

# *Worldwide alteration of lake mixing regimes in response to climate change*

Article

Accepted Version

Woolway, R. I. ORCID: <https://orcid.org/0000-0003-0498-7968>  
and Merchant, C. J. (2019) Worldwide alteration of lake mixing regimes in response to climate change. *Nature Geoscience*, 12. pp. 271-276. ISSN 1782-0908 doi: <https://doi.org/10.1038/s41561-019-0322-x> Available at <https://centaur.reading.ac.uk/82814/>

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To link to this article DOI: <http://dx.doi.org/10.1038/s41561-019-0322-x>

Publisher: Nature

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1 **Title**

2 Worldwide alteration of lake mixing regimes in response to climate change

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4 **Author information**

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6

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11

12 **Lakes hold much of Earth's accessible liquid freshwater, support biodiversity and**  
13 **provide key ecosystem services to people around the world. However, they are**  
14 **vulnerable to climate change, for example through shorter durations of ice cover, or**  
15 **through rising lake surface temperatures. Here we use a one-dimensional, numerical**  
16 **lake model to assess climate change impacts on mixing regimes in 635 lakes worldwide.**  
17 **We run the lake model with input data from four state-of-the-art model projections of**  
18 **21<sup>st</sup> century climate under two emissions scenarios. Under the scenario with higher**  
19 **emissions (Representative Concentration Pathway 6.0), many lakes are projected to**  
20 **have reduced ice cover; about a quarter of seasonally ice-covered lakes are permanently**  
21 **ice-free by 2080-2100. Surface waters are projected to warm, with a median warming**  
22 **across lakes of about 2.5°C, and the most extreme warming at about 5.5°C. The**  
23 **projections suggest that around 100 of the studied lakes are projected to undergo**  
24 **changes in their mixing regimes. About a quarter of these lakes which are currently**  
25 **classified as monomictic - that undergo one mixing event in most years - will become**  
26 **permanently stratified systems. About a sixth of these which are currently dimictic -**  
27 **that mix twice per year - will become monomictic. We conclude that many lakes will**  
28 **mix less frequently in response to climate change.**

29

30 Documented climate-related changes in lakes include shorter durations of winter ice  
31 cover<sup>1-4</sup> and higher lake surface temperatures<sup>5-9</sup>. Recent global studies of lake surface  
32 temperature trends show that many lakes, predominantly those that experience seasonal ice  
33 cover, are warming at rates in excess of ambient air temperature<sup>7-8</sup>. Studies of lake  
34 temperature responses to climate change have improved our understanding of the  
35 consequences of warming on lake ecosystems<sup>10, 11</sup>. Here, we assess for 635 globally  
36 distributed large lakes how projected climate trends are likely to change lake stratification  
37 and mixing. Because these aspects of lake dynamics exert significant control on nutrient  
38 fluxes, oxygenation and biogeochemical cycling<sup>12, 13</sup>, considering stratification and mixing is  
39 critical for anticipating the repercussions of temperature change throughout lake  
40 environments and associated ecosystems.

41

42 **Stratification and mixing regimes in lakes**

43 Thermal stratification occurs in lakes as a result of the thermal-expansion properties of water.  
44 The time evolution of stratification is determined by the balance between turbulence, which  
45 acts to enhance mixing, and buoyancy forces, which act to suppress turbulence and result in a

46 vertical layering<sup>14</sup>. 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)<sup>14, 15</sup>.  
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<sup>16</sup> 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<sup>17</sup>). 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<sup>18, 19</sup>  
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<sup>20, 21</sup>, 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 20<sup>th</sup> 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<sup>2</sup> in area) and  
97 situated north of 40°N, where the global lake abundance is highest<sup>18</sup>. 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 **Climate-related changes in lake mixing regimes**

101 To project future changes in mixing class, the lake model is forced by four climate  
102 projections available from the Inter-Sectoral Impact Model Intercomparison Project<sup>22</sup>,  
103 namely, HadGEM2-ES, GFDL-ESM2M, IPSL-CM5A-LR and MIROC5 (see Methods for  
104 details), under two Representative Concentration Pathway (RCP) scenarios. The main figures  
105 presented here show the results from the lake model forced with bias-corrected HadGEM2-  
106 ES projections. To indicate the uncertainty of projections, we show or quote the spread of  
107 results from the lake model across all four climate model projections. Changes projected for  
108 2080-2100 are quoted relative to the period 1985-2005.

109  
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  $-29\pm 8$  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  $24\pm 5\%$  of lakes that display winter ice cover in the historic period  
122 will be ice-free by the end of the 21<sup>st</sup> century under the RCP 6.0 scenario. The increase in  
123 annual mean lake surface temperature is projected to be  $1.1\pm 0.4^{\circ}\text{C}$  and  $2.3\pm 0.6^{\circ}\text{C}$  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  $5.4\pm 1.1^{\circ}\text{C}$  under RCP 6.0.  
126  $99\pm 0.5\%$  of lakes are projected to increase in mean temperature under RCP 2.6, and all  
127 ( $100\pm 0\%$ ) 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 21<sup>st</sup>  
133 century (Fig. 3, Fig. S9-S10). Specifically, in the projections under RCP 2.6 and 6.0,  
134 respectively,  $59\pm 7$  and  $96\pm 15$  lakes change mixing class.

136 The most common identified alteration in mixing class ( $25\pm 5\%$  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 21<sup>st</sup> 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 21<sup>st</sup> 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<sup>10</sup> and the formation  
144 of deep-water dead zones<sup>12</sup>, respectively. Oxygen depletion at depth can be detrimental to the  
145 habitat for fish<sup>23</sup> and can modify biogeochemical processes resulting in, for example, the  
146 potential release of phosphorus and ammonium into the water column<sup>24</sup> and the production of  
147 potentially toxic metal ions<sup>25</sup>.

148  
149 The second most common identified alteration in mixing class (across the model  
150 ensemble) is a change from dimictic to warm monomictic ( $17\pm 5\%$  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<sup>26</sup> and the production and biodiversity of phytoplankton<sup>27</sup>.

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<sup>28</sup>. 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<sup>29</sup>, increased inflow of cold water from retreating glaciers<sup>30</sup>,  
167 thermal pollution from nuclear plants<sup>31</sup>, and changes in the magnitude of influent water<sup>32</sup>,  
168 which will be particularly important for lakes with short residence times or extensive lake  
169 level variations<sup>33</sup>. Changes in lake transparency can also influence the mixing regime of  
170 lakes<sup>34</sup>, 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<sup>35, 36</sup> and the vertical  
173 thermal structure will be constrained strongly by fetch<sup>37</sup>. 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<sup>38, 39</sup>. 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

181 distribution of lake mixing regime alterations is heterogeneous, because climatic conditions  
182 interact with lake-specific contexts, particularly geomorphology. The projections do not  
183 support simple expectations of regional consistency in lake responses whereby lakes in a  
184 given region will change similarly. Changes in lake temperature will not always translate to  
185 changes in lake mixing regimes: some of the lakes which are projected to experience the  
186 highest surface warming are not projected to undergo a change in their mixing class. Most  
187 lakes that are projected to alter in their mixing regimes currently display anomalous mixing  
188 behaviour relative to their dominant mixing classification in some years. Specifically, two-  
189 thirds of lakes that are projected to experience an alteration in their mixing regimes had at  
190 least three years of anomalous mixing regime during the period 1985 to 2005. Lakes that are  
191 currently classified as warm monomictic but fail to mix fully during some winters presently  
192 account for 60% of those that are projected to become meromictic (i.e., permanently  
193 stratified) in the future. Lakes that are currently seasonally ice-covered and are classified as  
194 dimictic but also experience some ice-free winters are projected to become predominantly  
195 monomictic by the end of the 21<sup>st</sup> century. Thus, the projections confirm the intuition that  
196 those lakes that currently exhibit anomalous years relative to their usual mixing class are  
197 more likely to transition to a different mixing regime in the future.

