Worldwide alteration of lake mixing regimes in response to climate change

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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 21st 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 a quarter of seasonally ice-covered lakes are 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 at about 5.5°C. The projections suggest that around 100 of the studied lakes are projected to undergo changes in their mixing regimes. About a quarter of these lakes which are currently classified as monomictic - that undergo one mixing event in most years - will become permanently stratified systems. About a sixth of these which are currently dimictic - that mix twice per year - 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 for 635 globally distributed large lakes how projected climate trends are likely to change lake stratification and mixing. Because these aspects of lake dynamics exert significant control on nutrient fluxes, oxygenation and biogeochemical cycling[12, 13], considering stratification and mixing is critical for anticipating 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

46 vertical layering[14]. The vertical layering that exists during stratification exerts strong control
47 on the transport of nutrients and oxygen between the surface and deep water of lakes and the
48 vertical distribution and composition of lake biota. Lakes that are permanently mixed
49 (continuous cold/warm polymictic) or those that mix frequently (discontinuous cold/warm
50 polymictic) differ markedly in their physical, chemical and biological functioning from lakes
51 that are stratified permanently (meromictic) or semi-permanently (oligomictic, characterised
52 by variable temporal periods of incomplete mixing, interspersed with occasional mixing)[14, 15].
53 Lakes that stratify seasonally can be classed as dimictic if they have two stratification
54 seasons, or monomictic (cold or warm) if they stratify only once per year (see Methods; Fig.
55 S1). Seasonal mixing serves as a basis for lake regime classification[16] and as a necessary
56 component of projecting how lake ecosystems will respond to climate change.

57
58 The mixing class to which a lake belongs depends primarily on (i) whether or not it
59 experiences ice cover annually, and (ii) the number of times during a year in which it
60 stratifies continuously (Fig. S1). Ice-covered lakes tend to occur in less-maritime, high-
61 latitude and high-elevation regions (Fig. 1A). Satellite observations of 635 lakes from 1995 to
62 2011 (Table S1), ~50% of which experienced ice cover annually, illustrate that the
63 climatological duration of ice cover varies systematically with mean air temperature (Fig. 1B;
64 produced using air temperature from the ERA-Interim reanalysis[17]). With regards to the
65 stratification criterion for mixing class, surface water temperature observations can be used to
66 distinguish between dimictic and monomictic (cold or warm) lakes (Fig. 1C, 1D): in warm
67 monomictic lakes, surface water temperature does not cool below 4°C (near the maximum
68 density of freshwater), while in cold monomictic lakes, surface water temperature does not
69 warm above 4°C. No lake surface water temperature threshold separates thermally stratifying
70 and polymictic lakes, as other factors can have a substantial influence, notably lake depth
71 (e.g., shallow lakes can mix easily). The global heterogeneity of lake sizes and depths[18, 19]
72 suggests that lake-mixing classes should be heterogeneously distributed.

73
74 **Global patterns of lake mixing regimes**
75 In this study, we assess the contemporary mixing class of 635 lakes worldwide, by
76 developing a classification scheme applied to numerical simulation results from a lake model,
77 and then use this model to project future mixing classes under climate change scenarios. This
78 approach enables meromictic, oligomictic, monomictic, dimictic and polymictic mixing
79 classes to be determined.

80
81 To assess the contemporary mixing classes, we first optimise key parameters of the
82 lake model, FLake[20, 21], to represent the dynamics of each individual lake. The optimisation
83 constrains the model to represent observed lake surface water temperature time series (see
84 Methods). The ability of the optimised lake model to represent a wide range of lake dynamics
85 is evaluated by comparing simulations with independent temperature observations, ice cover
86 and lake mixing regimes under historic climate conditions. Good agreement is obtained (Fig.
87 S2-S7). Particularly relevant to multi-decadal projection is that the lake model is able to
88 simulate accurately historic multi-decadal variations in lake temperature back to the start of
89 the 20th century (Fig. S4) and to identify successfully the mixing regime of 72% of lakes for
90 which independent mixing regime classifications were found (Fig. S7; Table S2). Up to 85%

91 of inter-decadal variability in lake surface temperature is explained by the lake model forced
92 with representations of historic climate conditions.
93
94   The identified lake mixing regimes demonstrate a diverse array of mixing types (Fig.
95 1E-1F). Dimictic lakes are most common in our global dataset (Fig. S8), a result of the
96 majority of our study lakes being relatively large (all studies lakes exceed 27 km^2 in area) and
97 situated north of 40°N, where the global lake abundance is highest[18]. The proportion of
98 dimictic and polymictic lakes is large in north temperate latitudes, as expected, and
99 meromictic lakes are common in the tropics (Fig. 1E-1F).
100
101 **Climate-related changes in lake mixing regimes**
102 To project future changes in mixing class, the lake model is forced by four climate
103 projections available from the Inter-Sectoral Impact Model Intercomparison Project[22],
104 namely, HadGEM2-ES, GFDL-ESM2M, IPSL-CM5A-LR and MIROC5 (see Methods for
105 details), under two Representative Concentration Pathway (RCP) scenarios. The main figures
106 presented here show the results from the lake model forced with bias-corrected HadGEM2-
107 ES projections. To indicate the uncertainty of projections, we show or quote the spread of
108 results from the lake model across all four climate model projections. Changes projected for
109 2080-2100 are quoted relative to the period 1985-2005.
110
111   The responses of lake mixing regimes to climate change are complex and may not be
112 associated closely with change in any one climatic variable. Rather, the mixing regime of a
113 lake will depend on changes in a combination of climatic factors that contribute to the lake
114 heat budget (e.g., air temperature, solar and thermal radiation, cloud cover, wind speed,
115 humidity). Under future scenarios RCP 2.6 and 6.0, we project that the number of annual ice-
116 covered days will decrease substantially (Fig. 2A, 2B) by 2080-2100. For RCP 2.6, the
117 decrease is on average (across all lakes that are seasonally ice covered during the historic
118 period) 15 days, the standard deviation of this mean change across the four-member ensemble
119 being 5 days. For RCP 6.0, the projected mean change is -29±8 days. In the most extreme
120 cases under RCP 6.0, the projected decreases of ice-covered days exceed 60 days. The
121 simulations project that 24±5% of lakes that display winter ice cover in the historic period
122 will be ice-free by the end of the 21st century under the RCP 6.0 scenario. The increase in
123 annual mean lake surface temperature is projected to be 1.1±0.4ºC and 2.3±0.6ºC under RCP
124 2.0 and 6.0, respectively (Fig. 2C, 2D), by 2080-2100. For individual lakes, projected
125 warming can be higher, the largest projected increase being 5.4±1.1ºC under RCP 6.0.
126 99±0.5% of lakes are projected to increase in mean temperature under RCP 2.6, and all
127 (100±0%) increase under RCP 6.0.
128
129   Decreases in winter ice cover and increases in lake surface temperatures would be
130 expected qualitatively to modify the distribution of lake mixing regimes. Next, we investigate
131 the global extent and magnitude of response in the projections to quantify this expectation.
132 The projections suggest that alterations in lake mixing regimes will occur during the 21st
133 century (Fig. 3, Fig. S9-S10). Specifically, in the projections under RCP 2.6 and 6.0,
134 respectively, 59±7 and 96±15 lakes change mixing class.
135

136   The most common identified alteration in mixing class (25±5 % of altered lakes under
137   RCP 6.0) is a change from warm monomictic to meromictic. This means that a significant
138   minority of lakes that do not currently experience ice cover and stratify once annually are
139   projected to become permanently stratified systems by the end of the 21st century. In addition,
140   all of the lakes identified as being oligomictic during the historic period transition to the
141   meromictic class by 2080-2100. A lack of vertical mixing by the end of the 21st century will
142   result in reduced upwelling of nutrients from deep to shallow waters and a decrease in deep-
143   water oxygen concentrations, which can lead to reduced lake productivity[10] and the formation
144   of deep-water dead zones[12], respectively. Oxygen depletion at depth can be detrimental to the
145   habitat for fish[23] and can modify biogeochemical processes resulting in, for example, the
146   potential release of phosphorus and ammonium into the water column[24] and the production of
147   potentially toxic metal ions[25].

148

149   The second most common identified alteration in mixing class (across the model
150   ensemble) is a change from dimictic to warm monomictic (17±5 % of altered lakes under
151   RCP 6.0) (Fig. 3, Fig. S9-S10). This alteration occurs when lakes that were historically ice
152   covered no longer freeze in winter but still stratify during summer. The projected absence of
153   winter ice has implications for those lake ecosystems including, among other things, changes
154   in water quality[26] and the production and biodiversity of phytoplankton[27].

155

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

176

177   There is scattered evidence of mixing regime alterations already taking place, and
178   ecological consequences of these changes are starting to appear[38, 39]. Our projections of future
179   lake-mixing regime alterations span a wide range of locations, sizes, and climatic contexts,
180   and suggest a complex pattern of lake responses to climate change. The geographical

4

distribution of lake mixing regime alterations 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 similarly. Changes in lake temperature will not always translate to changes in lake mixing regimes: some of the lakes which 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 in 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 regime during the period 1985 to 2005. Lakes that are currently classified as warm monomictic but fail to mix fully during some winters presently account for 60% of those that are projected to become meromictic (i.e., permanently stratified) in the future. Lakes that are currently seasonally ice-covered and are classified as dimictic but also experience some ice-free winters are projected to become predominantly monomictic by the end of the 21st 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.

