Lake heatwaves under climate change

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Nature

Peer reviewed version

Cyswllt i'r cyhoeddiad / Link to publication

02. May. 2024

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17

18 **Summary**

19 Lake ecosystems, and the organisms that live within them, are vulnerable to temperature

20 change[1–5], including the increased occurrence of thermal extremes[6]. However, very little is

21 known about lake heatwaves—periods of extreme warm lake surface water temperature—and

22 how they may change under global warming. Here we use satellite observations and a

23 numerical model to investigate changes in lake heatwaves for hundreds of lakes worldwide

24 from 1901 to 2099. We show that lake heatwaves will become hotter and longer by the end of

25 the twenty-first century. For the high-greenhouse-gas-emission scenario (Representative

26 Concentration Pathway (RCP) 8.5), the average intensity of lake heatwaves, defined relative

27 to the historical period (1970 to 1999), will increase from 3.7 ± 0.1 to 5.4 ± 0.8 degrees Celsius

28 and their average duration will increase dramatically from 7.7 ± 0.4 to 95.5 ± 35.3 days. In the

29 low-greenhouse-gas-emission RCP 2.6 scenario, heatwave intensity and duration will increase

30 to 4.0 ± 0.2 degrees Celsius and 27.0 ± 7.6 days, respectively. Surface heatwaves are longer-

31 lasting but less intense in deeper lakes (up to 60 metres deep) than in shallower lakes during

32 both historic and future periods. As lakes warm during the twenty-first century[7,8], their

33 heatwaves will begin to extend across multiple seasons, with some lakes reaching a permanent

34 heatwave state. Lake heatwaves are likely to exacerbate the adverse effects of long-term

35 warming in lakes and exert widespread influence on their physical structure and chemical

36 properties. Lake heatwaves could alter species composition by pushing aquatic species and

37 ecosystems to the limits of their resilience. This in turn could threaten lake biodiversity[9] and

38 the key ecological and economic benefits that lakes provide to society.

39

40 **Main text:**

41 There is compelling evidence that climate change is leading to more frequent and intense

42 heatwaves over land[10,11] and at the surface of the ocean[12-16], increasing the risk of severe and

43 in some cases irreversible ecological and socioeconomic impacts[17]. In comparison, we know

44 much less about heatwaves in lakes and how they will change within a warming world. This
45 knowledge gap is of considerable concern given the high vulnerability of lakes, and the
46 ecosystem goods and services that they provide, to thermal extremes[6,18].

47

48 A lake heatwave event can be defined, similar to marine heatwaves[13,17,19], as a period in which
49 lake surface temperatures exceed a local and seasonally varying 90th percentile threshold,
50 relative to a baseline climatological mean (the average temperature for the day/month of year
51 evaluated over the base period), for at least five days (see Methods; Extended Data Fig. 1a).
52 Here, we quantify past changes and assess future ones for different lake heatwave
53 characteristics using a lake model forced with atmospheric data (air temperature, solar and
54 thermal radiation, wind speed, atmospheric pressure, humidity) from an ensemble of four bias-
55 corrected 20th and 21st century climate projections (see Methods). Specifically, using satellite-
56 derived lake surface temperatures to optimize key parameters of a lake model (i.e., to represent
57 the thermal dynamics of the individual lakes), we simulate daily temperatures for hundreds of
58 lakes worldwide (Extended Data Fig. 2a-c), and investigate how lake heatwave intensity and
59 duration respond to climate change. The ability of the optimized lake model to simulate lake
60 heatwaves is evaluated by comparing the simulations with satellite-derived lake temperatures
61 during the historic period (see Methods). Good agreement was obtained between simulations
62 and observations of lake heatwaves and also of mean lake surface temperatures (Extended Data
63 Fig. 3). Using the optimized model, we simulated daily lake surface temperatures for all studied
64 lakes from 1901 to 2099. Historical simulations used anthropogenic greenhouse gas and
65 aerosol forcing in addition to natural forcing, and cover the period 1901 to 2005. Future
66 projections, which represent the evolution of the climate system subject to three different
67 anthropogenic greenhouse gas emission scenarios covering the period 2006 to 2099, RCP 2.6
68 (low-emission scenario), 6.0 (medium-emission), and 8.5 (high-emission), are also
69 investigated. For all model experiments, the climatological mean used to define anomalies was
70 calculated relative to a 30-year base period (1970 to 1999).