198

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298

### 299 **Acknowledgements**

300 This analysis was funded by EUSTACE (EU Surface Temperature for All Corners of Earth)  
301 which has received funding from the European Union's Horizon 2020 Programme for  
302 Research and Innovation, under Grant Agreement no 640171. The authors also acknowledge  
303 the European Space Agency funding of the ARC-Lake project. We thank Martin Dokulil for  
304 providing lake temperature data for Mondsee and Wörthersee. RIW received funding from a  
305 European Union's Marie Skłodowska-Curie Individual Fellowship (#791812; INTEL  
306 project). This work benefited from participation in the Global Lake Ecological Observatory  
307 Network (GLEON).

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.

315 **Figure captions**

316

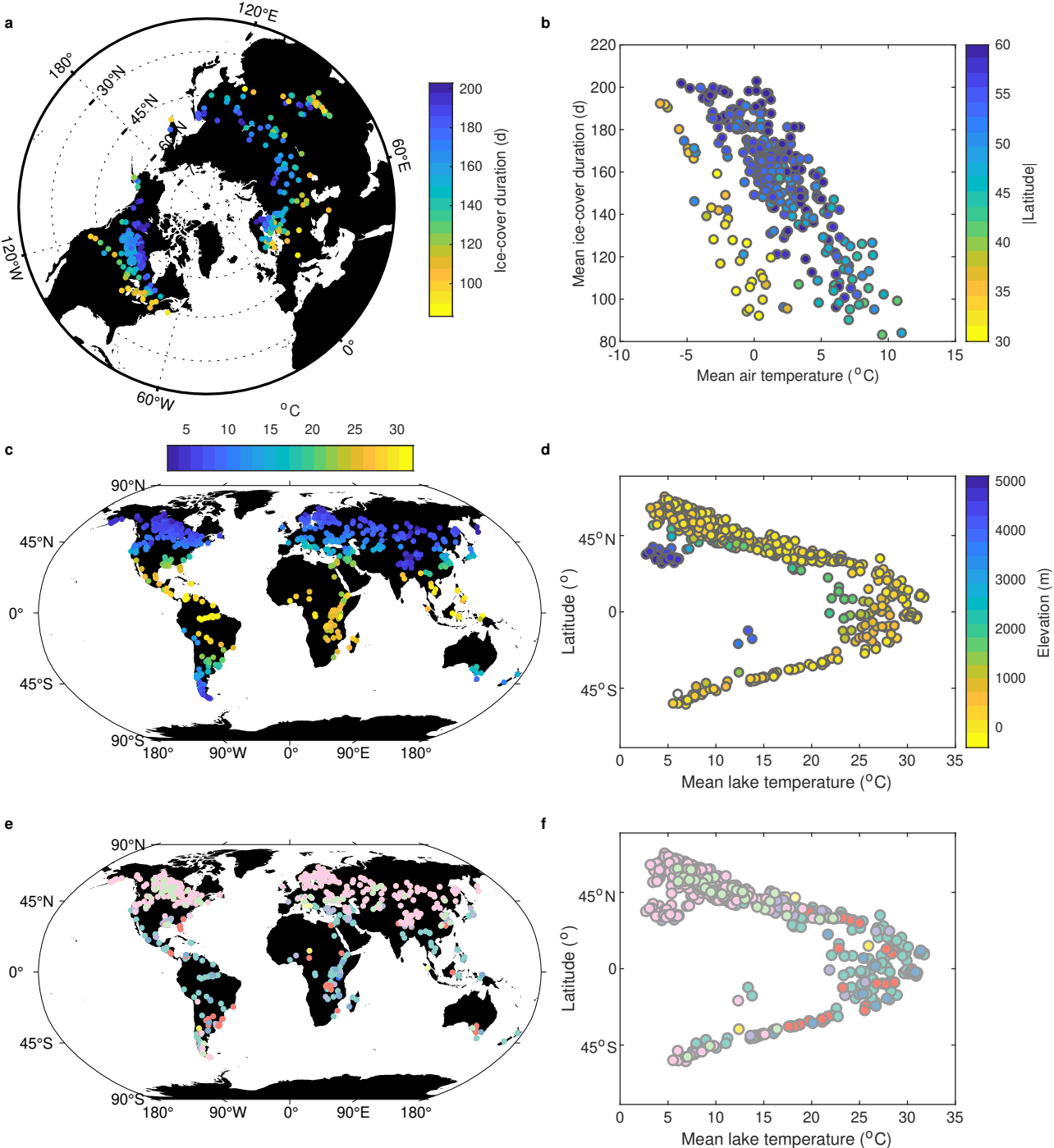
317 **Figure 1. Global patterns in annual mean (1995-2005) ice cover duration, lake surface**  
318 **temperature and lake mixing regimes.** (a) Satellite-derived ice cover duration and (b) their  
319 relationship with air temperature (from ERA-Interim<sup>17</sup>). (c) Global variations in satellite-  
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

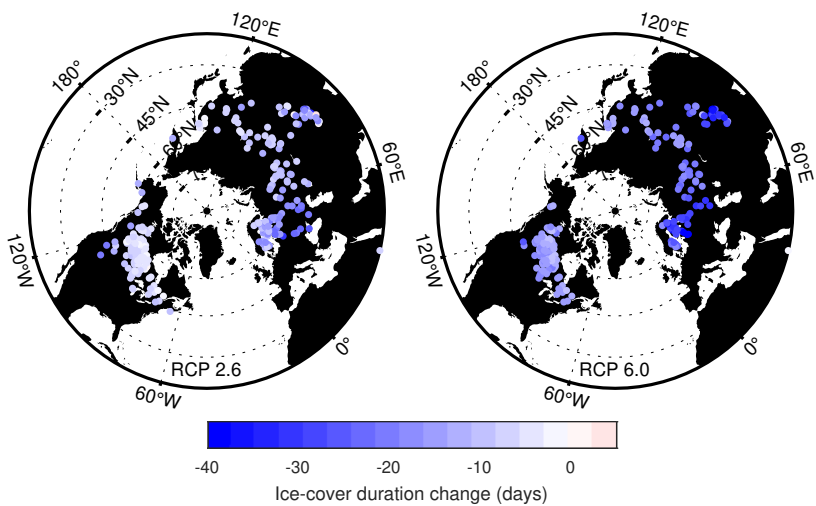
327 **Figure 2. Global changes (2080-2100 relative to 1985-2005) in annually averaged ice**  
328 **cover duration and lake surface water temperature.** (a) Changes in ice cover duration  
329 under RCP 2.6 and 6.0 (shown only for northern hemisphere lakes) from a lake model forced  
330 with bias-corrected 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

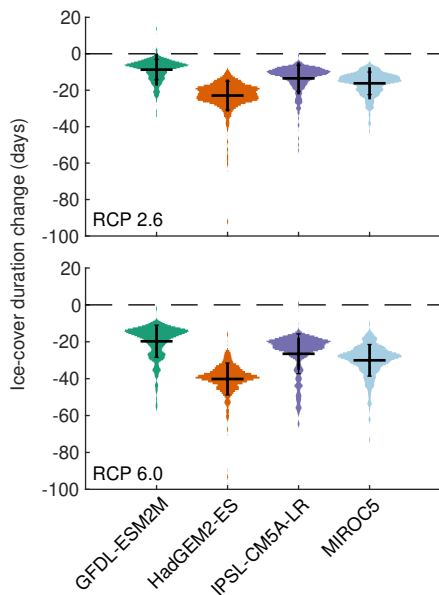
337 **Figure 3. Global changes (2080-2100 relative to 1985-2005) in lake mixing regimes.**  
338 Shown are climate-related changes in lake mixing regimes under (a) RCP 2.6 and (b) RCP  
339 6.0 using a lake model forced with bias-corrected HadGEM2-ES projections (comparison of  
340 lake mixing regime 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).