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296   thermal regime transitions in three deep alpine lakes in Austria induced by climate
297   change. *Freshwater Biol.* **62,** 1335-1345 (2017).
298

308

309 **Author Contributions**
310 Both authors developed the concept of the study, designed the analytical experiments,
311 interpreted the results and wrote the paper.
312

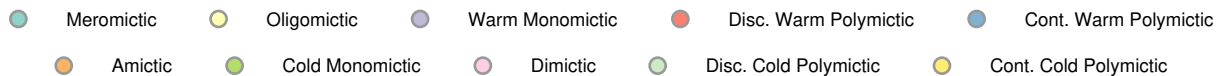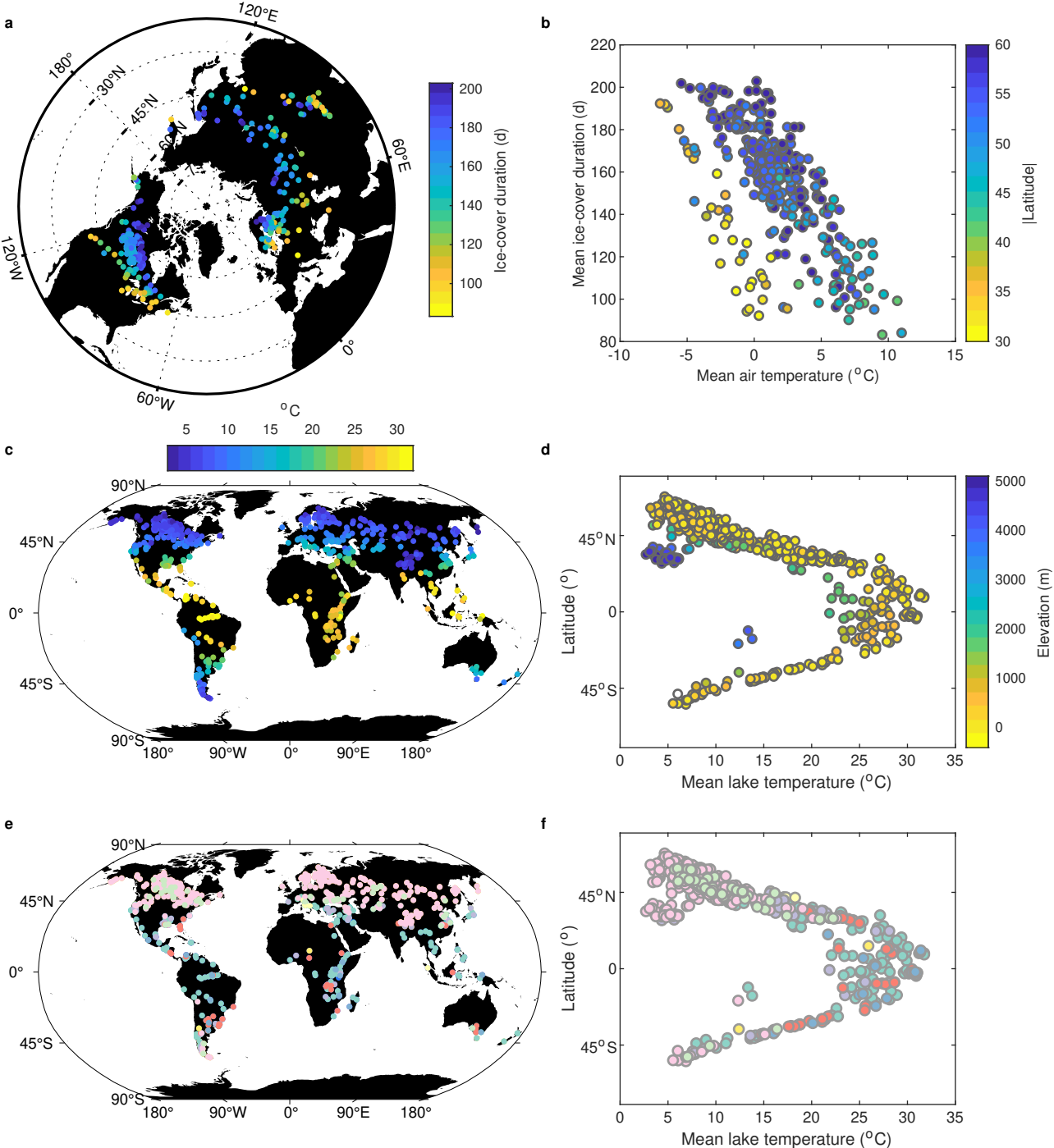313 **Financial and non-financial competing interests**
314 The authors do not have any competing financial or non-financial interests to declare.
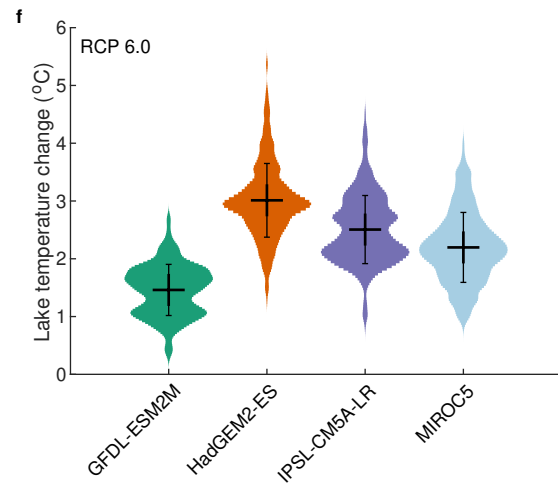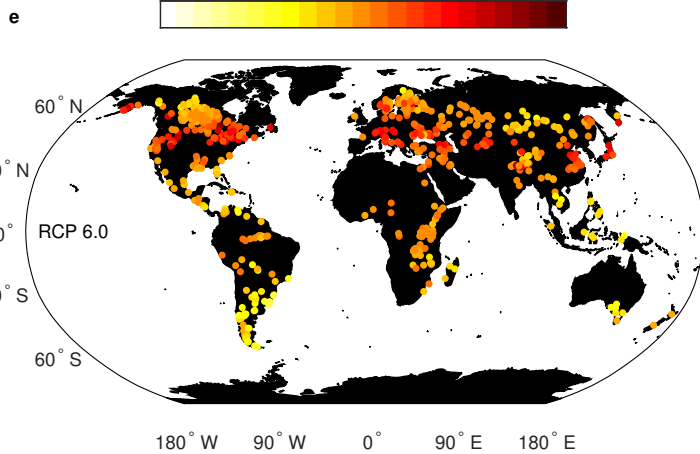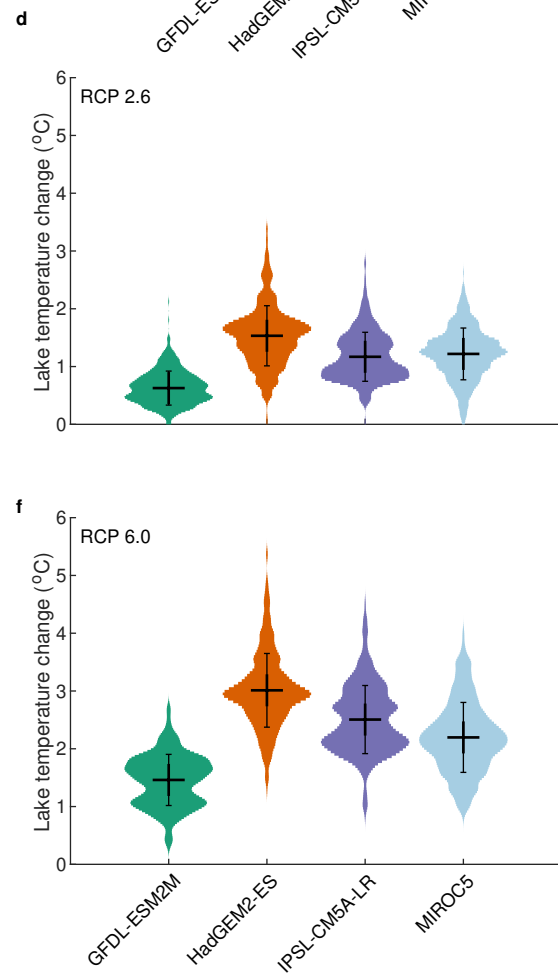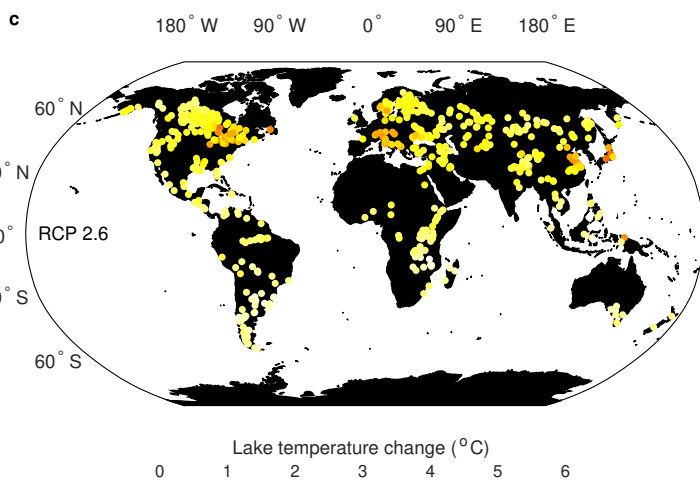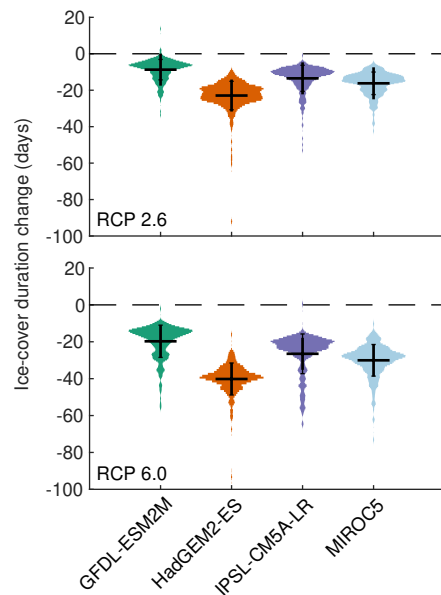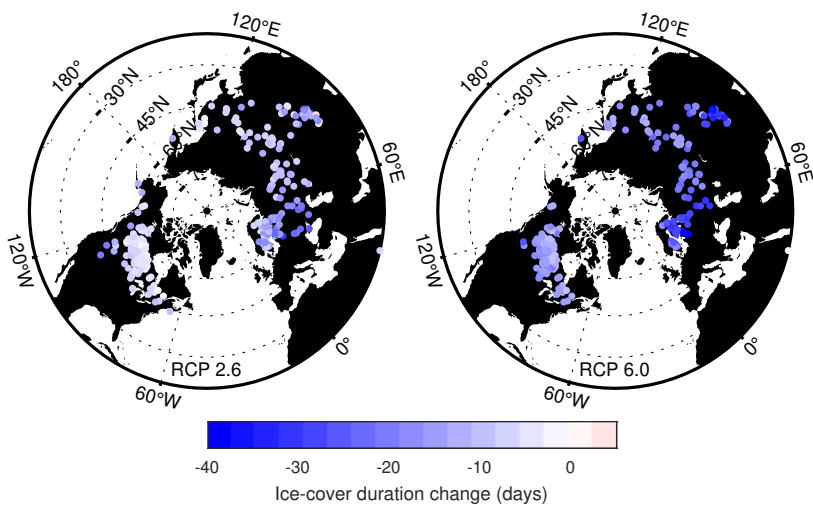
Figure captions

