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Worldwide alteration of lake mixing regimes in response to climate change

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Lakes hold much of Earth's accessible liquid freshwater, support biodiversity and provide key ecosystem services to people around the world. However, they are vulnerable to climate change, for example through shorter durations of ice cover, or through rising lake surface temperatures. Here we use a one-dimensional numerical lake model to assess climate change impacts on mixing regimes in 635 lakes worldwide. We run the lake model with input data from four state-of-the-art model projections of twenty-first-century climate under two emissions scenarios. Under the scenario with higher emissions (Representative Concentration Pathway 6.0), many lakes are projected to have reduced ice cover; about one-quarter of seasonally ice-covered lakes are projected to be permanently ice-free by 2080–2100. Surface waters are projected to warm, with a median warming across lakes of about 2.5 °C, and the most extreme warming about 5.5 °C. Our simulations suggest that around 100 of the studied lakes are projected to undergo changes in their mixing regimes. About one-quarter of these 100 lakes are currently classified as monomictic—undergoing one mixing event in most years— and will become permanently stratified systems. About one-sixth of these are currently dimictic—mixing twice per year—and will become monomictic. We conclude that many lakes will mix less frequently in response to climate change.

Documented climate-related changes in lakes include shorter durations of winter ice cover[1–4] and higher lake surface temperatures[5–9]. Recent global studies of lake surface temperature trends show that many lakes, predominantly those that experience seasonal ice cover, are warming at rates in excess of ambient air temperature[7,8]. Studies of lake temperature responses to climate change have improved our understanding of the consequences of warming on lake ecosystems[10,11]. Here, we assess how projected climate trends are likely to change lake stratification and mixing for 635 globally distributed lakes. As these aspects of lake dynamics exert substantial control on nutrient fluxes, oxygenation and biogeochemical cycling[12,13], it is critical that stratification and mixing are considered to anticipate the repercussions of temperature change throughout lake environments and associated ecosystems.

Stratification and mixing regimes in lakes

Thermal stratification occurs in lakes as a result of the thermal-expansion properties of water. The time evolution of stratification is determined by the balance between turbulence, which acts to enhance mixing, and buoyancy forces, which act to suppress turbulence and result in a vertical layering[14]. The vertical layering that exists during stratification exerts strong control on the transport of nutrients and oxygen between the surface and deep water of lakes and the vertical distribution and composition of lake biota. Lakes that are permanently mixed (continuous cold/warm polymictic) or those that mix frequently (discontinuous cold/warm polymictic) differ markedly in their physical, chemical and biological functioning from lakes that are stratified permanently (meromictic) or semi-permanently (oligomictic, characterized by variable temporal periods of incomplete mixing, interspersed with occasional mixing)[14,15]. Lakes that stratify seasonally can be classed as dimictic if they have two stratification seasons, or monomictic (cold or warm) if they stratify only once per year (see Methods; Supplementary Fig. 1). Seasonal mixing serves as a basis for the classification of lake regimes[16] and as a necessary component of projecting how lake ecosystems will respond to climate change.

The mixing class to which a lake belongs depends primarily on whether or not it experiences ice cover annually and the number of times during a year in which it stratifies continuously (Supplementary Fig. 1). Ice-covered lakes tend to occur in less-maritime, high-latitude and high-elevation regions (Fig. 1a). Satellite observations of 635 lakes (Supplementary Table 1), ~50% of which experienced ice cover annually, illustrate that the climatological duration of ice cover varies systematically with mean air temperature (Fig. 1b; produced using air temperature from the ERA-Interim reanalysis[17]). With regards to the stratification criterion for mixing class, surface water temperature observations can be used to distinguish between dimictic and monomictic (cold or warm) lakes (Fig. 1c,d): in warm monomictic lakes, the surface water temperature does not cool below 4 °C (near the maximum density of freshwater), whereas in cold monomictic lakes, the surface water temperature does not warm above 4 °C. No threshold in the lake surface water temperature separates thermally stratifying and polymictic lakes, as other factors can have a substantial influence, particularly lake depth (shallow lakes can mix easily). The global heterogeneity of lake sizes and depths[18,19] suggests that lake mixing classes should be heterogeneously distributed.

Global patterns of lake mixing regimes

In this study, we assess the contemporary mixing class of 635 lakes worldwide by developing a classification scheme applied to numerical simulation results from a lake model, and then use this model to project future mixing classes under climate change scenarios. This approach enables meromictic, oligomictic, monomictic, dimictic and polymictic mixing classes to be determined.