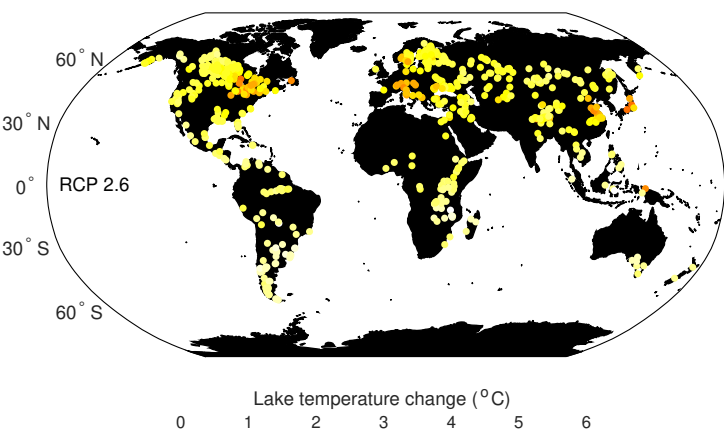
**a** Projected global change in ice cover and lake temperature



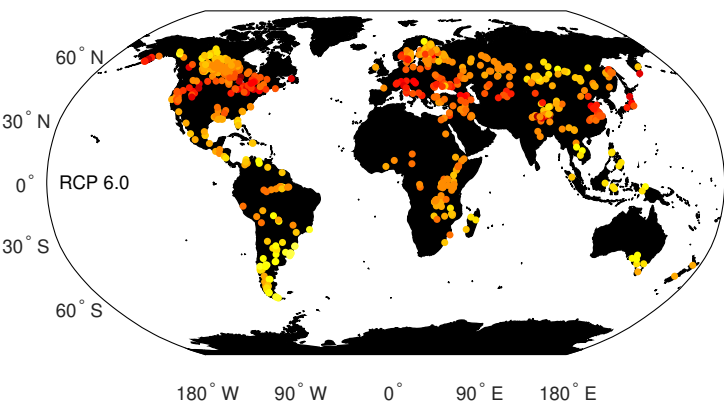
**b**



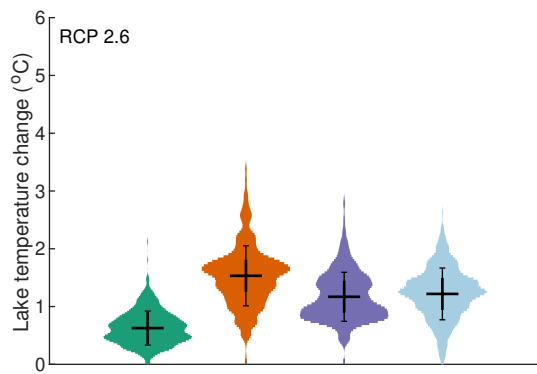
**c** 180° W 90° W 0° 90° E 180° E



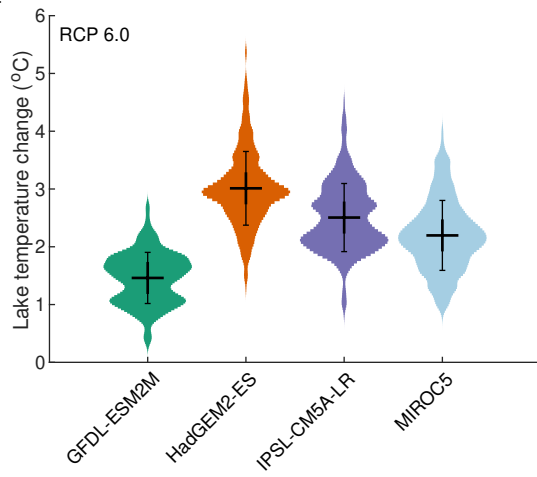
**e**



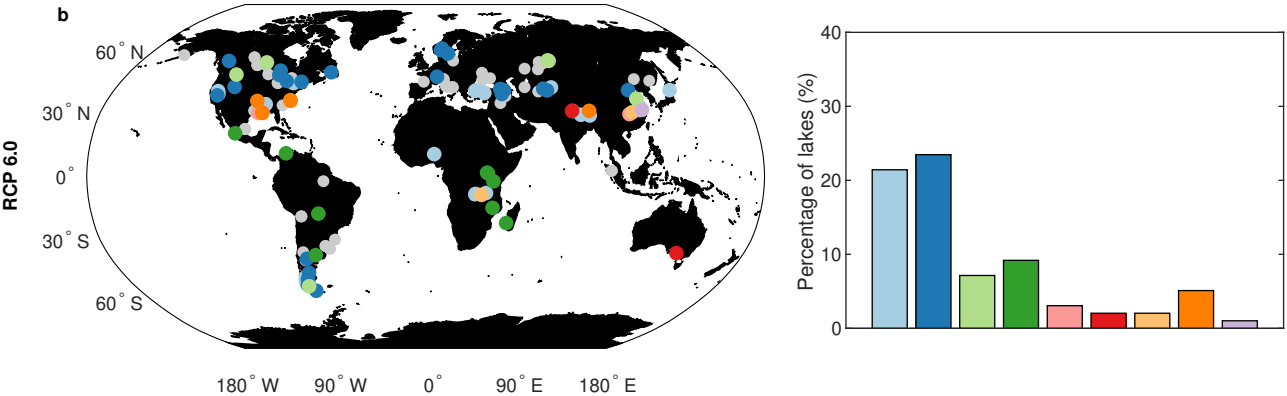
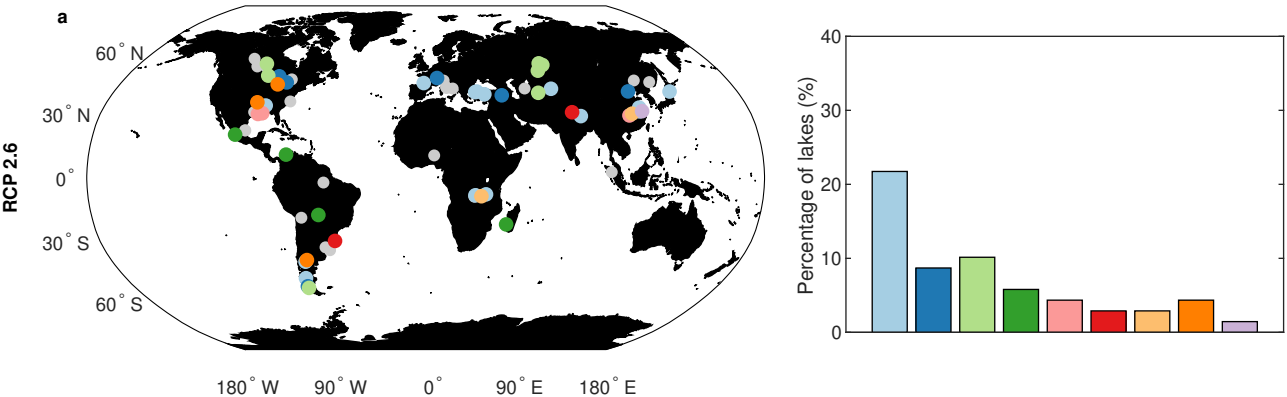
**d**



**f**



Projected global mixing regime alterations



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.