317 **Figure 1. Global patterns in annual mean (1995-2005) ice cover duration, lake surface**
318 **temperature and lake mixing regimes.** (a) Satellite-derived ice cover duration and (b) their
319 relationship with air temperature (from ERA-Interim[17]). (c) Global variations in satellite-
320 derived lake surface water temperature and (d) their relationship with latitude and elevation.
321 (e) Global variations in modelled lake mixing regimes and (f) their relationship with latitude
322 and lake surface water temperature. Mixing regimes were identified using the classification
323 scheme of ref. 16, extended to include an oligomictic class, evaluated from a lake model
324 forced by bias-corrected HadGEM2-ES projections. (Lake mixing regimes identified while
325 using bias-corrected projections from other climate models are shown in Fig. S8).

326

327 **Figure 2. Global changes (2080-2100 relative to 1985-2005) in annually averaged ice**
328 **cover duration and lake surface water temperature.** (a) Changes in ice cover duration
329 under RCP 2.6 and 6.0 (shown only for northern hemisphere lakes) from a lake model forced
330 with bias-corrected HadGEM2-ES projections, and (b) all climate model projections from
331 ISIMIP2b, showing also the kernel density estimates (horizontal widths of coloured areas).
332 Changes are also shown for the annual average lake surface temperature under (c-d) RCP 2.6
333 and (E-F) RCP 6.0, showing results from the lake model forced with HadGEM2-ES
334 projections (c and e) as well as all models (d and f). In Figs 2b, 2d, 2f, the mean and standard
335 deviation is also shown (black).

336

337 **Figure 3. Global changes (2080-2100 relative to 1985-2005) in lake mixing regimes.**
338 Shown are climate-related changes in lake mixing regimes under (a) RCP 2.6 and (b) RCP
339 6.0 using a lake model forced with bias-corrected HadGEM2-ES projections (comparison of
340 lake mixing regime alterations identified while using bias-corrected climate projections from
341 other climate models are shown in Figs S9-S10). Every lake that experiences a mixing regime
342 alteration is shown in grey in the maps and the most frequent mixing regime alterations
343 (encompassing 80% of the identified mixing regime shifts) are shown with individual colours
344 (see legend).

a Ice-cover duration (d)

b Mean ice-cover duration (d) vs Mean air temperature (°C), |Latitude|

c °C

d Latitude (°) vs Mean lake temperature (°C), Elevation (m)

e

f Latitude (°) vs Mean lake temperature (°C)

Meromictic   Oligomictic   Warm Monomictic   Disc. Warm Polymictic   Cont. Warm Polymictic

Amictic   Cold Monomictic   Dimictic   Disc. Cold Polymictic   Cont. Cold Polymictic

Projected global change in ice cover and lake temperature

Projected global mixing regime alterations

Legend:
- Warm Mono. - Meromictic
- Dimictic - Warm Mono.
- Disc. Cold Poly. - Dimictic
- Cont. Warm Poly. - Disc. Warm Poly.
- Disc. Col. Poly. - Disc. Warm Poly.
- Disc. Warm Poly. - Warm Mono.
- Disc. Warm Poly. - Meromictic
- Dimictic - Disc. Warm Poly.
- Disc. Cold Poly. - Warm Mono.
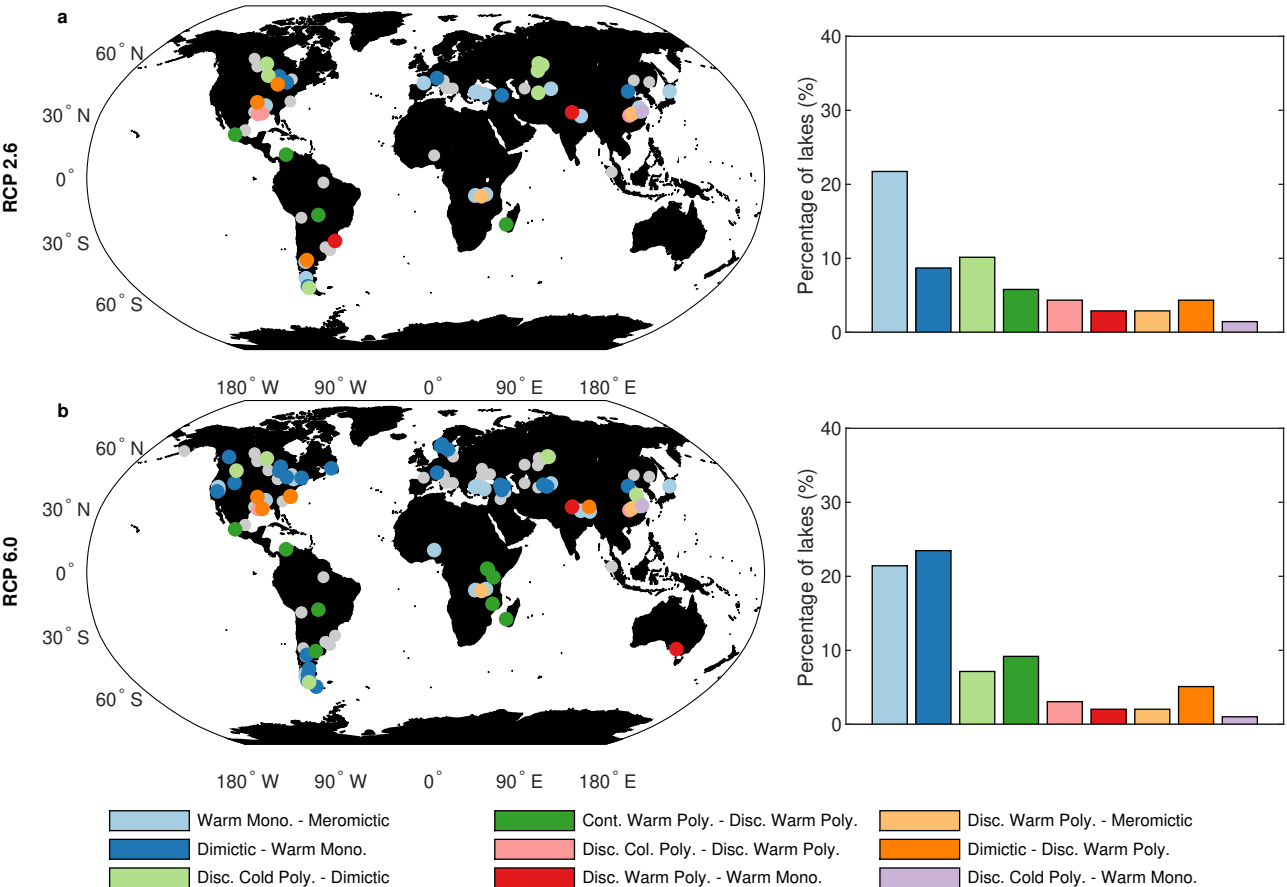
Methods

Methods, including statements of data availability and any associated references, are
available in the online Methods.

Online Methods

Study sites - The lakes investigated in this study (*n* = 635) vary in their geographic
and morphological characteristics (Table S1).

    Satellite-derived lake temperature and ice cover data - We utilize lake surface
temperatures from the ATSR (Along Track Scanning Radiometer) Reprocessing for Climate:
Lake Surface Water Temperature and Ice Cover (ARC-Lake) dataset[40], available at
http://www.laketemp.net. In outline, 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. 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 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 in order to average across the
intra-lake 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 K for daytime and −0.1±0.5 K for night-time matches. ARC-Lake
data have been independently validated as part of other studies[45] and used to validate 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 from the daily-mean temperature time-series the
periods during which a lake was likely partially or wholly ice covered, we follow ref. 48, and
characterise this as the period during which the lake-mean surface water temperature is <1°C.
This corresponds closely to presence of lake ice cover 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 (Fig. S2, Fig. S5).