To assess the contemporary mixing classes, we first optimize key parameters of the lake model, FLake[20,21], to represent the dynamics of each individual lake. The optimization constrains the model to

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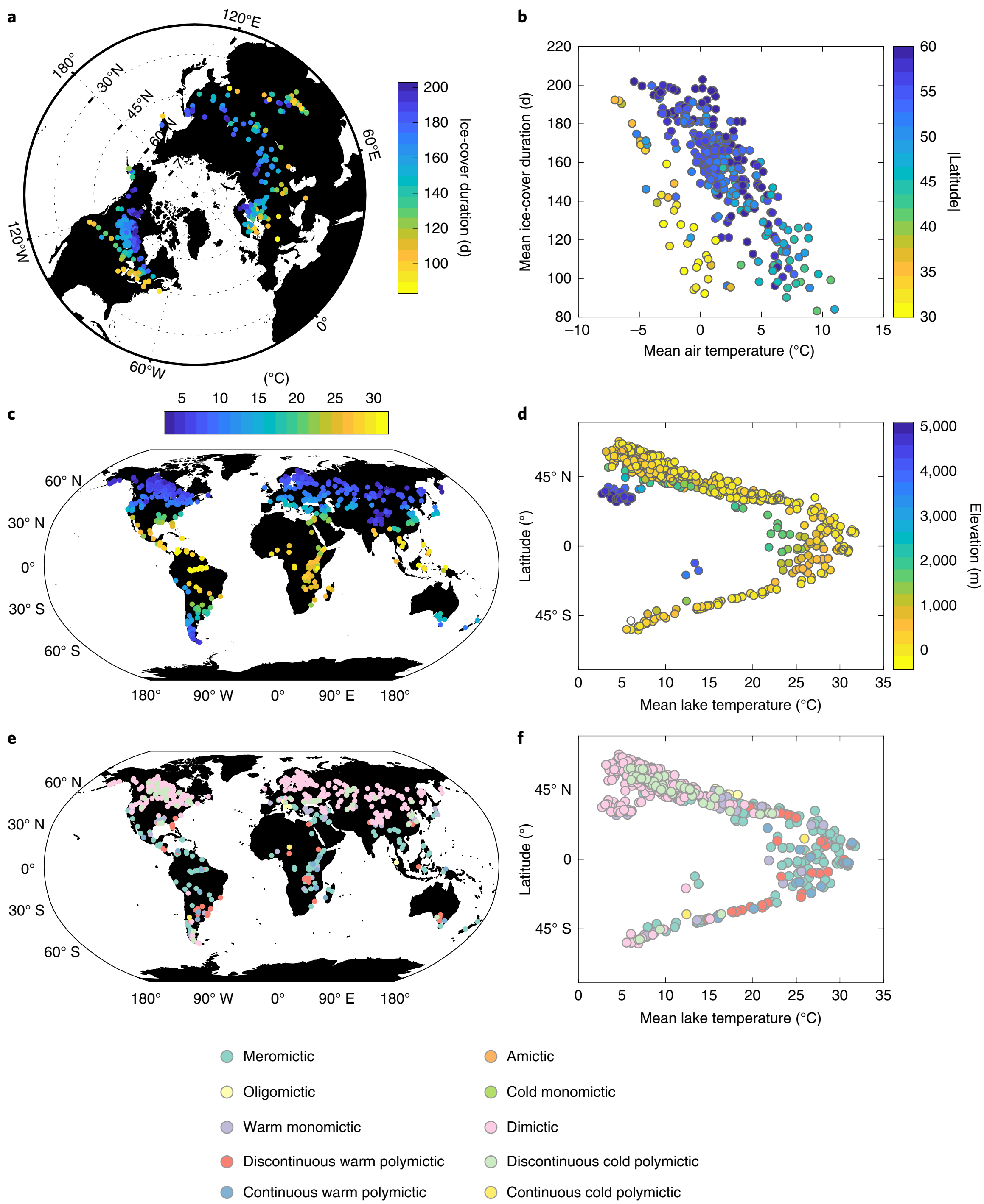

Fig. 1 | Global patterns in annual mean ice-cover duration, lake surface temperature and lake mixing regimes for the period 1995–2005. a, Map of satellite-derived ice-cover duration. **b**, Mean satellite-derived ice-cover duration versus air temperature coloured according to latitude (colour scale). Data for **b** from ERA-Interim[17]. **c**, Global variation in satellite-derived lake surface water temperature. **d**, The relationship of satellite-derived lake surface water temperature with latitude and elevation (colour scale). **e**, Global variations in modelled lake mixing regimes. **f**, The relationship of modelled lake mixing regime with latitude and lake surface water temperature. Mixing regimes were identified using the classification scheme of ref. [16], extended to include an oligomictic class, evaluated from a lake model forced by bias-corrected HadGEM2-ES projections. (Lake mixing regimes identified using bias-corrected projections from other climate models are shown in Supplementary Fig. 8).

represent observed lake surface water temperature time series (see Methods). The ability of the optimized lake model to represent a wide range of lake dynamics is evaluated by comparing simulations with independent temperature observations, ice cover and lake mixing regimes under historic climate conditions. Good agreement is obtained (Supplementary Figs. 2–7). The lake model is able to accurately simulate historic multidecadal variations in lake temperature back to the start of the twentieth century (Supplementary Fig. 4) and to successfully identify the mixing regime of 72% of lakes for which independent mixing regime classifications were found

(Supplementary Fig. 7; Supplementary Table 2), supporting its utility for multidecadal projections. Up to 85% of interdecadal variability in lake surface temperature is explained by the lake model forced with representations of historic climate conditions.