71

72 Simulated lake heatwave events from 1901 to 2099 are summarized to produce a set of
73 characteristics for lake heatwaves. We derived metrics for duration (time between start and end
74 dates of a lake heatwave event) and intensity (mean temperature anomaly over the heatwave).
75 We also use an intensity-based lake heatwave category to define the relative strength of each
76 lake heatwave (e.g., Extended Data Fig. 1b), where each event is classed as being Moderate,
77 Strong, Severe, or Extreme following the definitions of ref. 20. These categories are defined
78 by the maximum intensity of each lake heatwave event scaled by the threshold temperature
79 anomaly exceeding the climatological mean. A "Moderate" category is defined as a period of
80 time in which the lake surface temperature is above the 90th percentile of the climatological
81 distribution; "Strong" if the largest temperature anomaly during the event is more than twice
82 as large as the difference between the seasonal average and the 90th percentile; "Severe" if the
83 largest anomaly is more than triple the difference; and "Extreme" at four times or greater. We
84 calculated time series of the annual average intensity and average duration of lake heatwave
85 events, as well as the total number of lake heatwave days within a year, and the number of days
86 belonging to each of the defined lake heatwave categories. The season of lake heatwave
87 occurrence was also investigated.

88

89　Our global lake temperature simulations suggest that a typical lake heatwave event, averaged
90　for all years from 1970 to 1999, had an average intensity of 3.7±0.1 °C and lasted, on average,
91　7.7±0.4 days (quoted uncertainties represent the standard deviation from the lake model driven
92　by the four climate model projections). Lake heatwave intensity and duration vary depending
93　on the climate model projection used with a range of 0.1 °C and 0.8 days, respectively, across
94　the lake-climate model ensembles (i.e., difference between the minimum and maximum of the
95　simulations). Hereafter, for each lake heatwave metric quoted, we also provide the minimum
96　and maximum from the four climate model ensembles (i.e., [min, max]). During the 21st
97　century, lake heatwave intensity and duration was projected to increase considerably
98　worldwide (Fig. 1). Some lakes have already experienced noticeable change in recent decades
99　(Extended Data Fig. 1c-f). The magnitude of change of these lake heatwave metrics during the
100　21st century increases with the severity of the RCP scenario. For the low greenhouse gas
101　emission scenario, the average intensity of lake heatwaves, averaged for all years from 2070 to
102　2099, will increase to 4.0±0.2 [3.7, 4.2] °C and the average duration will increase 3-fold to
103　27.0±7.6 days [16.1, 33.7]. Under the high greenhouse gas emissions scenario, the intensity
104　and duration of lake heatwaves will be much greater by the end of the 21st century. The average
105　intensity of lake heatwaves will increase to 5.4±0.8 [4.3, 6.1] °C, and the average duration of
106　lake heatwaves will increase 12-fold to 95.5±35.3 [45.8, 125.6] days (Fig. 1). Similar to marine
107　heatwaves[12,13], the intensity of lake heatwaves is linked to temperature variability. It is higher
108　in regions with high surface temperature variability such as high latitude lakes[8], and lower in
109　regions with low variability, such as in tropical lakes (Fig. 1c). However, the projected lake
110　heatwave events at higher latitudes tended to be relatively short-lived compared to those
111　experienced in low-latitude lakes, in particular under future climate change (Fig. 1f).

112

113　Our simulations also showed a dependence of the average intensity and duration of heatwave
114　events on average lake depth ($\log_{10}$ transformed) (Fig. 1g-i). To investigate this depth
115　dependence further, we first separated the studied lakes according to the thermal regions in
116　which they reside. By following the definitions of ref. 8, we separated the studied lakes into
117　nine thermal regions, which are categorized according to their seasonal patterns of surface
118　temperature (Extended Data Fig. 2d-g). Given the preponderance of lakes in high, northern
119　latitudes[21] (Extended Data Fig. 2g), over 70% of our studied lakes are situated within the three
120　northernmost thermal regions: Northern Frigid ($n = 87$), Northern Cool ($n = 313$), and Northern
121　Temperate ($n = 123$). Within each of the nine thermal regions, we calculated the relationship
122　between lake depth and the intensity and duration of lake heatwaves (Extended Data Fig. 4-6).
123　For lakes situated in the Northern Cool region, where the majority of the studied lakes are
124　located, we calculated a statistically significant ($p < 0.001$) relationship between lake depth
125　and lake heatwave intensity ($R^2_{adj} = 0.72$) and duration ($R^2_{adj} = 0.42$) under RCP 8.5 (Fig. 1g-
126　i). Similar relationships were also observed under different climate trajectories as well as within
127　the other thermal regions with a sufficient number of lakes to make such comparisons
128　(Extended Data Fig. 4-6). Overall, we find that deeper lakes experience less intense but longer
129　lasting lake heatwaves. This depth effect is primarily because surface temperature anomalies
130　in deep lakes, due to their large thermal inertia, are (i) less sensitive to day-to-day changes in
131　atmospheric forcing and short-term climatic extremes and (ii) surface thermal anomalies are

132 eroded more slowly[22,23]. Additional lake-specific factors, such as the surrounding topography
133 and mixing regimes, as well as temporal variations in these lake attributes and over-lake
134 meteorology (e.g., wind speed), can also be important for influencing heatwaves in lakes.
135 However, our analysis suggests that lake depth explains a large proportion of the variability in
136 lake heatwaves within each lake thermal region.