    Lake model - To simulate depth-resolved lake temperatures, as 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 which 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,

9

390   [51]. It has been tested extensively in past studies, including detailed validations across a
391   spectrum of lake contexts. FLake has been used previously for validated simulation of the
392   vertical temperature profile as well as changes to the mixing regime of polymictic and
393   dimictic lakes[34, 52-53], and has been shown to reproduce accurately bottom water temperatures
394   as well as the depth and seasonality of the upper mixed layer and thermocline in meromictic
395   lakes[45, 54, 55]. The model has also been used to reproduce past variability in ice cover timing,
396   intensity and duration[56], and to investigate the thermal response of polymictic, monomictic
397   and lakes to large-scale climatic shifts[57]. The integrated approach implemented in FLake
398   allows a realistic representation of the major physics behind turbulent and diffusive heat
399   exchange in lakes, including a module to describe the vertical temperature structure of the
400   thermally active layer of bottom sediments, as well as its interaction with the water column
401   above. The lakes investigated in this study all have depths <60 m, an established criterion for
402   applicability of the FLake model in global studies[46, 50], except that deeper lakes are included
403   for which we had independent validation of the lake model's ability to simulate mixing
404   regime (Table S1).

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

410   The prognostic variables needed to initialise FLake simulations include (i) mixed
411   layer temperature, (ii) mixed layer depth, (iii) bottom temperature, (iv) mean temperature of
412   the water column, (v) temperature at the ice (if present) upper surface and (vi) ice thickness
413   (if present). In order to initialise the model runs from physically reasonable fields, we
414   initialise runs from a perpetual-year solution for the lake state. To find this solution for the
415   initialisation state, the model parameters are set as follows: mean depth was extracted from
416   the Hydrolakes database[19], which include observational and geo-statistical model estimates of
417   lake depths worldwide; K_d was set to 3 m^{-1} (ref. 50); lake ice albedo was set to 0.6 (ref. 21).
418   The perpetual-year solution is obtained by repeating the forcing from a representative year
419   and running FLake until the annual cycle in modelled lake state is stabilised. The forcing data
420   to derive the initialisation conditions are from the ERA-Interim reanalysis product[17],
421   available at a latitude-longitude resolution of 0.75°.

422   To optimize FLake simulations for each lake, we then use the model-tuning algorithm
423   of ref. 58. This approach estimates the model parameters (lake depth, K_d, and ice albedo;
424   Table S1) to reproduce optimally the observed surface temperature dynamics, specifically by
425   minimising the mean square differences between model and ARC-Lake surface water
426   temperature over the satellite period (1995-2011), in simulations initialised from the
427   perpetual year solution described above. The lake-specific parameters for the model are thus
428   set without reference to any in situ data or to the climate model forcing fields used for
429   historical-period simulation and future projections (see below). Note that while the
430   optimisation is based solely on surface temperature, energy budget considerations suggest
431   that there is some calibration of the temperature profile features, such as development of the
432   thermocline depth, that need to be well represented in order for the surface temperature
433   evolution over time to be calibrated successfully. It is a significant strength of the analysis
434   that the FLake model can be optimised using only surface temperatures and then diagnose

435　successfully the mixing classification of many lakes in which this information was
436　independently available (see below).
437
438　　　　*Simulations forced by climate model projections* – To drive FLake and evaluate lake
439　temperature, ice cover, and mixing regime responses to climate change, we use bias-corrected
440　climate model projections from the Inter-Sectoral Impact Model Intercomparison Project
441　(ISIMIP2b), specifically using projections from GFDL-ESM2M, HadGEM2-ES, IPSL-
442　CM5A-LR, and MIROC5 for historic (1911-2005) and future periods (2081-2100) under two
443　scenarios: RCP 2.6 and RCP 6.0. These pathways encompass a range of potential future
444　global radiative forcing from anthropogenic greenhouse gases and aerosols, and results span a
445　range of potential impacts on lake temperature, ice cover, and mixing regimes. Other
446　commonly used RCP scenarios, RCP 4.5 and RCP 8.5, are not included in ISIMIP2b as they
447　were either considered too high for evaluating future climate impacts (RCP 8.5) or to not
448　provide enough span (RCP 4.5).
449　　　　We downloaded the data needed to drive FLake from ISIMIP2b
450　(https://www.isimip.org/protocol/#isimip2b), including projections of air temperature at 2 m,
451　wind speed at 10 m, surface solar and thermal radiation, and specific humidity, which were
452　available at a daily time step and at a grid resolution of 0.5º. Time series data were extracted
453　for the grid point situated closest to the centre of each lake, defined as the maximum distance
454　to land, calculated using the distance-to-land dataset of ref. 59.
455　　　　To verify that FLake, driven by the climate model projections, is able to simulate
456　multi-decadal variations in lake surface temperature (and can therefore be informative with
457　respect to future climate change impacts), we compared the FLake simulations from 1915 to
458　2005 with in-situ measurements from two European lakes, Mondsee and Wörthersee. Lake
459　surface temperature data from these lakes were extracted from the yearbooks of the
460　hydrographic service Austria (https://www.bmlfuw.gv.at/wasser/wasser-
461　oesterreich/wasserkreislauf/hydrographische_daten/jahrbuecher.html). Each of the lakes were
462　sampled daily at a depth of ~0.2 m at the lake-level gauging station. This sampling was
463　performed between 08:00 and 10:00 throughout the observational period, thus limiting the
464　inconsistencies introduced by sampling at different times during a diel cycle, which in some
465　lakes can be very large[60]. Lake temperature simulations, using each of the four model
466　projections in ISIMIP2b, show coherence with inter-annual variability on multi-decadal
467　scales (Fig. S4). Further comparisons of this nature on more widespread lakes would give
468　even greater confidence in long-term simulations, but we were unable to source consistent in
469　situ observations of this length for other lakes.
470　　　　Modelled summer average lake surface temperature driven by the climate model data
471　were also compared with in-situ summer-average lake surface temperatures ($n = 19$) from ref.
472　61, including data from Baikal, Lake Biwa, Bodensee, Lake Erie, Sea of Galilee, Lake Garda,
473　Lac Léman, Lake Huron, Lake Michigan, Neusiedler See, Peipsi, Saimaa, Lake Superior,
474　Lake Tahoe, Lake Taihu, Lake Tanganyika, Lake Taupo, Vänern and Vättern (Fig S3).
475　　　　Simulated lake ice cover duration was validated against ARC-Lake estimates (Fig.
476　S5) of ice cover duration using the proxy measure of the sustained <1°C period[48]. The proxy
477　measure of ice cover was also compared with directly observed ice cover duration from the
478　Global Lake and River Ice Phenology Database[62] (Fig. S6). To illustrate the accuracy of the
479　proxy metric, the observed ice cover duration was also compared against the simulated period

480 of non-zero ice thickness from the FLake model (Fig. S6). We compared the climatological
481 durations of ice cover in model and observations. The latter comparison requires lakes that
482 were available in both the ARC-Lake dataset (and thus were simulated by FLake) as well as
483 in the Global Lake and River Ice Phenology Database for a substantially overlapping time
484 period. Thirteen such lakes were available. The modelled average number of ice-covered
485 days agreed well with those observed (Fig. S6).
486   Climate-related impacts are assessed as the difference in mean lake conditions (e.g.,
487 mean lake temperature, mean number of ice-covered days, and identified mixing regime)
488 between the period 1985-2005 ('historic' period) and 2080-2100 ('future' period).
489
490   *Lake mixing class* - To classify lakes according to their mixing regimes, during both
491 the historic and future periods, we apply the commonly used classification scheme of ref. 16.
492 The terminology of lake mixing regimes is determined by (i) whether a lake experiences ice
493 cover, and (ii) how many times a lake's water column mixes vertically on an annual basis.
494 Lewis produced a flow diagram describing how to identify a lake's mixing regime (Fig. S1).
495 Lewis' classification scheme identifies five main lake mixing types: amictic, polymictic,
496 monomictic, dimictic, and meromictic. In brief, amictic lakes are those that are persistently
497 ice covered; polymictic lakes are those that mix frequently; monomicitc lakes experience one
498 vertical mixing event per year, typically in winter when the vertical temperature difference
499 within a lake is close to zero; dimictic lakes experience two mixing events per year, one
500 following the summer stratified period and the other following the inversely stratified winter
501 period; and meromictic lakes are those that are persistently stratified. Polymictic lakes can be
502 divided further into discontinuous or continuous polymictic, the latter representing a lake that
503 mixes daily. Monomictic and dimictic lakes can be separated further into 'cold' or 'warm'
504 lakes depending on whether or not they experience ice cover annually. Lewis' classification
505 scheme, according to the above definitions, identifies nine mixing regime types: meromictic,
506 warm monomictic, discontinuous warm polymictic, continuous warm polymictic, amictic,
507 cold monomictic, dimictic, discontinuous cold polymictic, and continuous cold polymictic
508 (Fig. S1). In addition to the nine mixing regime types identified by ref. 16 we also distinguish
509 oligomictic lakes in the global classification. Oligomictic lakes are those that are persistently
510 stable in most years, yet completely mix in some years.
511   To determine which mixing regime a lake belongs to according to their vertical
512 temperature profiles, we follow ref. 63-65 and characterise a lake as being mixed when the
513 difference (absolute) between its surface temperature and that at depth (i.e., bottom
514 temperature) is less than 1ºC. This is evaluated from the modelled lake temperatures (i.e.,
515 depth-resolved) during the historic and future periods. As an example, we would define a
516 dimictic lake as a lake that (i) experiences winter ice cover, (ii) has an ice-free period, (iii)
517 warms above 4ºC with regards to its surface temperature and (iv) experiences two mixing
518 periods within a given year (Fig. S1). For each lake, we determine the mixing class for each
519 year, and assign the overall mixing class to be the dominant model mixing class for the
520 historic and future periods. To differentiate oligomictic and meromictic lakes, all years during
521 each historic or future periods are used to assess whether the lake mixes occasionally. Annual
522 mixing classes are generally consistent across a period: 80% of lakes have the same class for
523 >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 ref. 66-69, and the World Lake Database (Table S2). In these comparisons we did not separate mixing regimes within an individual class. For example, we did not distinguish between cold and warm monimictic 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 (Fig. S7) and 73% for the other (IPSL-CM5A-LR).