The lake mixing regimes identified demonstrate a diverse array of mixing types (Fig. 1e,f). Dimictic lakes are most common in our global dataset (Supplementary Fig. 8)—a result of the majority of our study lakes being relatively large (all studies lakes exceed 27 km² in area) and situated north of 40° N, where the global lake abundance is highest[18]. The proportion of dimictic and polymictic lakes is large in northern temperate latitudes, as expected, and meromictic lakes are common in the tropics (Fig. 1e,f).

Climate-related changes in lake mixing regimes

To project future changes in mixing class, the lake model is forced by four climate projections available from the Inter-Sectoral Impact Model Intercomparison Project[22], namely, HadGEM2-ES, GFDL-ESM2M, IPSL-CM5A-LR and MIROC5 (see Methods for details), under two Representative Concentration Pathway (RCP) scenarios. The three figures in this paper show the results from the lake model forced with bias-corrected HadGEM2-ES projections. To indicate the uncertainty of projections, we show or quote the spread of results from the lake model across all four climate model projections. Changes projected for 2080–2100 are quoted relative to the period 1985–2005.

The responses of lake mixing regimes to climate change are complex and may not be associated closely with change in any one climatic variable. The mixing regime of a lake will instead depend on changes in a combination of climatic factors that contribute to the lake heat budget (such as air temperature, solar and thermal radiation, cloud cover, wind speed, humidity). Under future scenarios RCP 2.6 and 6.0, we project that the number of annual ice-covered days will decrease substantially (Fig. 2a,b) by 2080–2100. For RCP 2.6, the average decrease is 15 days (across all lakes that are seasonally ice covered during the historic period) and the standard deviation of this mean change across the four-member ensemble is 5 days. For RCP 6.0, the projected mean change is -29 ± 8 days. In the most extreme cases under RCP 6.0, the projected decreases in ice-covered days exceed 60 days. The simulations project that 24 ± 5% of lakes that display winter ice cover in the historic period will be ice-free by the end of the twenty-first century under RCP 6.0. The increase in annual mean lake surface temperature is projected to be 1.1 ± 0.4 °C and 2.3 ± 0.6 °C under RCP 2.0 and 6.0, respectively (Fig. 2c,d), by 2080–2100. For individual lakes, projected warming can be higher, the largest projected increase being 5.4 ± 1.1 °C under RCP 6.0; 99 ± 0.5% of lakes are projected to experience higher mean tempeartures under RCP 2.6, and all (100 ± 0%) increase under RCP 6.0.

Decreases in winter ice cover and increases in lake surface temperatures would be expected qualitatively to modify the distribution of lake mixing regimes. Next, we investigate the global extent and magnitude of response in the projections to quantify this expectation. The projections suggest that alterations in lake mixing regimes will occur during the twenty-first century (Fig. 3, Supplementary Figs. 9,10). Specifically, in the projections under RCP 2.6 and 6.0, 59 ± 7 and 96 ± 15 lakes change mixing class, respectively.

The most common identified alteration in mixing class (25 ± 5% of altered lakes under RCP 6.0) is a change from warm monomictic to meromictic. This means that a substantial minority of lakes that do not now experience ice cover and stratify once annually are projected to become permanently stratified systems by the end of the twenty-first century. In addition, all of the lakes identified as being oligomictic during the historic period transition to the meromictic class by 2080–2100. A lack of vertical mixing by the end of the twenty-first century will result in reduced upwelling of nutrients from deep to shallow waters and a decrease in deep-water oxygen concentrations, which can lead to reduced lake productivity[10] and the formation of deep-water dead zones[12], respectively. Oxygen depletion at depth can be detrimental to the habitat for fish[23] and can modify biogeochemical processes resulting in, for example, the potential release of phosphorus and ammonium into the water column[24] and the production of potentially toxic metal ions[25].

The second most common alteration in mixing class identified (across the model ensemble) is a change from dimictic to warm monomictic (17 ± 5 % of altered lakes under RCP 6.0) (Fig. 3, Supplementary Figs. 9,10). This alteration occurs when lakes that were historically ice covered no longer freeze in winter but still stratify during summer. The projected absence of winter ice has implications for those lake ecosystems, including (among other things) changes in water quality[26] and the production and biodiversity of phytoplankton[27].