345 **Methods**

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

348

349 **Online Methods**

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

352

353 *Satellite-derived lake temperature and ice cover data* - We utilize lake surface  
354 temperatures from the ATSR (Along Track Scanning Radiometer) Reprocessing for Climate:  
355 Lake Surface Water Temperature and Ice Cover (ARC-Lake) dataset<sup>40</sup>, available at  
356 <http://www.laketemp.net>. In outline, the ARC-Lake surface water temperatures were obtained  
357 as follows. Within prescribed lake boundaries a water-detection algorithm using the  
358 reflectance channels of the ATSR-2 and AATSR instruments was applied to determine the  
359 extent of each lake during the ATSR-2/AATSR period. Within these boundaries, a Bayes'  
360 theorem calculation of the probability of clear sky conditions was performed for each image  
361 pixel, day and night<sup>41</sup>. For pixels with high clear-sky probability, the lake surface water  
362 temperature was retrieved from the ATSR-2/AATSR thermal imagery, using an optimal  
363 estimation method adapted from radiative-transfer physics-based techniques extensively  
364 validated for sea surface temperature<sup>42</sup>. Temperature estimates were gridded and spatio-  
365 temporally gap-filled using dynamically interpolating empirical orthogonal functions<sup>43</sup>. For a  
366 fuller account, refer to ref. 40. Daily lake-mean time-series were obtained by averaging  
367 across the lake area. Lake-mean surface temperatures are used in order to average across the  
368 intra-lake heterogeneity of surface water temperature responses to climate change<sup>44</sup> and to  
369 correspond to the lake-mean model used (see below).

370 The effectiveness of the lake product retrieval algorithms in ARC-Lake has  
371 previously been assessed using a dataset of matches to in situ temperature data, consisting of  
372 52 observation locations covering 16 lakes and >5,500 individual matches<sup>40</sup>. Overall,  
373 agreement was  $-0.2 \pm 0.7$  K for daytime and  $-0.1 \pm 0.5$  K for night-time matches. ARC-Lake  
374 data have been independently validated as part of other studies<sup>45</sup> and used to validate lake  
375 simulations<sup>46, 47</sup>. In this study we use daily averaged LSWTs, calculated as the average of the  
376 day and night-time retrievals. To assess from the daily-mean temperature time-series the  
377 periods during which a lake was likely partially or wholly ice covered, we follow ref. 48, and  
378 characterise this as the period during which the lake-mean surface water temperature is  $< 1^\circ\text{C}$ .  
379 This corresponds closely to presence of lake ice cover from in-situ observations<sup>48</sup>.

380 The ARC-Lake observations were also used to quantify global patterns in mean lake  
381 temperatures and as part of the validation (see below) of the modelled surface temperatures  
382 and ice cover duration in lakes globally (Fig. S2, Fig. S5).

383

384 *Lake model* - To simulate depth-resolved lake temperatures, as required to identify  
385 mixing regimes in lakes, we used the one-dimensional thermodynamic lake model FLake<sup>20</sup>,  
386 <sup>21</sup>. FLake is a simplified lake model that is in some instances less accurate than other more  
387 computationally expensive models<sup>49</sup>, but which can be efficiently coupled with climate  
388 models and is useful for evaluating the impact of climate change projections on lakes<sup>45</sup>.  
389 FLake is used widely both for research and as a component in numerical weather prediction<sup>50</sup>.

390 <sup>51</sup>. 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<sup>34, 52-53</sup>, 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<sup>45, 54, 55</sup>. The model has also been used to reproduce past variability in ice cover timing,  
396 intensity and duration<sup>56</sup>, and to investigate the thermal response of polymictic, monomictic  
397 and lakes to large-scale climatic shifts<sup>57</sup>. 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<sup>46, 50</sup>, 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<sup>19</sup>, 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<sup>17</sup>,  
421 available at a latitude-longitude resolution of  $0.75^\circ$ .

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 0.5°. 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](https://www.bmlfuw.gv.at/wasser/wasser-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<sup>60</sup>. 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  $<1^{\circ}\text{C}$  period<sup>48</sup>. 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<sup>62</sup> (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; monomictic 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 1°C. 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 4°C 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.

524 To validate the modelled lake mixing regimes during the historic period, as simulated  
525 by FLake driven by each ISIMIP2b model run, we compared results with literature-derived  
526 descriptions from 85 lakes, including those described by ref. 66-69, and the World Lake  
527 Database (Table S2). In these comparisons we did not separate mixing regimes within an  
528 individual class. For example, we did not distinguish between cold and warm monimictic and  
529 continuous and discontinuous polymictic, as this information was not available frequently in  
530 the literature. Lake mixing regimes assessed from the FLake simulations were in agreement  
531 with those from these sources in 72% of cases for three of the ISIMIP2b model runs (Fig. S7)  
532 and 73% for the other (IPSL-CM5A-LR).

533

#### 534 **Data availability**

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

539

#### 540 **Code availability**

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

542

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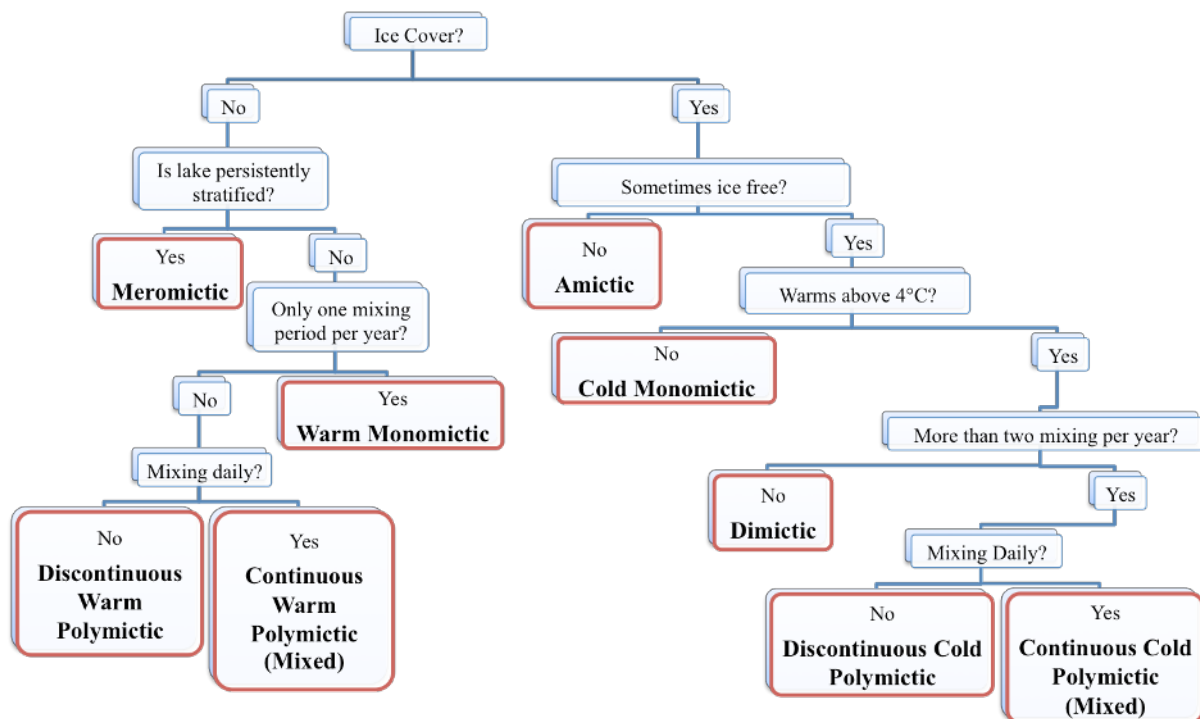
**Worldwide alteration of lake mixing regimes in response to climate change**