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.

Code availability

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

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Supporting information for

Worldwide alteration of lake mixing regimes in response to climate change

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Introduction

The supporting information presented here provides more comprehensive details that complement the analyses presented in the main text, allowing a more complete assessment of our findings.
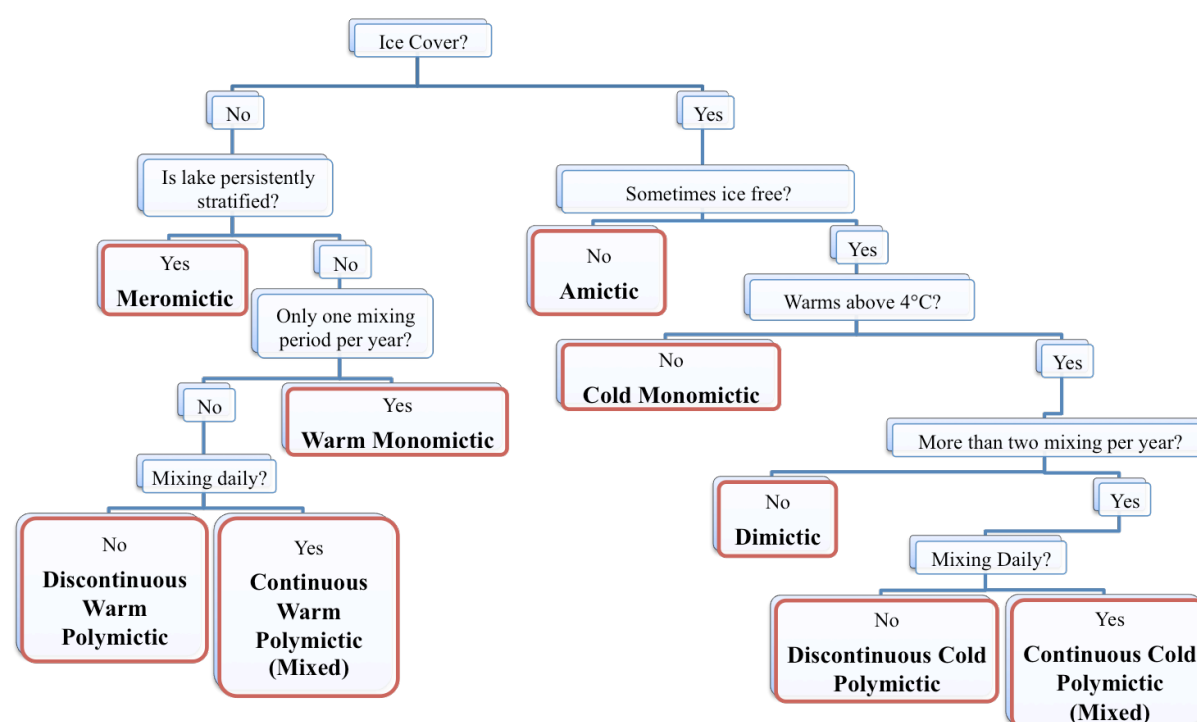
Figure S1. Classification scheme used in this study to determine the mixing regimes of lakes. Modified from ref. 16. The criteria used to define a stratified (or mixed) period is when the top minus bottom (modelled) lake temperature difference (absolute) exceeds (or is lower than) 1°C (see Methods). To assess from the lake surface temperatures (observed or modelled) the period during which a lake is likely ice covered, we follow ref. 48, and characterise this as the period during which the lake-mean surface water temperature is <1°C (see Methods). In addition to the nine mixing regime types identified by ref. 16 we also include oligomictic lakes in the mixing regime classification. Oligomictic lakes are almost persistently stable, mixing only rarely. Specifically, oligomictic lakes do not mix every year but still completely mix in some years.
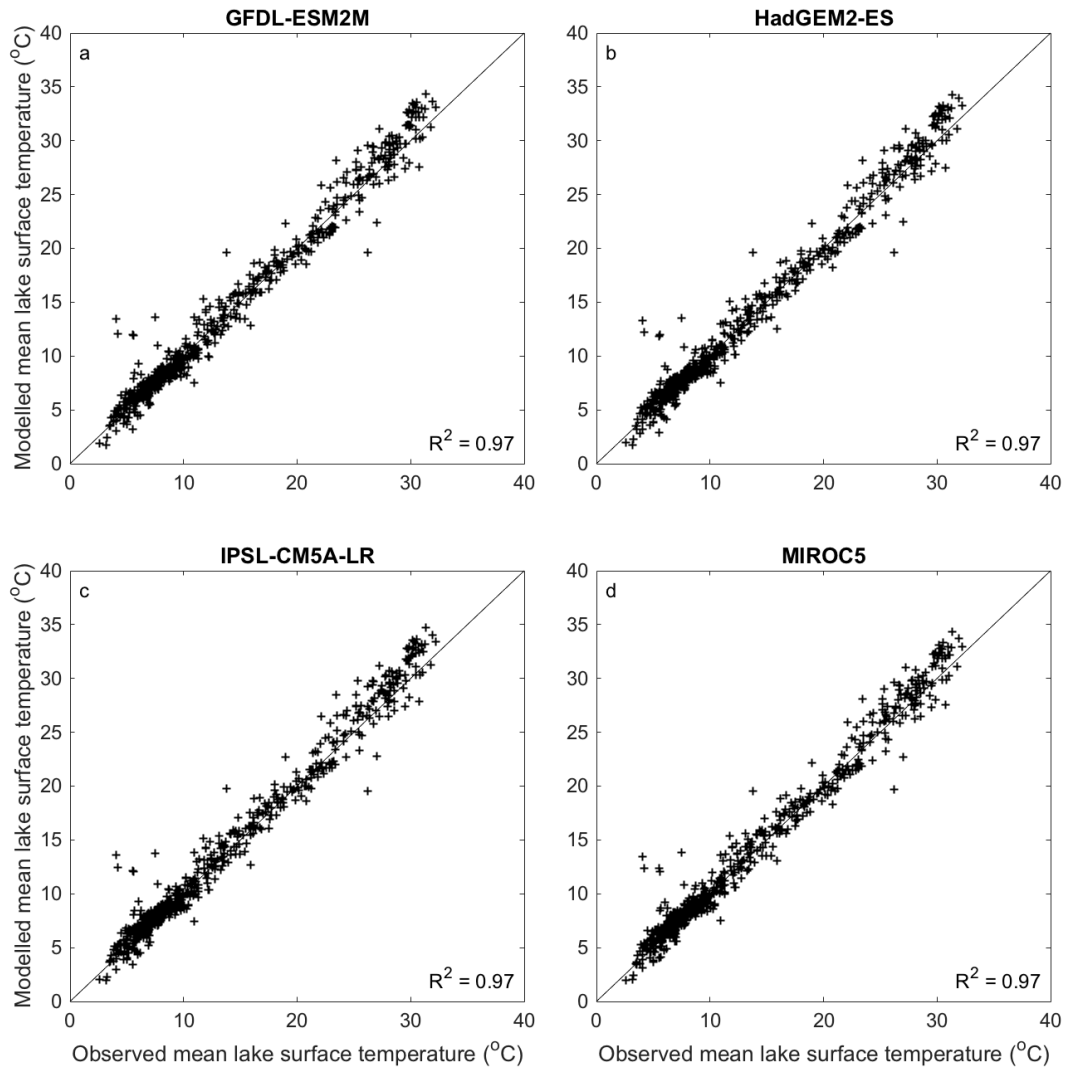
Figure S2. Comparison of annual mean (1995-2005) modelled and observed satellite-derived lake surface water temperatures for 635 lakes in which lake temperature data were available and used in this study. The modelled lake temperatures represent those simulated by a lake model forced with bias-corrected climate projections available from the Inter-Sectoral Impact Model Intercomparison Project, namely (A) GFDL-ESM2M, (B) HadGEM2-ES, (C) IPSL-CM5A-LR and (D) MIROC5. Time series data needed to drive the lake model from each climate projection were extracted for the grid point situated closest to the centre of each lake.