A very small number of altered lakes are projected to experience fewer continuous periods of stratification and, as a result, to transition from dimictic to polymictic mixing classes. Such an increase in mixing can be a result of changes in any of the meteorological drivers acting at the lake surface. Short-term variations in surface wind speed, for example, can play an important role in lake stratification and mixing, and could nudge some lakes to a different mixing regime[28]. However, the influence of changes in wind speed would be expected to have the most pronounced effects on the mixing regime of shallow lakes. All the lakes that are projected to undergo an increase in the number of mixing events per year are among the shallowest 1% of the lakes studied. Other factors that were not considered in this study may also be important for alterations in mixing regimes in specific lakes, such as groundwater inputs[29], increased inflow of cold water from retreating glaciers[30], thermal pollution from nuclear plants[31] and changes in the magnitude of influent water[32], which will be particularly important for lakes with short residence times or extensive lake level variations[33]. Changes in lake transparency can also influence the mixing regime of lakes[34], but are not expected to be a dominant driver of mixing regime alterations in large lakes, such as those included in this study. The influence of transparency on lake mixing and stratification has been shown to decrease with increasing lake size[35,36] and the vertical thermal structure would be constrained strongly by fetch[37]. Thus, transparency is expected to have a greater influence on the vertical thermal structure of relatively small lakes compared with larger ones, as investigated in this study.

There is scattered evidence of mixing regime alterations already taking place, and the ecological consequences of these changes are starting to appear[38,39]. Our projections of future lake mixing regime alterations span a wide range of locations, sizes and climatic contexts, and suggest a complex pattern of lake responses to climate change. The geographical distribution of alterations in lake mixing regimes is heterogeneous, because climatic conditions interact with lake-specific contexts—particularly geomorphology. The projections do not support simple expectations of regional consistency in lake responses whereby lakes in a given region will change in a similar manner. Changes in lake temperature will not always translate to changes in lake mixing regimes: some of the lakes that are projected to experience the highest surface warming are not projected to undergo a change in their mixing class. Most lakes that are projected to alter their mixing regimes currently display anomalous mixing behaviour relative to their dominant mixing classification in some years. Specifically, two-thirds of lakes that are projected to experience an alteration in their mixing regimes had at least three years of anomalous mixing regimes during the period 1985–2005. Lakes that are classified as warm monomictic at present but fail to mix fully during some winters account for 60% of those that are projected to become meromictic (that is, permanently stratified) in the future. Lakes that are seasonally ice-covered and are classified as dimictic at present, but also experience some ice-free winters,

