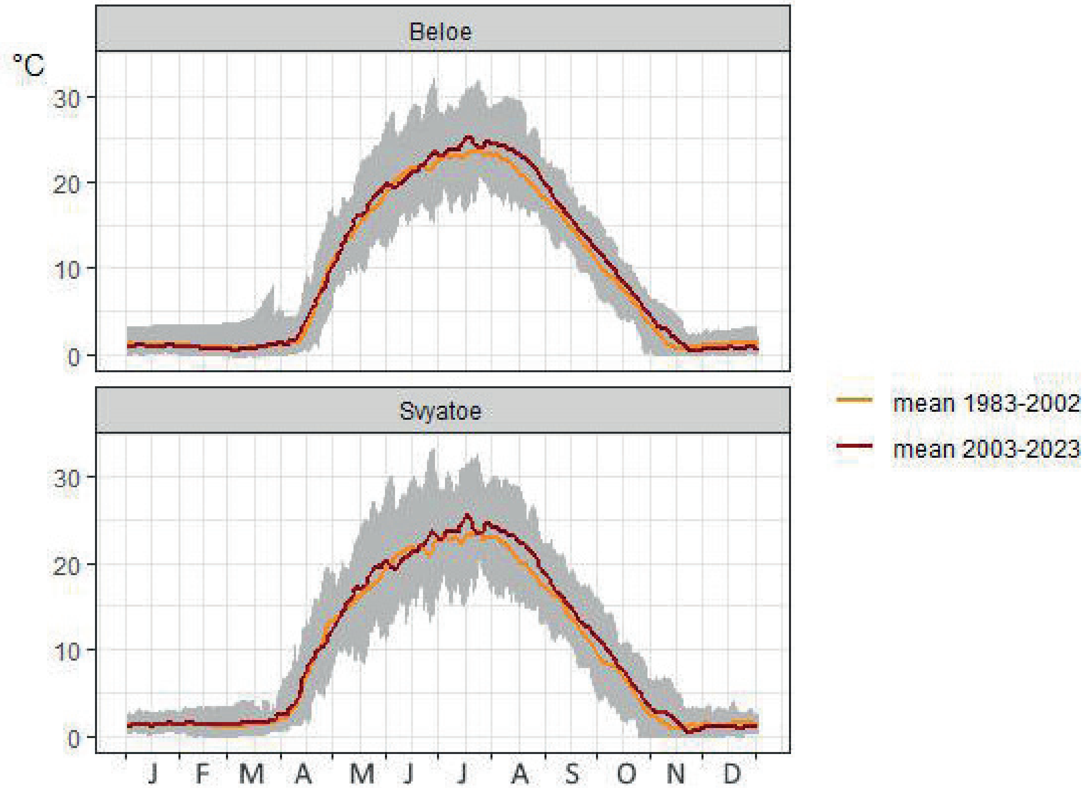

Fig. 4. Variation of surface water temperature of lakes Beloe and Svyatoe (grey) and mean daily surface water temperatures for periods of 1983–2002 and 2003–2023

Table 2. Mean linear trend coefficients for characteristics of climate, ice phenology and thermal regime of lakes Beloe and Svyatoe over various aggregation periods