R. Iestyn Woolway<sup>1\*</sup>, Christopher J. Merchant<sup>1,2</sup>

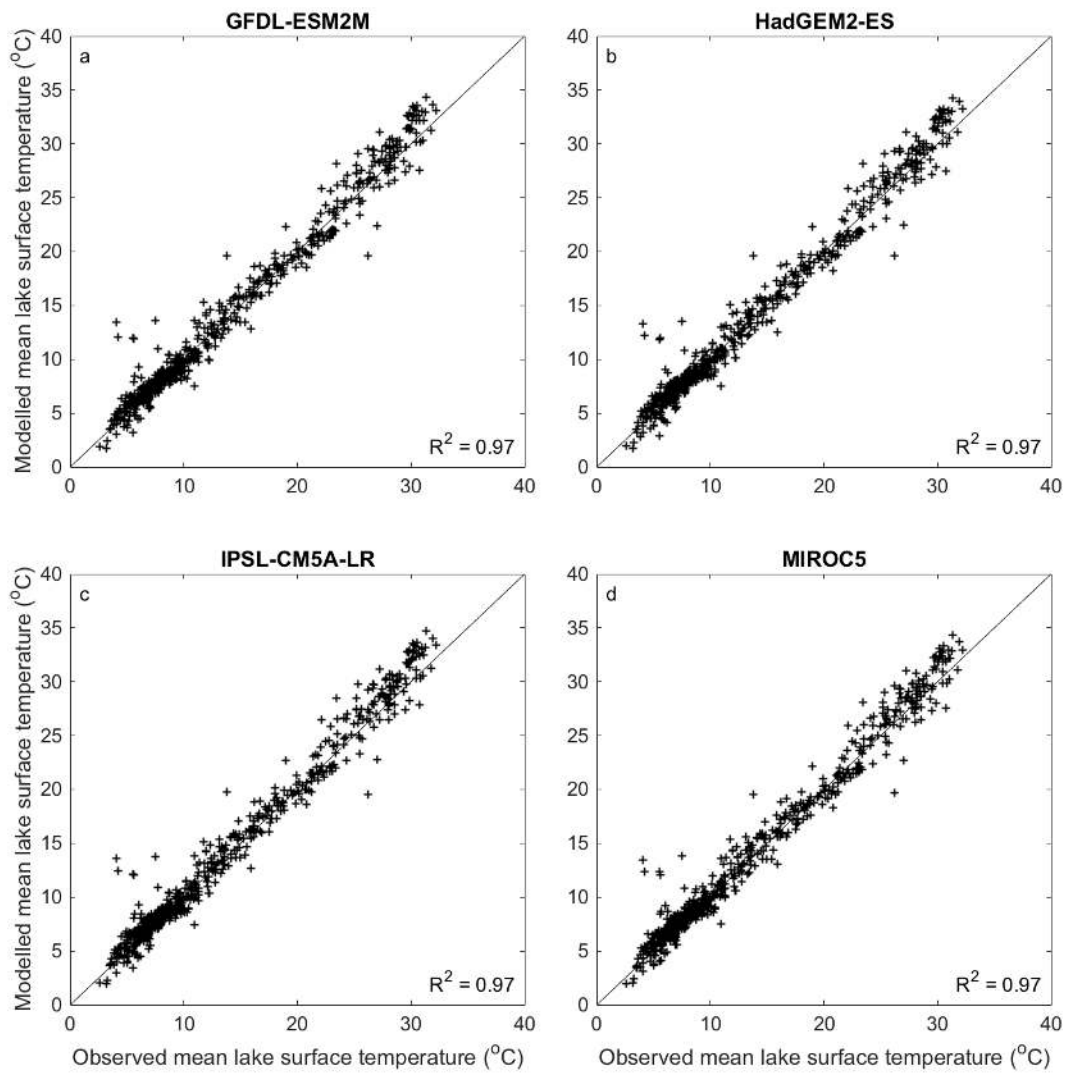
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  2. National Centre for Earth Observation, University of Reading, Reading, UK
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**Introduction**

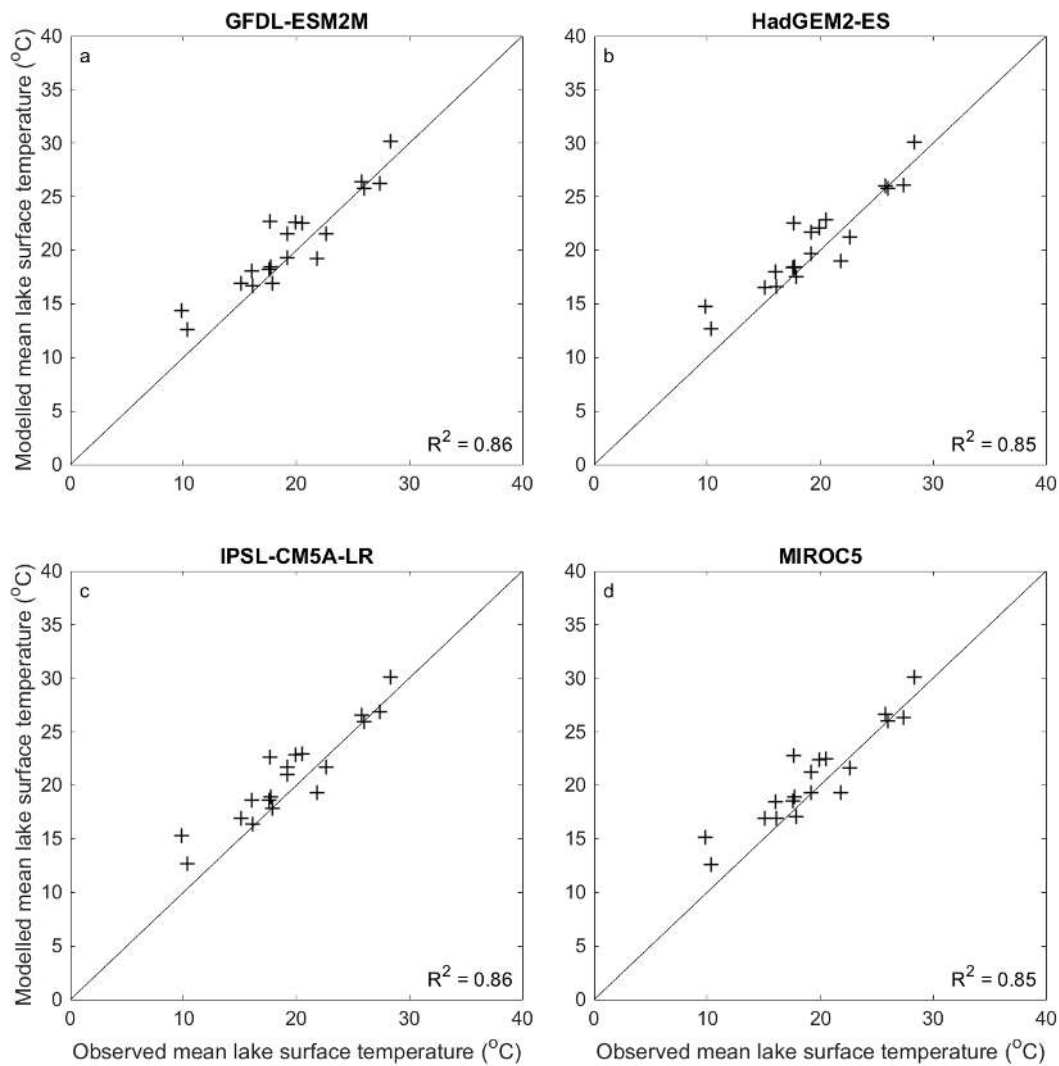
The supporting information presented here provides more comprehensive details that complement the analyses presented in the main text, allowing a more complete assessment of our findings.