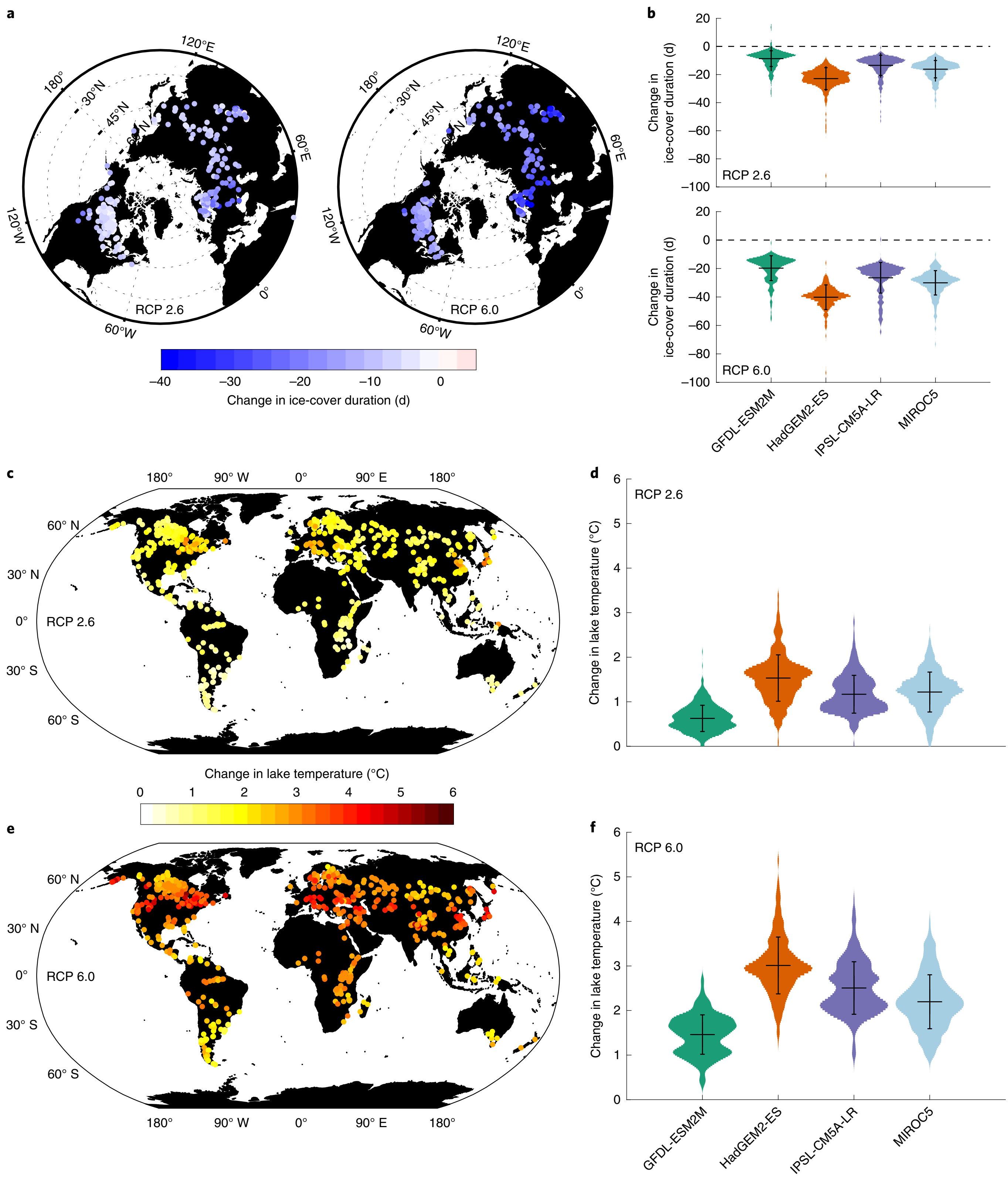

Fig. 2 | Global changes in annually averaged ice-cover duration and lake surface water temperature. All changes are for 2080–2100 relative to 1985–2005. **a**, Changes in ice-cover duration under RCP 2.6 and 6.0 (shown only for Northern Hemisphere lakes) from a lake model forced with bias-corrected HadGEM2-ES projections. **b**, All climate model projections from ISIMIP2b for RCP 2.6 and RCP 6.0. The kernel density estimates are also shown by the horizontal widths of the coloured areas. **c**–**f**, Changes in the annual average lake surface temperature under RCP 2.6 (**c**,**d**) and RCP 6.0 (**e**,**f**), showing results from the lake model forced with HadGEM2-ES projections (**c**,**e**) or all models (**d**,**f**). In **b**, **d** and **f** the mean (horizontal line) and s.d. (error bars) are also shown (black).