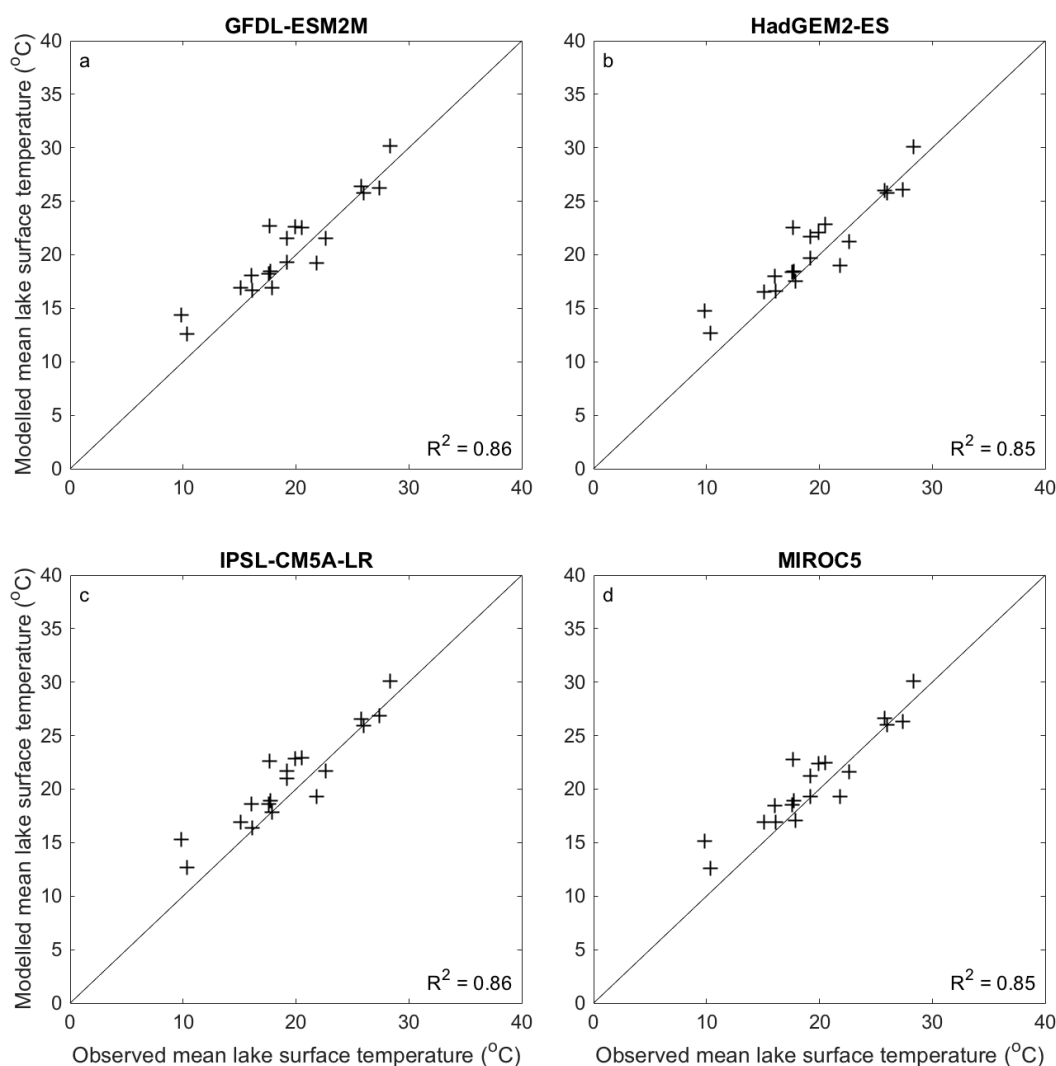
Figure S3. Comparison of summer-average modelled and observed lake surface water temperatures. In-situ summer-average lake surface temperatures are from ref. 61 and include data from Baikal, Lake Biwa, Bodensee, Lake Erie, Sea of Galilee, Lake Garda, Lac Léman, Lake Huron, Lake Michigan, Neusiedler See, Peipsi, Saimaa, Lake Superior, Lake Tahoe, Lake Taihu, Lake Tanganyika, Lake Taupo, Vänern and Vättern. Modelled lake surface temperatures represent those simulated by a lake model forced with bias-corrected climate projections available from the Inter-Sectoral Impact Model Intercomparison Project, namely (A) GFDL-ESM2M, (B) HadGEM2-ES, (C) IPSL-CM5A-LR and (D) MIROC5. Time series data needed to drive the lake model from each climate projection were extracted for the grid point situated closest to the centre of each lake.
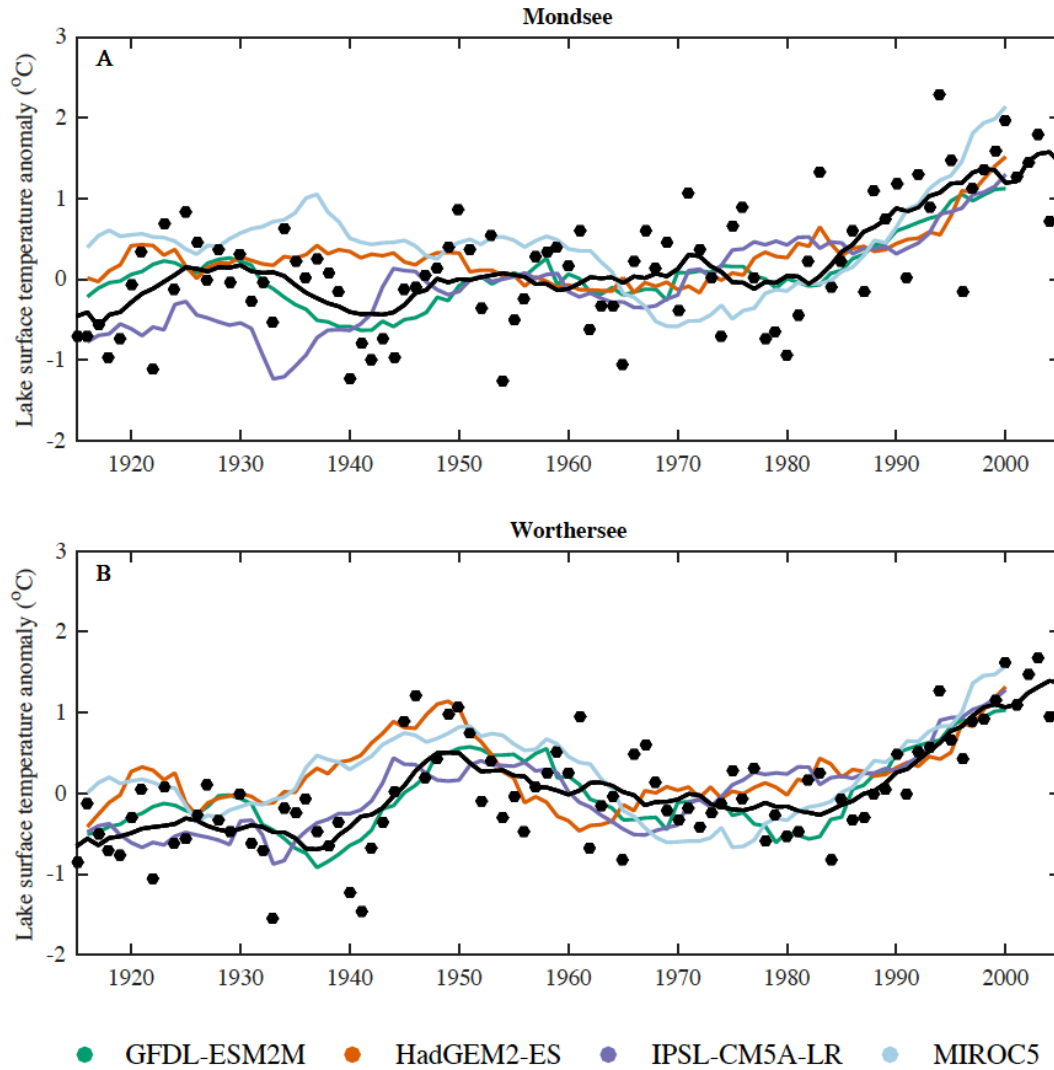
Figure S4. Comparison of observed (black) and modelled (colour) annual mean lake surface temperature anomalies from 1915 to 2005. Modelled lake surface temperatures represent those simulated by a lake model forced with bias-corrected climate projections available from the Inter-Sectoral Impact Model Intercomparison Project, namely, GFDL-ESM2M (green), HadGEM2-ES (orange), IPSL-CM5A-LR (purple) and MIROC5 (blue). Comparisons are shown for two European lakes (Mondsee and Wörthersee), for which long-term in-situ lake surface temperatures were available. Lake temperatures are shown as annual averages (observed; black points) and with an 11-year moving average (solid lines). All temperatures are shown as anomalies relative to 1951-1980. Time series data needed to drive the lake model from each climate projection were extracted for the grid point situated closest to the centre of these lakes.
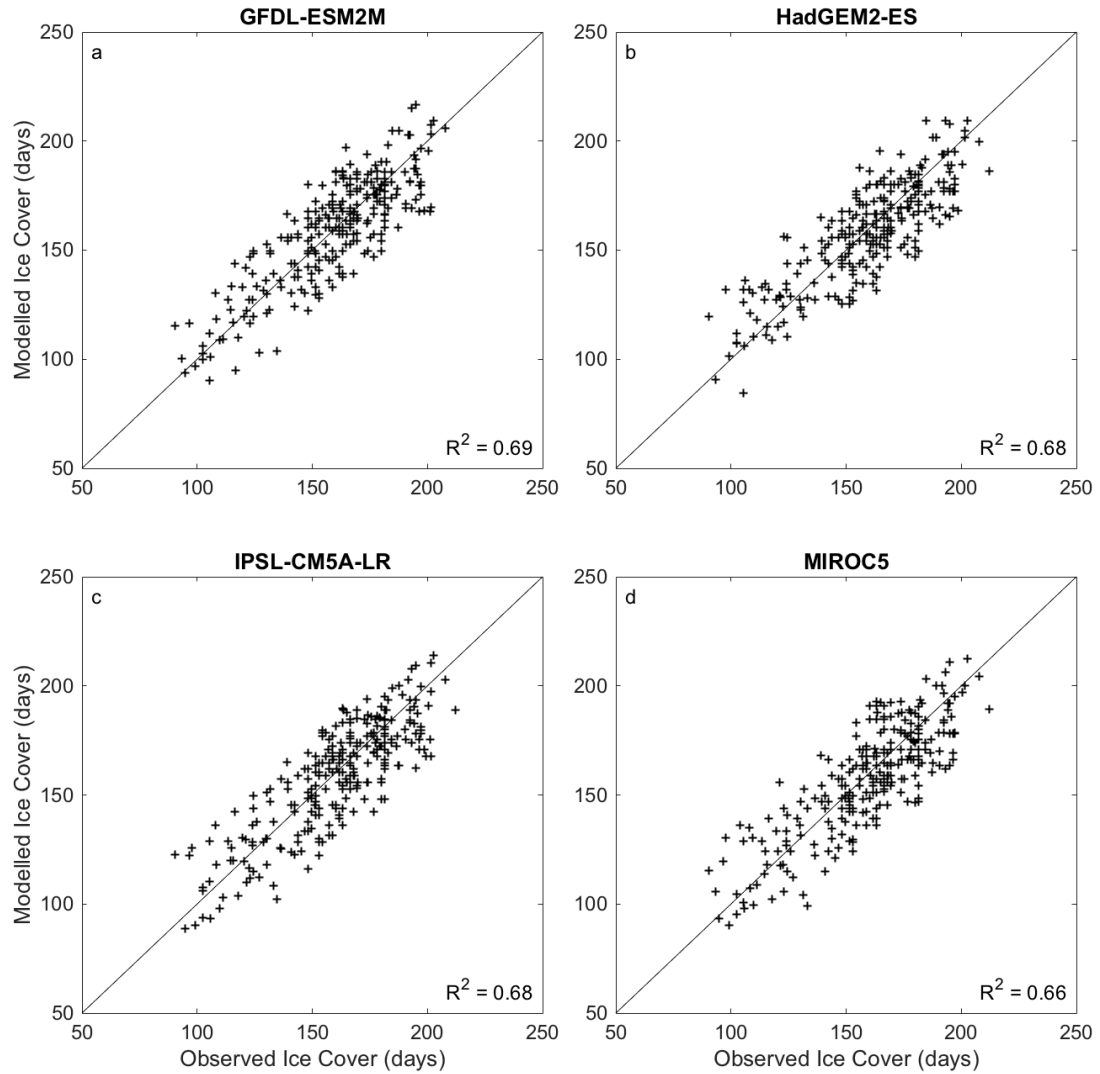