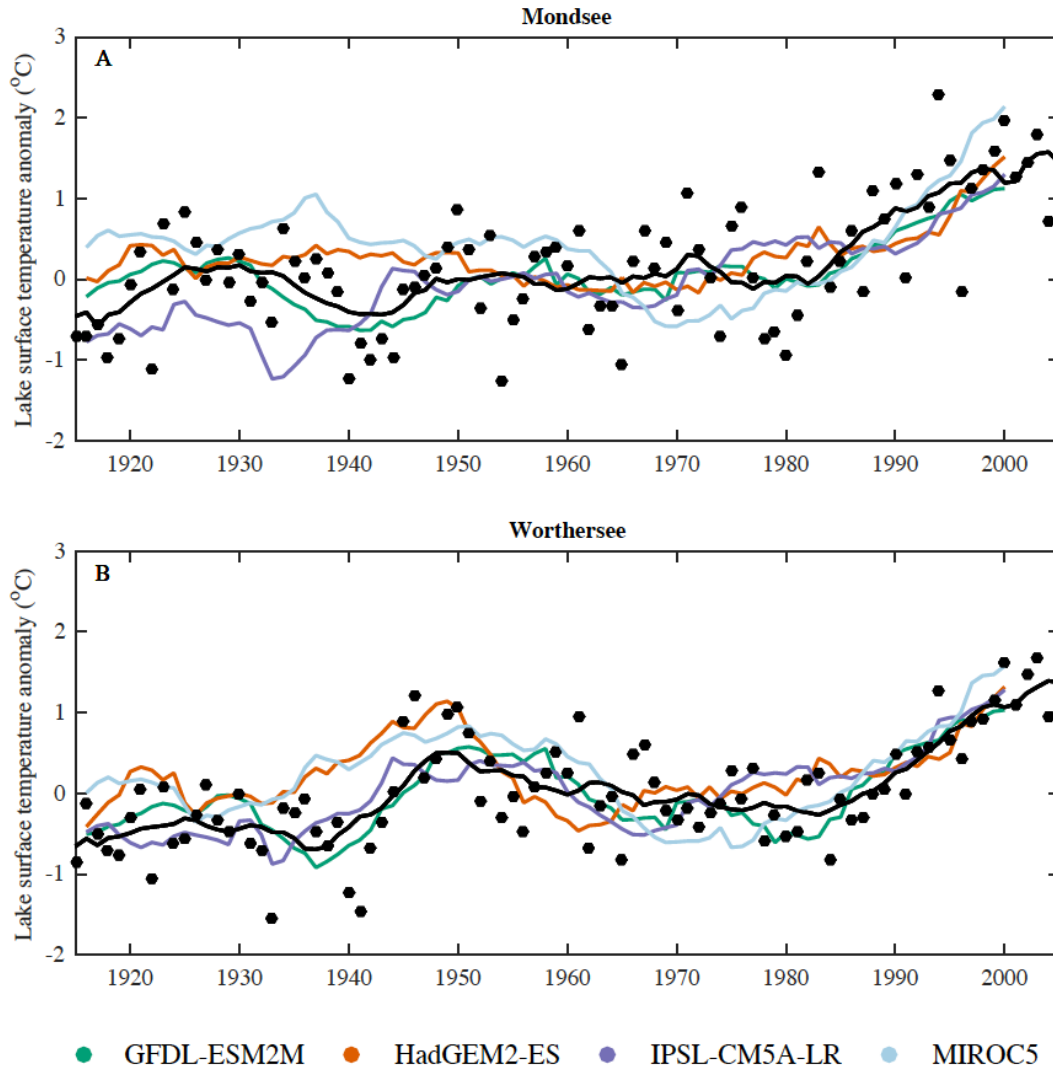
**Figure S1.** Classification scheme used in this study to determine the mixing regimes of lakes. Modified from ref. 16. The criteria used to define a stratified (or mixed) period is when the top minus bottom (modelled) lake temperature difference (absolute) exceeds (or is lower than) 1°C (see Methods). 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.

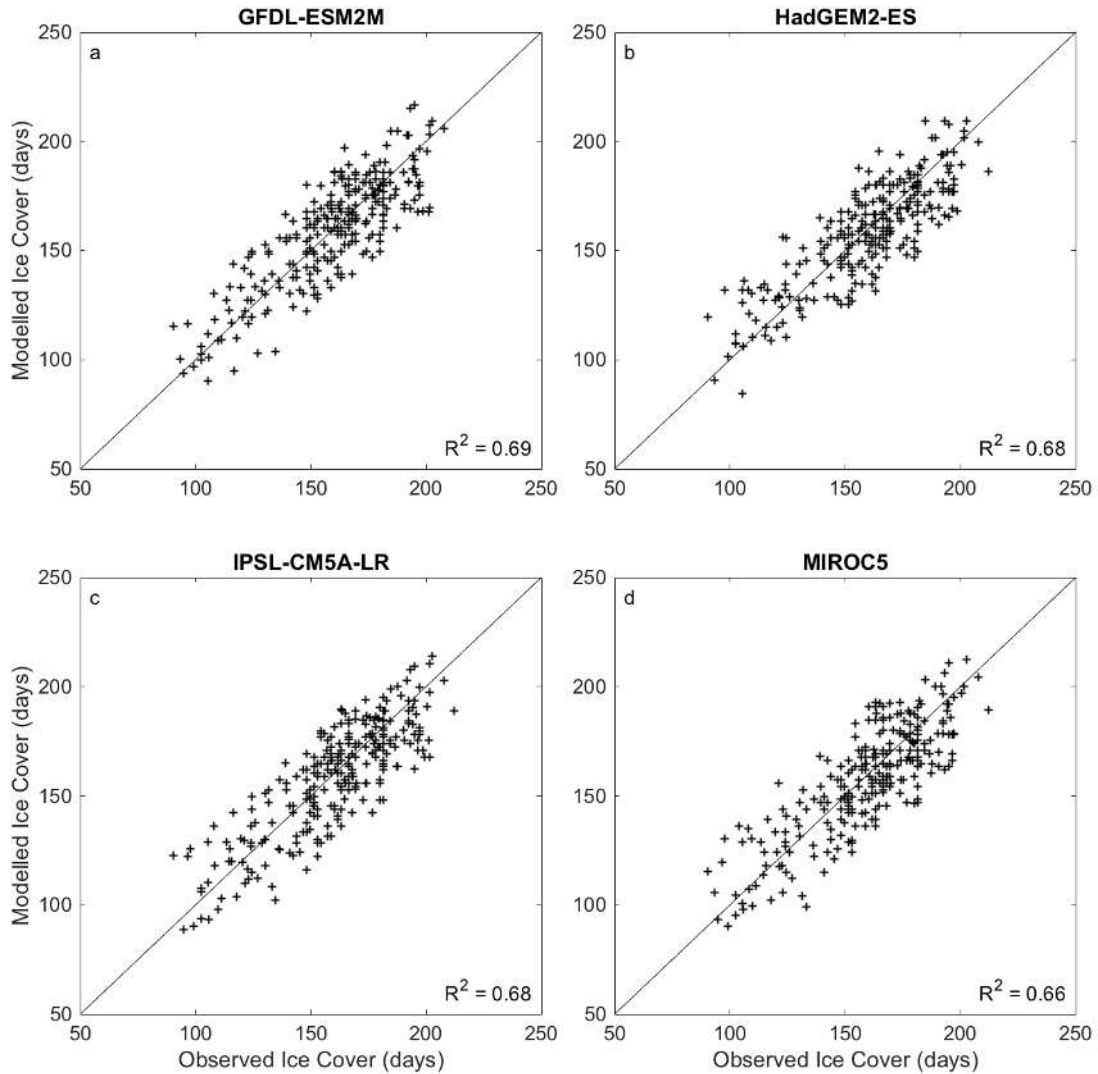


**Figure S3.** Comparison of summer-average modelled and observed lake surface water temperatures. In-situ summer-average lake surface temperatures are from ref. 61 and include data from Baikal, Lake Biwa, Bodensee, Lake Erie, Sea of Galilee, Lake Garda, Lac Léman, Lake Huron, Lake Michigan, Neusiedler 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.