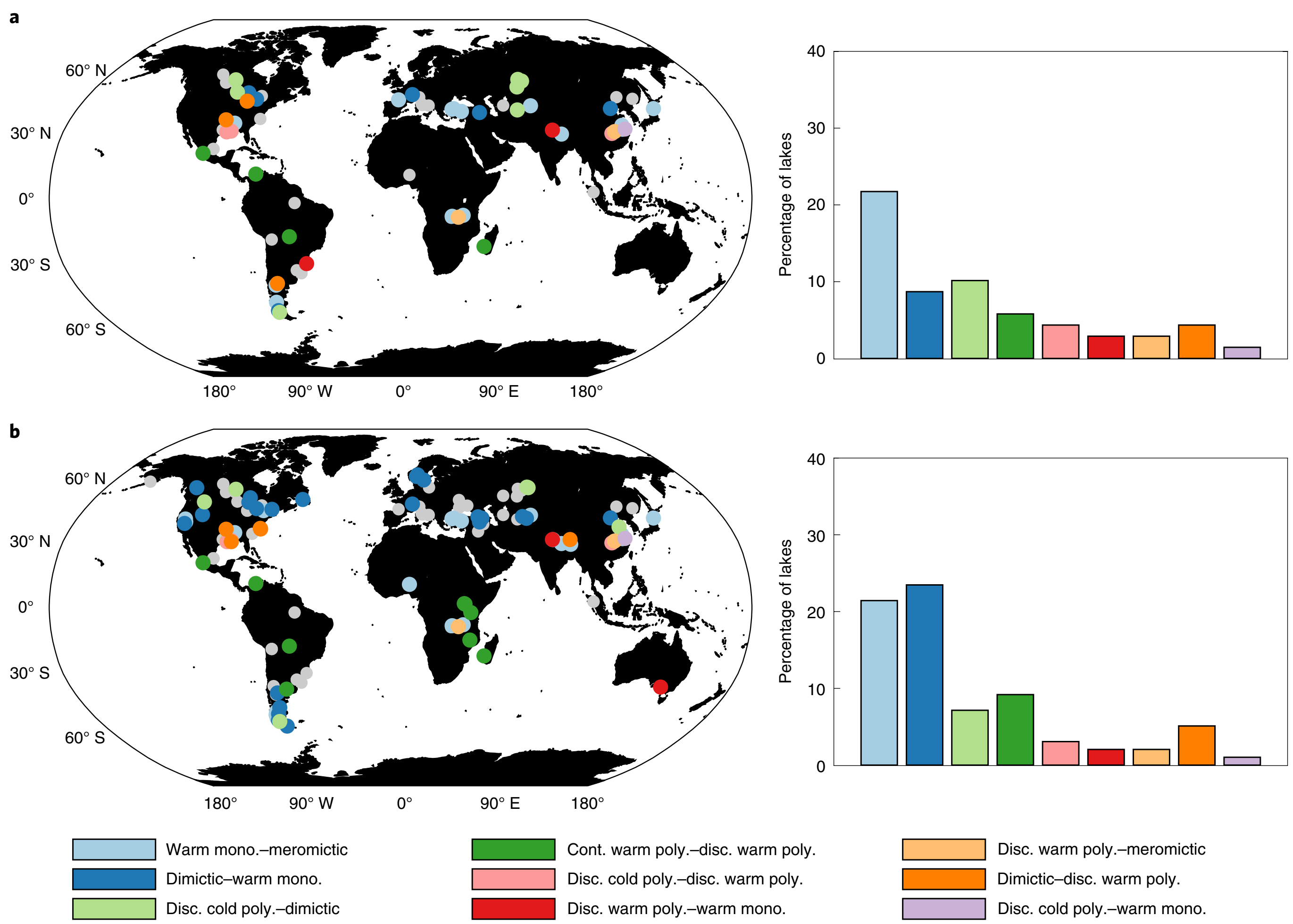

Fig. 3 | Global changes in lake mixing regimes. All changes are for 2080–2100 relative to 1985–2005. **a**,**b**, Climate-related changes in lake mixing regimes under RCP 2.6 (**a**) and RCP 6.0 (**b**) using a lake model forced with bias-corrected HadGEM2-ES projections (comparisons of lake mixing regime alterations identified using bias-corrected climate projections from other climate models is shown in Supplementary Figs. 9,10). Every lake that experiences a mixing regime alteration is shown in grey in the maps and the most frequent mixing regime alterations (encompassing 80% of the identified mixing regime shifts) are shown with individual colours (see legend). Cont., continuous; disc., dicontinuous; mono., monomictic; poly., polymictic.

are projected to become predominantly monomictic by the end of the twenty-first century. Thus, the projections confirm the intuition that those lakes that currently exhibit anomalous years relative to their usual mixing class are more likely to transition to a different mixing regime in the future.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41561-019-0322-x.

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Author contributions

Both authors developed the concept of the study, designed the analytical experiments, interpreted the results and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Study sites. The lakes investigated in this study ($n=635$) vary in their geographic and morphological characteristics (Supplementary Table 1).

Satellite-derived lake temperature and ice-cover data. We use lake surface temperatures from the Along Track Scanning Radiometer (ATSR) Reprocessing for Climate: Lake Surface Water Temperature and Ice Cover (ARC-Lake) dataset[40]. Briefly, the ARC-Lake surface water temperatures were obtained as follows. Within prescribed lake boundaries a water-detection algorithm using the reflectance channels of the ATSR-2 and AATSR instruments was applied to determine the extent of each lake during the ATSR-2/AATSR period considered (1995–2011). Within these boundaries, a Bayes' theorem calculation of the probability of clear-sky conditions was performed for each image pixel, day and night[41]. For pixels with high clear-sky probability, the lake surface water temperature was retrieved from the ATSR-2/AATSR thermal imagery, using an optimal estimation method adapted from radiative-transfer physics-based techniques that have been extensively validated for sea surface temperature[42]. Temperature estimates were gridded and spatio-temporally gap-filled using dynamically interpolating empirical orthogonal functions[43]. For a fuller account, refer to ref. [40]. Daily lake-mean time series were obtained by averaging across the lake area. Lake-mean surface temperatures are used to average across the intralake heterogeneity of surface water temperature responses to climate change[44] and to correspond to the lake-mean model used (see below).

The effectiveness of the lake product retrieval algorithms in ARC-Lake has previously been assessed using a dataset of matches to in situ temperature data, consisting of 52 observation locations covering 16 lakes and >5,500 individual matches[40]. Overall, agreement was -0.2 ± 0.7 °C for daytime and -0.1 ± 0.5 °C for night-time matches. ARC-Lake data have been independently validated as part of other studies[45] and used to corroborate lake simulations[46,47]. In this study we use daily averaged LSWTs, calculated as the average of the day- and night-time retrievals. To assess the periods during which a lake was probably partially or wholly ice covered from the daily mean temperature time series, we follow ref. [48], and characterize this as the period during which the lake-mean surface water temperature is <1 °C. This corresponds closely to the presence of ice cover on lakes from in situ observations[48].

The ARC-Lake observations were also used to quantify global patterns in mean lake temperatures and as part of the validation (see below) of the modelled surface temperatures and ice-cover duration in lakes globally (Supplementary Figs. 2,5).