137

138 The RCP scenario had a strong influence on the projected intensity of events and therefore the
139 exposure to the most extreme lake heatwaves during the 21st century (Fig. 2). During, and
140 particularly towards the latter stages of the 20th century (averaged for all years from 1970 to
141 1999), the majority of lake heatwave events worldwide were categorized as Moderate (70±3.2
142 [66.5, 73.9] %) with relatively few Strong events (22±2.8 [19.5, 25.2] %) and very few Severe
143 (4±0.6 [3.0, 4.4] %) or Extreme (4±0.3 [3.3, 4.0] %) events. Under the RCP 2.6 scenario, future
144 projections suggest that by the end of the 21st century (averaged for all years from 2070 to
145 2099) there will be a more even partition between the four lake heatwave categories (i.e., %
146 contributions of Moderate : Strong : Severe : Extreme = 28±9.6 [20.5, 41.9] : 40±2.2 [37.3,
147 42.5] : 14±3.5 [9.2, 16.8] : 18±6.8 [9.9, 25.4]) indicating an increase in Strong, Severe and
148 Extreme lake heatwaves. Under RCP 8.5, Extreme lake heatwaves were projected to make up
149 the majority of all events (65±17.4%) by the end of the 21st century (Fig. 2), whereas Moderate
150 events were rare (4±3.1%; % contributions of Moderate : Strong : Severe : Extreme = 4±3.1
151 [1.6, 11.3] : 14±9.1 [7.3, 27.7]: 17±3.9 [12.1, 21.7]: 65±17.4 [39.4, 79.0]).

152

153 During the historical period, lake heatwaves were prominent features in lakes during Spring,
154 Summer and/or Fall with ~27±3%, ~38±4%, and ~24±4%, respectively, of the lakes studied
155 experiencing a lake heatwave event, on average, within a given year. As the climate warms
156 during the 21st century, and lake heatwaves become more intense and longer lasting, the time
157 of year in which they occur will also change (Fig. 3). Specifically, under the high greenhouse
158 gas emission scenario we project that by the end of the 21st century, lake heatwaves will no
159 longer be restricted to a single season but will extend across multiple seasons (Fig. 3e-l). Under
160 this scenario, 35±3% of the lakes included in our simulations experienced heatwaves that began
161 in Spring and ended in Summer (Fig. 3f), and/or began in Summer and ended in Fall (38±3%;
162 Fig. 3g). By the end of the century, more than 17±2% of lakes experienced a lake heatwave
163 event that began in Spring and was maintained until Fall (Fig. 3j).

164

165 By the end of the 21st century, the total annual duration of lake heatwave days per year, which
166 is typically greater at lower latitudes (Fig. 4b-c) and in deeper lakes (Fig. 4d-e; Extended Data
167 Fig. 7-8), is projected to increase considerably (Fig. 4a). In particular, under RCP 8.5, the
168 global average total duration of lake heatwave days, averaged for all years from 2070 to 2099,
169 will increase 12-fold to 219±44 [155.1, 254.4] days, compared to 17±3 [14.8, 20.0] days during
170 the historic period (i.e., averaged for all years from 1970 to 1999). Some lakes will also reach
171 a permanent lake heatwave state, which we define as when lake surface temperatures exceed
172 the lake heatwave threshold continuously over a full calendar year. The number of studied
173 lakes that will experience a permanent heatwave state will increase during the 21st century, but
174 will differ depending on the RCP scenario considered (Fig. 4e). Under RCP 8.5, over 80.5±47
175 [18, 124] of the studied lakes will reach a permanent heatwave state by 2099 (Fig. 4f). Seasonal

ice cover, which is important for a range of lake ecosystem services as well as the regulation of the hydrological cycle[24], will influence the number of lakes that experience a permanent heatwave, since lakes that freeze annually will not experience a heatwave throughout the entire year. For the studied lakes that are projected to be ice-free by 2070-2099, the number of which will increase during the 21st century (Extended Data Fig. 9a), we project that approximately half (45±22%) of these will reach a permanent heatwave state by 2099 under RCP 8.5 (Extended Data Fig. 9b). The influence on lake heatwaves of increasingly ice-free winters is already apparent in Lake Vättern, Sweden[25] (Extended Data Fig. 1c, e).