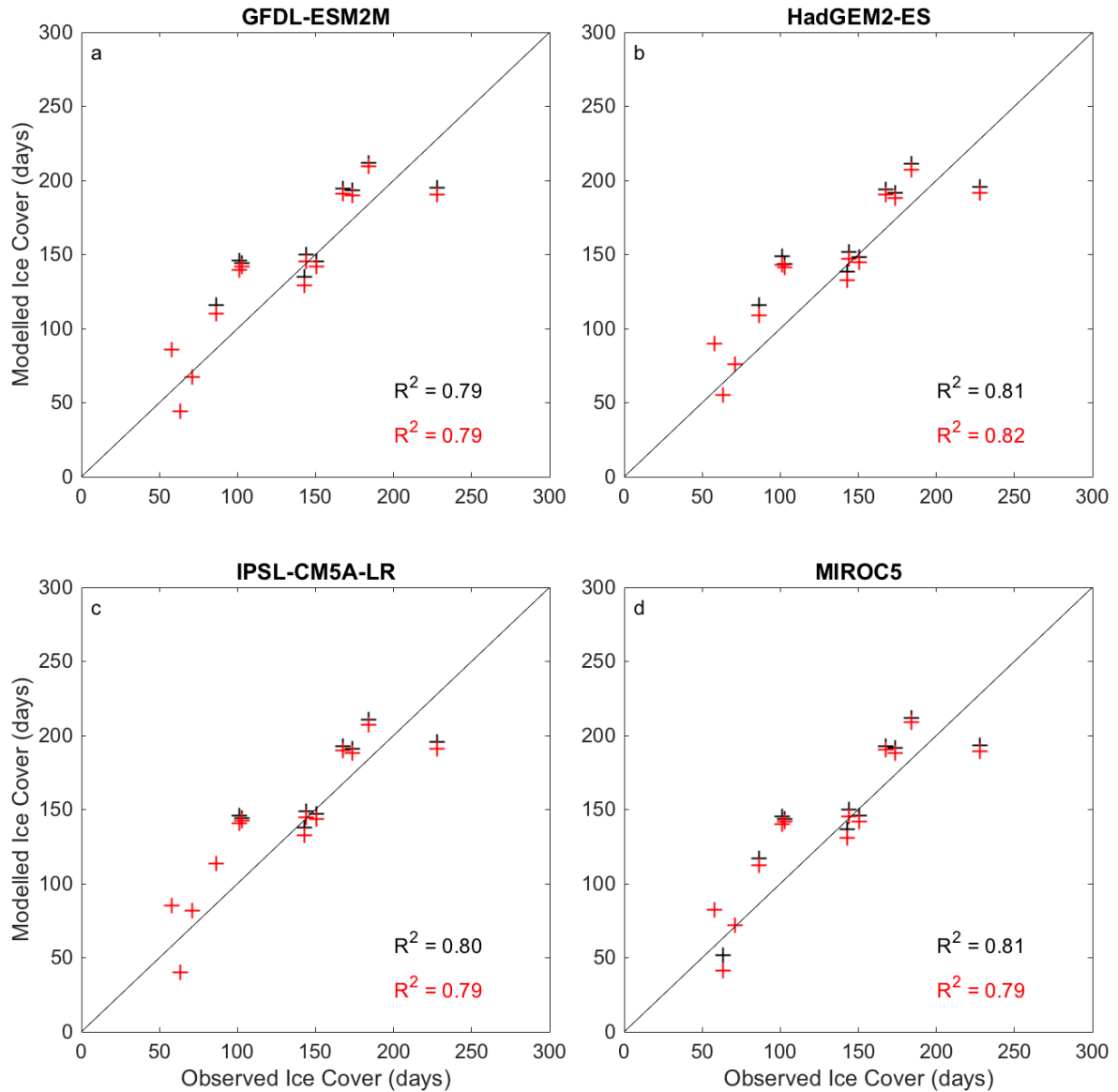


**Figure S4.** Comparison of observed (black) and modelled (colour) annual mean lake surface temperature anomalies from 1915 to 2005. Modelled lake surface temperatures represent those simulated by a lake model forced with bias-corrected climate projections available from the Inter-Sectoral Impact Model 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 Würthersee), 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.