Figure S5. Comparison of modelled and observed (1995-2005) ice cover duration (in days) for the studied lakes which experienced ice cover. The modelled lake temperatures represent those simulated by a lake model forced with bias-corrected climate projections available from the Inter-Sectoral Impact Model Intercomparison Project, namely (A) GFDL-ESM2M, (B) HadGEM2-ES, (C) IPSL-CM5A-LR and (D) MIROC5. Time series data needed to drive the lake model from each climate projection were extracted for the grid point situated closest to the centre of each lake. To assess from the lake surface temperatures (observed or modelled) the period during which a lake is likely ice covered, we follow ref. 48, and characterise this as the period during which the lake-mean surface water temperature is <1°C.
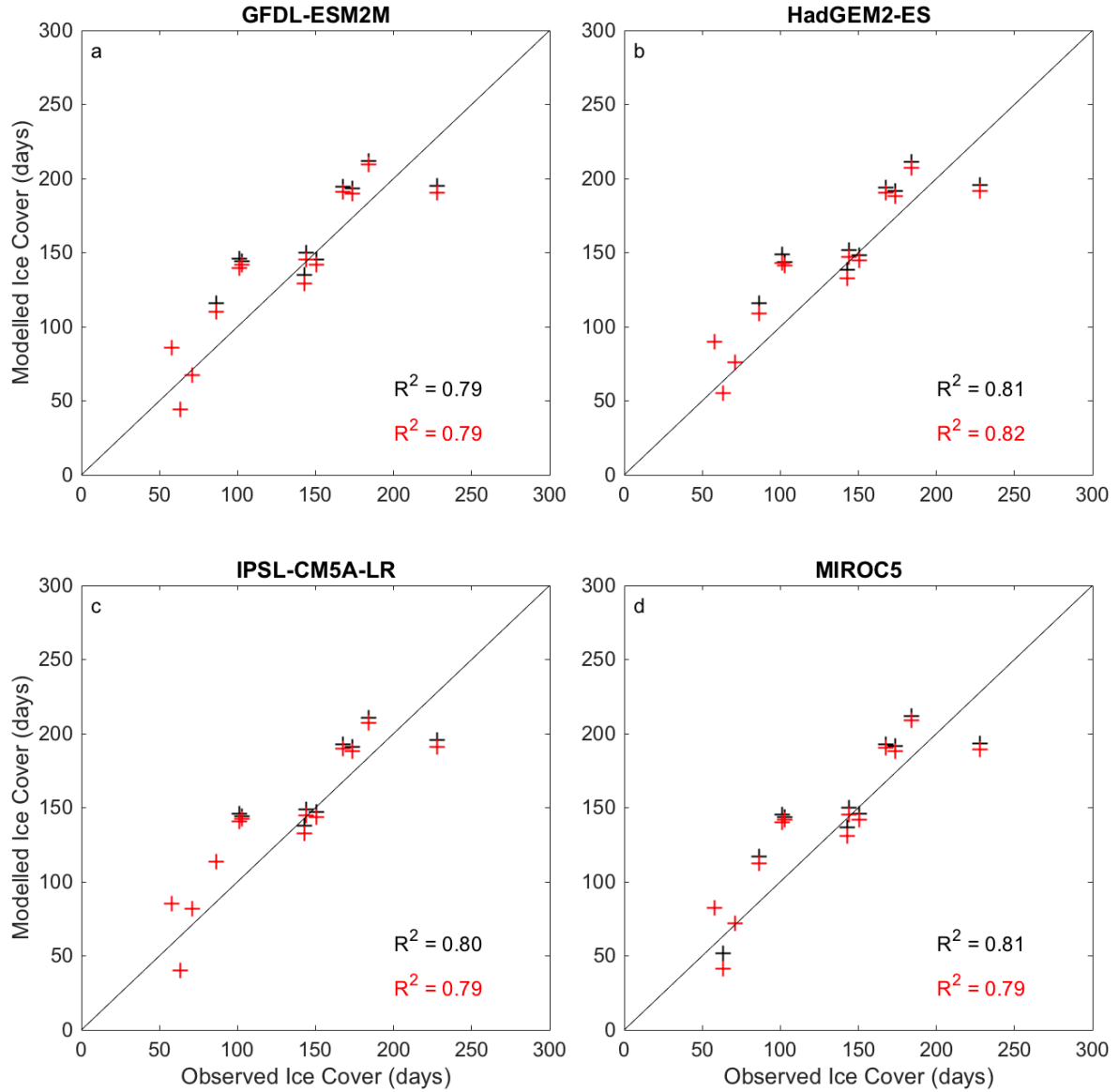
Figure S6. Comparison of modelled and observed (1995-2005) ice cover duration (in days) for lakes in which in-situ ice cover data were available and used in this study. The modelled lake temperatures represent those simulated by a lake model forced with bias-corrected climate projections available from the Inter-Sectoral Impact Model Intercomparison Project, namely (A) GFDL-ESM2M, (B) HadGEM2-ES, (C) IPSL-CM5A-LR and (D) MIROC5. Time series data needed to drive the lake model from each climate projection were extracted for the grid point situated closest to the centre of each lake. To assess from the modelled lake surface temperatures the period during which a lake is likely ice covered, we (i) follow ref. 48 and characterise this as the period during which the lake-mean surface water temperature is <1°C (black), and (ii) use the simulated period of non-zero ice thickness from the lake model (red). Observed ice cover data are from the Global Lake and River Ice Phenology Database[62]. Note that the average period of ice cover calculated for each lake will be based on a different time period, depending on the years in which observed ice cover data were available. Specifically, for some lakes only a few years of data are available, and thus the average observed ice cover duration will be different to that calculated using a 20-year period (e.g., Fig. S5).