Lake model. To simulate depth-resolved lake temperatures, as is required to identify mixing regimes in lakes, we used the one-dimensional thermodynamic lake model FLake[20,21]. FLake is a simplified lake model that is in some instances less accurate than other more computationally expensive models[49], but can be efficiently coupled with climate models and is useful for evaluating the impact of climate change projections on lakes[45]. FLake is used widely both for research and as a component in numerical weather prediction[50,51]. It has been tested extensively in past studies, including detailed validations across a spectrum of lake contexts. FLake has been used previously for validated simulations of the vertical temperature profiles, as well as changes to the mixing regimes, of polymictic and dimictic lakes[31,34,52], and has been shown to accurately reproduce bottom water temperatures as well as the depth and seasonality of the upper mixed layer and thermocline in meromictic lakes[45,53,54]. The model has also been used to reproduce past variability in ice-cover timing, intensity and duration[55], and to investigate the thermal response of polymictic, monomictic and dimictic lakes to large-scale climatic shifts[56]. The integrated approach implemented in FLake allows a realistic representation of the major physics behind turbulent and diffusive heat exchange in lakes; it includes a module to describe the vertical temperature structure of the thermally active layer of bottom sediments, as well as its interaction with the water column above. Most of the lakes investigated in this study all have depths <60 m, an established criterion for the applicability of the FLake model in global studies[46,50]; a few deeper lakes are included for which we had independent validation of the ability of FLake to simulate mixing regime (Supplementary Table 1).

The meteorological variables required to drive FLake are air temperature at 2 m, wind speed at 10 m, surface solar and thermal radiation, and specific humidity. Lake-specific parameters must be set to simulate individual lakes optimally in FLake. These parameters comprise fetch (m), which we fix in this study to the square root of the lake surface area, lake depth (m), lake ice albedo and the light attenuation coefficient (K_d, m^{-1}).

The prognostic variables needed to initialize FLake simulations include: (1) mixed-layer temperature, (2) mixed-layer depth, (3) bottom temperature, (4) the mean temperature of the water column, (5) temperature at the upper surface of the ice (if present) and (6) ice thickness (if present). To initialize the model runs from physically reasonable fields, we began each model run from a perpetual-year solution for the lake state. To find this solution for the initialization state, the model parameters are set as follows: mean depth was extracted from the Hydrolakes database[19], which includes observational and geo-statistical model estimates of lake depths worldwide; K_d was set to 3 m^{-1} (ref. [50]); and lake ice albedo was set to 0.6 (ref. [21]). The perpetual-year solution is obtained by repeating the forcing from a representative year and running FLake until the annual cycle in the modelled lake state is stabilized. The forcing data to derive the initialization conditions are from the ERA-Interim reanalysis product[17], available at a latitude and longitude resolution of 0.75°.

To optimize FLake simulations for each lake, we then use the model-tuning algorithm of ref. [57]. This approach estimates the model parameters (lake depth, K_d and ice albedo; Supplementary Table 1) to closely reproduce the observed surface temperature dynamics, specifically by minimizing the mean square differences between the model and ARC-Lake surface water temperatures over the satellite period, in simulations initialized from the perpetual-year solution described above. The lake-specific parameters for the model are thus set without reference to any in situ data or to the climate model forcing fields used for the historical-period simulation and future projections (see below). Note that although the optimization is based solely on surface temperature, energy budget considerations suggest that there is some calibration of the temperature profile features, such as development of the thermocline depth, that need to be well represented for the surface temperature evolution over time to be calibrated successfully. It is a strength of the analysis that the FLake model can be optimized using only surface temperatures and then used to successfully diagnose the mixing classification of many lakes in which this information was independently available (see below).

Simulations forced by climate model projections. To drive FLake and evaluate lake temperature, ice-cover and mixing regime responses to climate change, we use bias-corrected climate model projections from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b), specifically projections from GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC5 for historic (1911–2005) and future (2080–2100) periods under two scenarios: RCP 2.6 and RCP 6.0. These pathways encompass a range of potential future global radiative forcing from anthropogenic greenhouse gases and aerosols, and results span a range of potential impacts on lake temperature, ice cover and mixing regimes.

We downloaded the data needed to drive FLake from ISIMIP2b, including projections of air temperature at 2 m, wind speed at 10 m, surface solar and thermal radiation, and specific humidity, which were available at a daily time step and at a grid resolution of 0.5°. Time-series data were extracted for the grid point situated closest to the centre of each lake, defined as the maximum distance to land, and calculated using the distance-to-land dataset of ref. [58].

To verify that FLake, driven by the climate model projections, is able to simulate multidecadal variations in lake surface temperature (and would therefore be informative with respect to future climate change impacts), we compared the FLake simulations from 1915 to 2005 with in situ measurements from two European lakes, Mondsee and Wörthersee. Lake surface temperature data from these lakes were extracted from the yearbooks of the hydrographic service Austria (see ref. [59]). Each of the lakes were sampled daily at a depth of ~0.2 m at the lake-level gauging station. This sampling was performed between 08:00 and 10:00 throughout the observational period, thus limiting the inconsistencies introduced by sampling at different times during a diel cycle, which in some lakes can be very large[60]. Lake temperature simulations using each of the four model projections in ISIMIP2b show coherence with interannual variability on multidecadal scales (Supplementary Fig. 4). Further comparisons of this nature on more widespread lakes would give even greater confidence in long-term simulations, but we were unable to source consistent in situ observations of this length for other lakes.