parameter	unit (per decade)	Beloe			Svyatoe		
		1983-2003	1983-2013	1983-2023	1983-2003	1983-2013	1983-2023
mean air temperature (year)	°C	+0.50	+0.53**	+0.53***	+0.50	+0.53	+0.53
mean air temperature (April–November)	°C	+0.32	+0.70***	+0.48***	+0.32	+0.70***	+0.48***
mean wind speed (April–November)	m/s	–0.09*	–0.08**	–0.02	–0.09*	–0.08**	–0.02
ice-off date	days	–0.2	–0.7	–1.5*	–0.05	–0.8	–1.4
ice-on date	days	–0.2	+4.9*	+2.4*	+0.6	+6.1*	+3.1*
duration of ice cover	days	–1.3	–6.4*	–4.4**	–1.9	–7.8**	–5.0**
duration of stratification[1]	days	+3.6	+4.3	+2.4	+12.3	+10.4	+2.0
mean surface water temperature (year)	°C	+0.32	+0.40***	+0.26***	+0.24	+0.39***	+0.22***
mean surface water temperature (stratified period)	°C	+0.28	+0.39*	+0.27*	–0.08	+0.26	+0.32
max. surface water temperature (stratified period)	°C	+1.23	+0.96*	+0.44	+1.27	+0.97*	+0.42
maximum bottom water temperature (stratified period)	°C	–0.15	–0.09	+0.03	+0.69	+0.75	+0.65*
mean heat storage (year)	J/m²	+2.7*	+1.7**	+1.2***	+0.22	+0.28***	+0.17**
maximum heat storage (stratified period)	J/m²	+6.1*	+3.9**	+2.2*	+1.0	+0.7*	+0.3
mean Schmidt stability (stratified period)	J/m²	+2.5	+4.7*	+2.9	+0.1	+0.2	+0.04

*[1] duration of stratification for Lake Svyatoe given as the sum of days with difference between surface and bottom water temperature >1 °C. Significance levels: *p<0.05 **p<0.01 ***p<0.001*

ecosystems, significantly improving oxygen availability in deeper layers and reducing the risk of winter fish-kills and the accumulation of dissolved nutrient elements during winter (Woolway et al. 2020). However, increasing availability of light might lead to a rise in phytoplankton production.

The absence of significant changes in the duration of the stratified period and bottom water temperature in stratified Lake Beloe suggests that ecological conditions in its hypolimnion during summer remain nearly unchanged, although this can change with future warming. For shallow Lake Svyatoe, patterns of summer mixing do not seem to have changed significantly, but enhanced heating has caused higher water temperature in all of the layers, which may affect aquatic organisms and biogeochemical processes, causing faster eutrophication than in deeper lakes.

CONCLUSIONS

Our simulations show noticeable and statistically significant changes in the ice and thermal regime of the Kosino Lakes. Some of the most dramatic changes are found in the loss of ice cover at 4–5 days/decade. Later ice-on dates contribute more to this change then earlier ice break-up dates, much like in other lakes of the Northern Hemisphere (Sharma et al. 2021). In 1984–2023, mean surface water increases at 0.2–0.3 °C/decade for both lakes. The strongest changes occurred in 1983–2013 at 0.4 °C/decade, which is close to the global average trend for 1985–2009 of 0.34 °C/decade, but slightly less than was found for European lakes (O'Reilly et al., 2015). Maximum surface water temperature increases at +0.42–0.44 °C/decade, which is also coherent with the average trend for European lakes of +0.58 °C/decade (Dokulil et al. 2021).

Over the period of 1983–2023 no statistically significant changes in stratification duration have occurred for either the dimictic Lake Beloe or polymictic Lake Svyatoe, and water column stability in Lake Beloe only increased significantly in 1983–2013 and not in a larger aggregation period of 1983–2023. Maximum bottom water temperature in the polymictic Lake Svyatoe also increases at +0.65 °C/decade. These findings show that there is no significant trend towards strengthening of stratification in either the polymictic or dimictic lake. Changes in mixing regime are some of the most irregular, as opposing trends are found throughout global lakes (Woolway et al., 2020).

The lake surface water has warmed up almost two times slower than the atmospheric air (0.22–0.26 °C/decade vs 0.53 °C/decade, respectively), but surface water temperature is closely correlated with air temperature. This relationship suggests that the thermal feedback of increased evaporation is more significant in the Kosino Lakes than in many lakes globally (Dokulil et al. 2021; Woolway et al. 2020). Aggregations over different time periods show a large variation in trend estimations, which underlines the importance of long-term data availability for reliable estimates of climate-related changes in lakes. Wind speed plays only a small part in determining changes in lake water temperature or stratification.

The case study of Kosino Lakes shows that ice regime and water temperature are currently among the most affected physical characteristics of lakes in this region, while the duration and intensity of thermal stratification are more stable. This implies that the winter regime of lakes in Central Russia and their extreme thermal conditions require close attention in environmental research and planning.

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