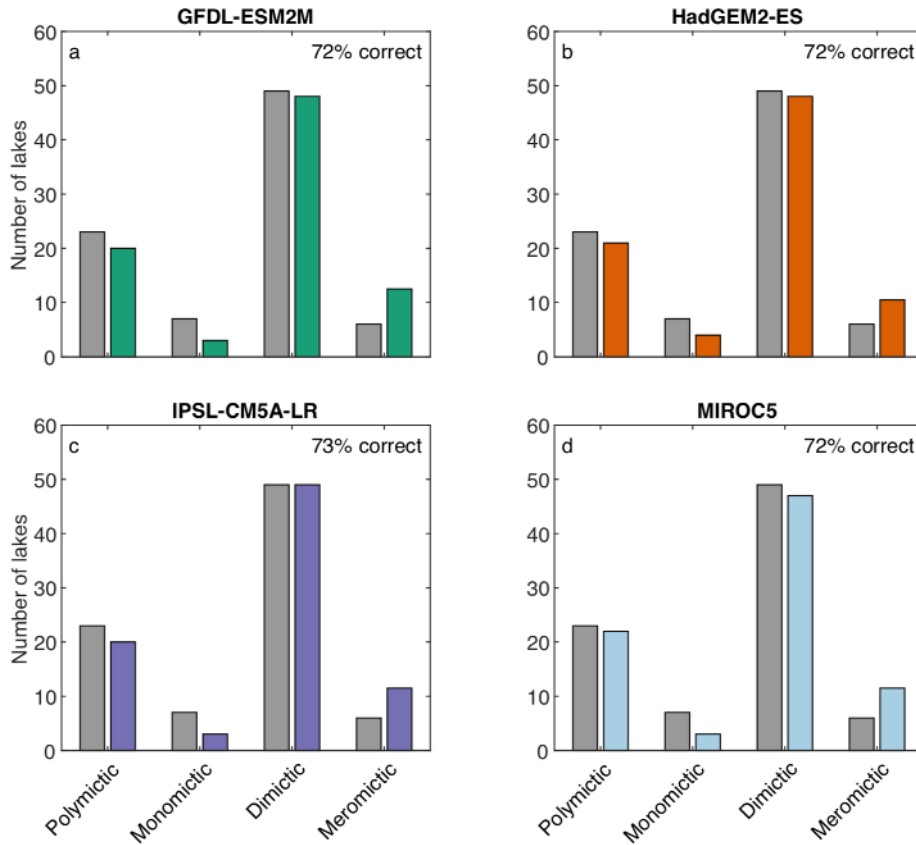




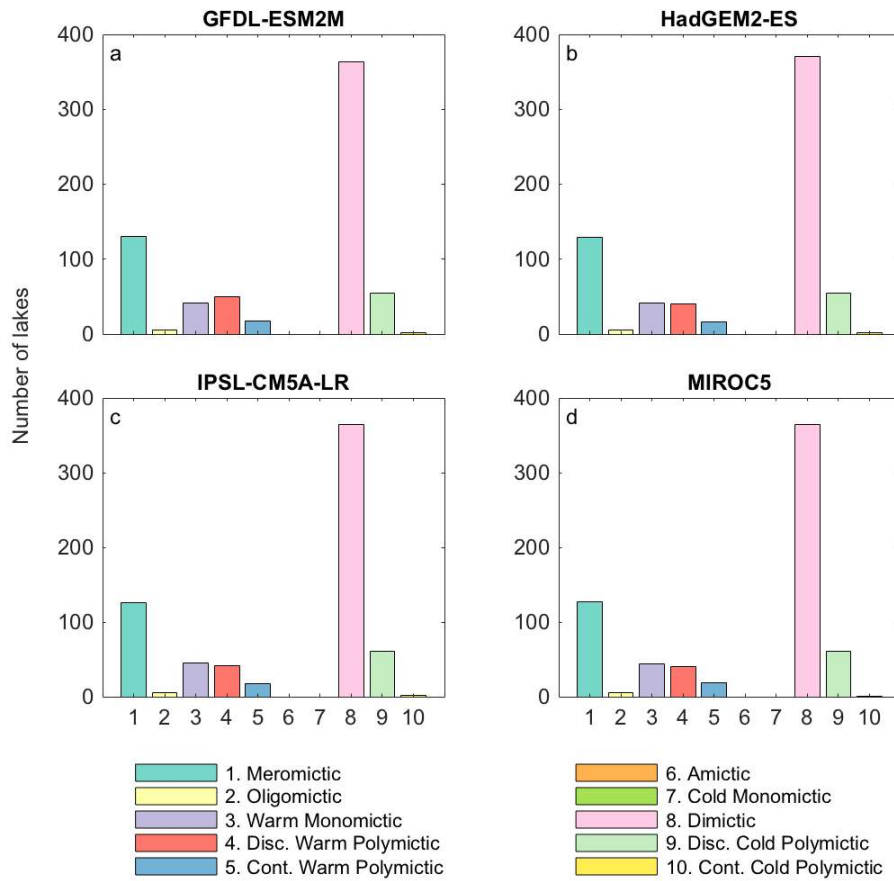
**Figure S5.** Comparison of modelled and observed (1995-2005) ice cover duration (in days) for the studied lakes which experienced ice cover. The modelled lake temperatures represent those simulated by a lake model forced with bias-corrected climate projections available from the Inter-Sectoral Impact 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  $<1^{\circ}\text{C}$ .



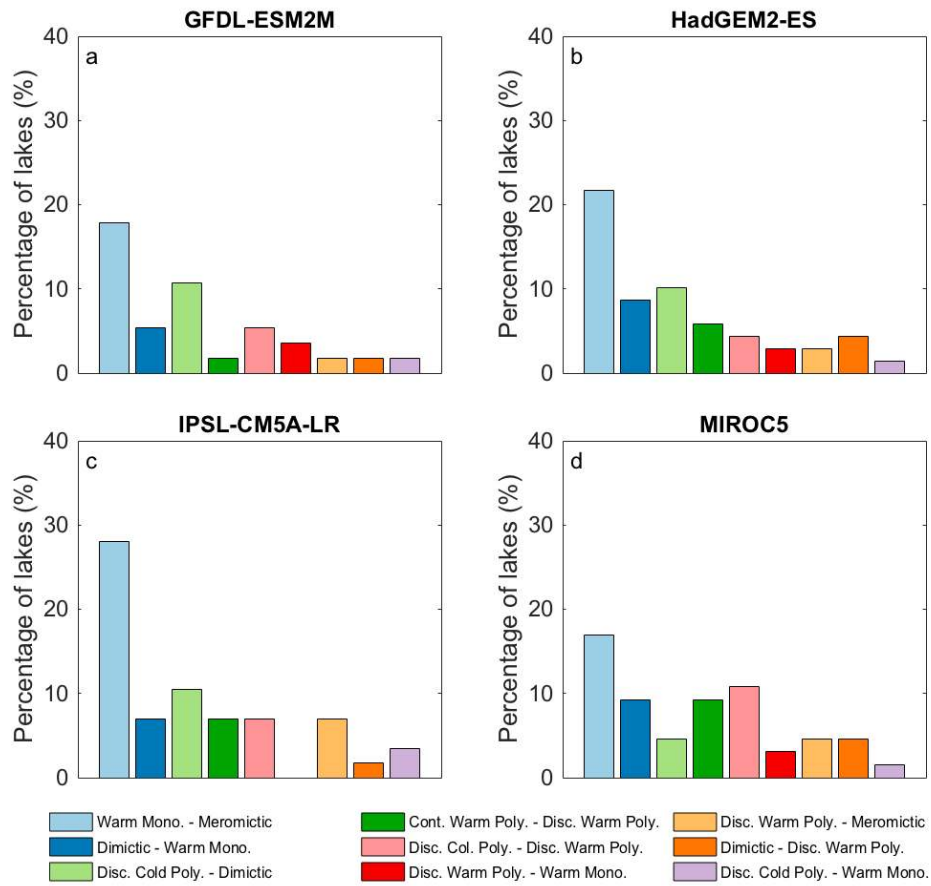
**Figure S6.** Comparison of modelled and observed (1995-2005) ice cover duration (in days) for lakes in which in-situ ice cover data were available and used in this study. The modelled lake temperatures represent those simulated by a lake model forced with bias-corrected climate projections available 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  $<1^{\circ}\text{C}$  (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<sup>62</sup>. 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).



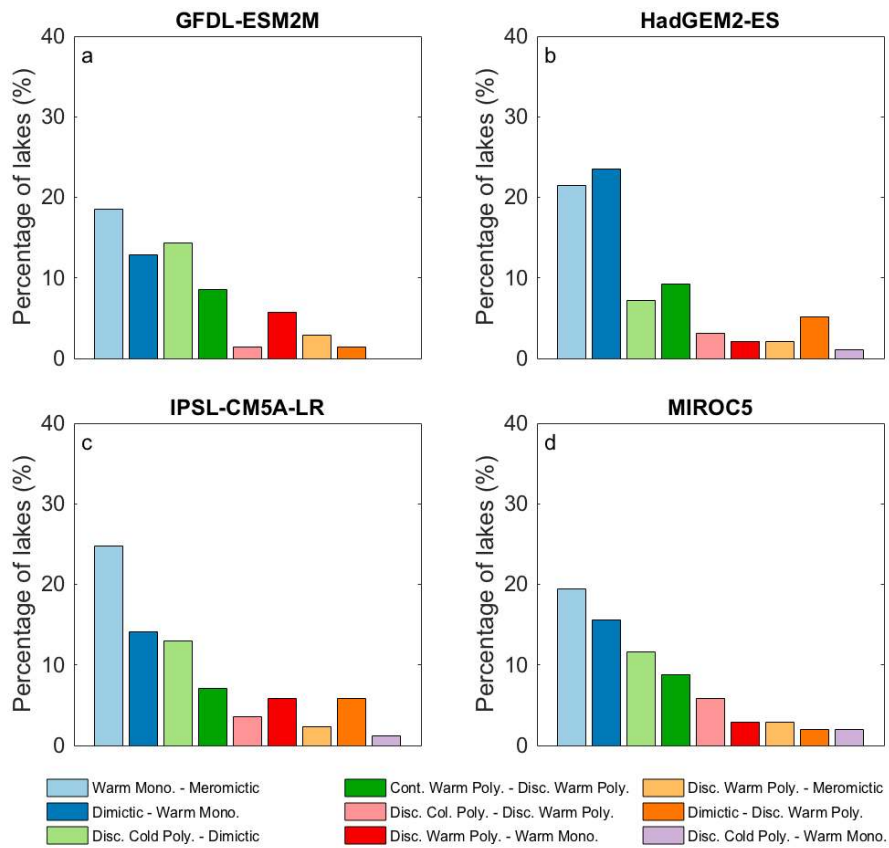
**Figure S7.** Comparison of modelled (grey) and literature defined (colour) mixing regimes of 85 lakes (Table S2). Modelled mixing regime classifications were defined following the method described in Fig. S1. Depth-resolved lake temperatures used in the lake mixing regime classification method were 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.