Modelled summer average lake surface temperature driven by the climate model data were also compared with in situ summer average lake surface temperatures ($n=19$) from ref. [61], including data from Baikal, Lake Biwa, Bodensee, Lake Erie, Sea of Galilee, Lake Garda, Lac Léman, Lake Huron, Lake Michigan, Neusiedler See, Peipsi, Saimaa, Lake Superior, Lake Tahoe, Lake Taihu, Lake Tanganyika, Lake Taupo, Vänern and Vättern (Supplementary Fig. 3).

Simulated lake ice-cover duration was validated against ARC-Lake estimates (Supplementary Fig. 5) of ice-cover duration using the proxy measure of the sustained <1 °C period[48]. The proxy measure of ice cover was also compared with directly observed ice-cover duration from the Global Lake and River Ice Phenology Database[62] (Supplementary Fig. 6). To illustrate the accuracy of the proxy metric, the observed ice-cover duration was also compared against the simulated period of non-zero ice thickness from the FLake model (Supplementary Fig. 6). We compared the climatological durations of ice cover in model and observations. The latter comparison requires lakes that were present in both the ARC-Lake dataset (and thus were simulated by FLake) and the Global Lake and River Ice Phenology Database for a substantially overlapping time period. Thirteen such lakes were available. The modelled average number of ice-covered days agreed well with those observed (Supplementary Fig. 6).

Climate-related impacts are assessed as the difference in mean lake conditions (for example, mean lake temperature, mean number of ice-covered days and identified mixing regime) between the periods 1985–2005 and 2080–2100.

Lake mixing class. To classify lakes according to their mixing regimes, during both the historic and future periods, we apply the commonly used classification scheme of ref. [16]. The terminology of lake mixing regimes is determined by whether a lake experiences ice cover, and how many times the water column of a lake mixes vertically on an annual basis. Lewis produced a flow diagram describing how to identify a lake's mixing regime[16] (Supplementary Fig. 1). Lewis's classification scheme identifies five main lake mixing types: amictic, polymictic, monomictic, dimictic and meromictic. In brief, amictic lakes are those that are persistently ice covered; polymictic lakes are those that mix frequently; monomictic lakes experience one vertical mixing event per year, typically in winter when the vertical temperature difference within a lake is close to zero; dimictic lakes experience two mixing events per year, one following the summer stratified period and the other following the inversely stratified winter period; and meromictic lakes are those that are persistently stratified. Polymictic lakes can be divided further into discontinuous or continuous polymictic, the latter representing a lake that mixes daily. Monomictic and dimictic lakes can be separated further into cold or warm lakes depending on whether or not they experience ice cover annually. Lewis's classification scheme, according to the above definitions, identifies nine mixing regime types: meromictic, warm monomictic, discontinuous warm polymictic, continuous warm polymictic, amictic, cold monomictic, dimictic, discontinuous cold polymictic and continuous cold polymictic (Supplementary Fig. 1). In addition to the nine mixing regime types identified by ref. [16], we also distinguish oligomictic lakes in the global classification. Oligomictic lakes are those that are persistently stable in most years, yet completely mix in some years.

To determine which mixing regime a lake belongs to according to their vertical temperature profiles, we follow refs. [63–65] and characterize a lake as being mixed when the (absolute) difference between its surface temperature and that at depth (that is, bottom temperature) is less than 1 °C. This is evaluated from the modelled lake temperatures (that is, depth-resolved) during the historic and future periods. As an example, we would define a dimictic lake as a lake that (1) experiences winter ice cover, (2) has an ice-free period, (3) warms above 4 °C with regards to its surface temperature and (4) experiences two mixing periods within a given year (Supplementary Fig. 1). For each lake, we determine the mixing class for each year, and assign the overall mixing class to be the dominant model mixing class for the historic and future periods. To differentiate oligomictic and meromictic lakes, all years during the historic and future periods are used to assess whether the lake mixes occasionally. Annual mixing classes are generally consistent across a period: 80% of lakes have the same class for >15 of the 20 years of the historic period, for example.

To validate the modelled lake mixing regimes during the historic period, as simulated by FLake driven by each ISIMIP2b model run, we compared results with literature-derived descriptions from 85 lakes, including those described by refs. [66–69], and the World Lake Database (Supplementary Table 2). In these comparisons we did not separate mixing regimes within an individual class. For example, we did not distinguish between cold and warm monomictic and continuous and discontinuous polymictic, as this information was not available frequently in the literature. Lake mixing regimes assessed from the FLake simulations were in agreement with those from these sources in 72% of cases for three of the ISIMIP2b model runs (Supplementary Fig. 7) and 73% for the other (IPSL-CM5A-LR).

Code availability

The lake model source code is available to download from http://www.flake.igb-berlin.de/.

Data availability

Satellite lake temperature data are available at http://www.laketemp.net. Observed lake surface temperature data are available at https://portal.lternet.edu/nis/mapbrowse?packageid=knb-lter-ntl.10001.3. Climate model projections are available at https://www.isimip.org/protocol/#isimip2b.

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