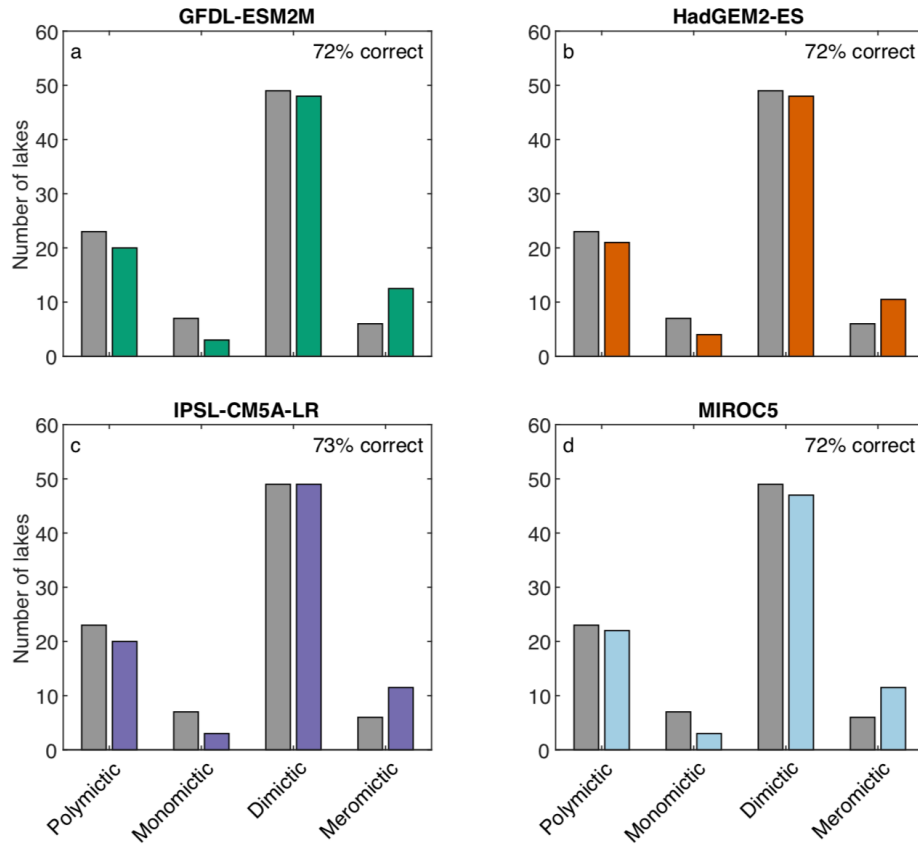
Figure S7. Comparison of modelled (grey) and literature defined (colour) mixing regimes of 85 lakes (Table S2). Modelled mixing regime classifications were defined following the method described in Fig. S1. Depth-resolved lake temperatures used in the lake mixing regime classification method were simulated by a lake model forced with bias-corrected climate projections available from the Inter-Sectoral Impact Model Intercomparison Project, namely (A) GFDL-ESM2M, (B) HadGEM2-ES, (C) IPSL-CM5A-LR and (D) MIROC5. Time series data needed to drive the lake model from each climate projection were extracted for the grid point situated closest to the centre of each lake. For each climate model projection, we also show (see inset) the percentage of correctly defined mixing regimes by the lake model driven by each of the bias-corrected climate model projections.
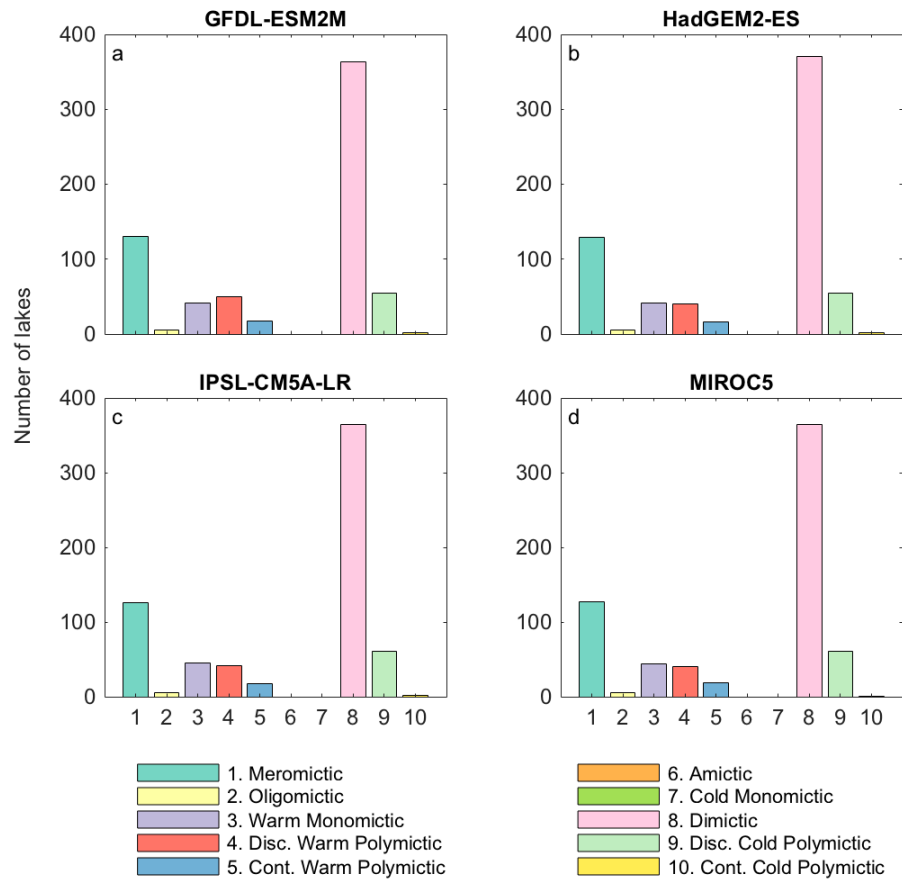
Figure S8. Comparison of modelled global lake mixing regimes identified using the classification scheme of ref. 16 and depth-resolved lake temperatures simulated by a lake model forced with bias-corrected climate projections, namely (A) GFDL-ESM2M, (B) HadGEM2-ES, (C) IPSL-CM5A-LR and (D) MIROC5.
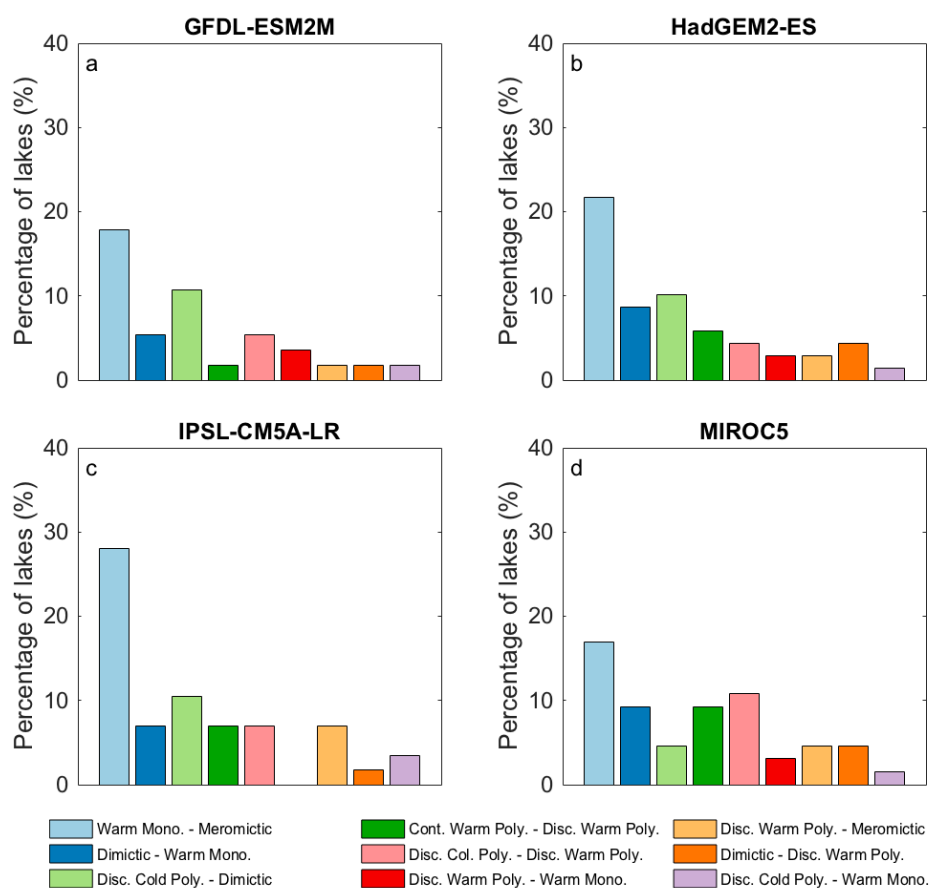
Figure S9. Comparison of climate-related changes in lake mixing regimes under RCP 2.6 using a lake model forced with bias-corrected climate projections, namely (A) GFDL-ESM2M, (B) HadGEM2-ES, (C) IPSL-CM5A-LR and (D) MIROC5.
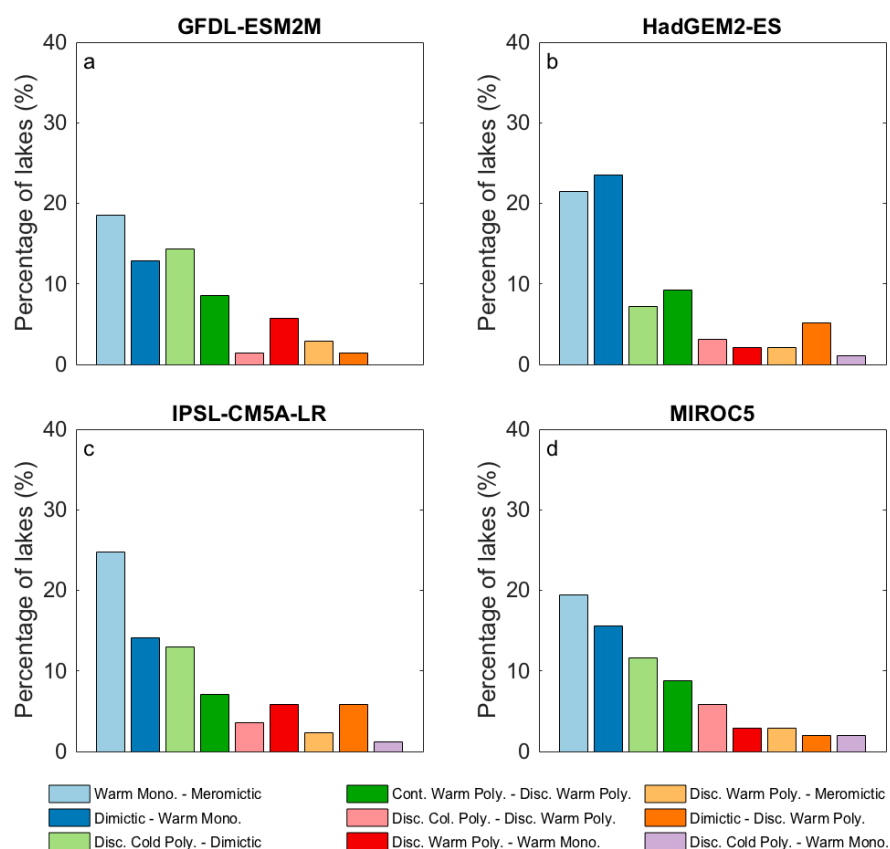
Figure S10. Comparison of climate-related changes in lake mixing regimes under RCP 6.0 using a lake model forced with bias-corrected climate projections, namely (A) GFDL-ESM2M, (B) HadGEM2-ES, (C) IPSL-CM5A-LR and (D) MIROC5.