The emergence of a permanent lake heatwave state implies that extremes in the traditional sense will no longer be 'extreme', and that there will be a substantial departure from the 'normal' lake heatwave conditions, that have shaped lake ecosystems in the past, to a new norm. This also suggests that the baseline period to maintain a 90th percentile definition into the future could also be changing, if understanding the true extremes for any specific time period was the focus of study. Indeed, by calculating a sliding 30-year climatological mean, our simulations show that the surface temperature of the studied lakes will warm considerably during the 21st century (Extended Data Fig. 9c). We test the influence of mean 21st century surface temperature change on lake heatwaves by repeating our analysis after detrending the lake surface temperature anomalies i.e., after removing the long-term warming signal[15]. Whilst these metrics no longer strictly capture heatwaves, as least following the definitions of refs 12-14, 16-17, 19 they are still useful in identifying extremes for any specific time period and for investigating the primary drivers. The detrended surface temperature anomalies still demonstrate an increase in 'heatwave' intensity and duration during the 21st century (RCP 8.5). However, these changes are much-reduced compared to those calculated when the long-term warming signal is included, particularly in terms of intensity which is influenced considerably by the mean warming rate[26].

The choice of baseline and whether or not to detrend a time series prior to calculating lake heatwaves[15] depends on the application. A fixed baseline, as we have used here, is appropriate for understanding impacts on species that adapt slowly (e.g., at evolutionary timescales); for example, to identify how lake heatwaves may affect local species/ecosystems in the future. However, if a species can adapt over, for example, decadal timescales to changing temperatures, then a sliding baseline[15] might be more appropriate, although there would presumably be limits to the extent of possible adaptation. Given that micro-evolutionary rates for a given species are unlikely to change rapidly enough to account for general rates of warming over the 21st century, then the ability of a species to survive, or the effects on its fitness through competition or interactions with other trophic levels, will depend on the tolerance and effects of the increased temperature. Thus, although many aspects of species' responses to shifting thermal regimes remain unclear, using a shifting baseline or a detrended time series might not be effective for determining the potential ecological effects that lake heatwaves may have in the future.

We expect that the increases in the intensity and duration of lake heatwaves that we have described here will emerge as agents of disturbance to lake ecosystems in the near-future, as

has already occurred on land during atmospheric heatwaves, with reported mass mortality of birds and mammals[27,28] and significant effects on human health[29]. Moreover, while atmospheric heatwaves in terrestrial environments can dissipate rapidly, lake heatwaves may dissipate at a much lower rate as a result of the higher thermal capacity of water than air, and indirect effects of lake heatwaves on water level, caused by increased evaporation[24], and on changing stratification and mixing patterns[7], so intensifying the ecological response. Aquatic organisms in regions close to their critical thermal maximum will be especially affected by lake heatwaves[6], leading to possibly extreme population loss, as has been documented in the marine environment[17]. The effects of heatwaves on freshwater species might be mitigated by exploiting the temporal and spatial variation within a lake, including phenological change[30] and a potential thermal refuge at depth[31]. However, phenological change can lead to food-web desynchronisation[32] and the increased number of heatwave days that we forecast may limit a seasonal escape, while a potential refuge in deeper and cooler water has not prevented past mortality events caused by thermal extremes[6]. In addition, dispersal to cooler sites at higher elevation, or higher latitude[33,34], will be constrained by the fragmented nature of lakes in the landscape, exacerbated by the worldwide increase in the number of dams[35]. Where local extinctions and range contractions in lakes involve 'keystone species', ecosystem effects could be particularly severe, via habitat loss and alterations to food web dynamics and species-interactions. A departure from historical lake thermal conditions, in combination with increased anthropogenic dispersal, may allow non-native species from warmer regions to become established and thrive[36], further disrupting freshwater food webs. These complex interactions are hard to forecast but the extreme heatwave in the summer of 2003 in central Europe illustrated the range of effects that might be expected including increased thermal stability and hypolimnetic oxygen depletion[37], production of cyanobacterial blooms[38] and a regime shift from pelagic to benthic productivity[39].

There is increasing appreciation of the link between climate change and increasing extreme events and concern over their ecological effects on fresh waters, including those of heatwaves but also storms[40,41] and droughts[42]. These 'pulse events' are likely to amplify any negative consequences of long-term 'ramp effects' such as warming water. Our projections of future increases of heatwave duration and intensity for lakes may be conservative, as climate models tend to underestimate the influence of climatic extremes on various ecosystems[43]. Nonetheless, our analysis of changes to the physical environment of lakes point towards emerging challenges to lake biodiversity and the benefits lakes provide to human populations.

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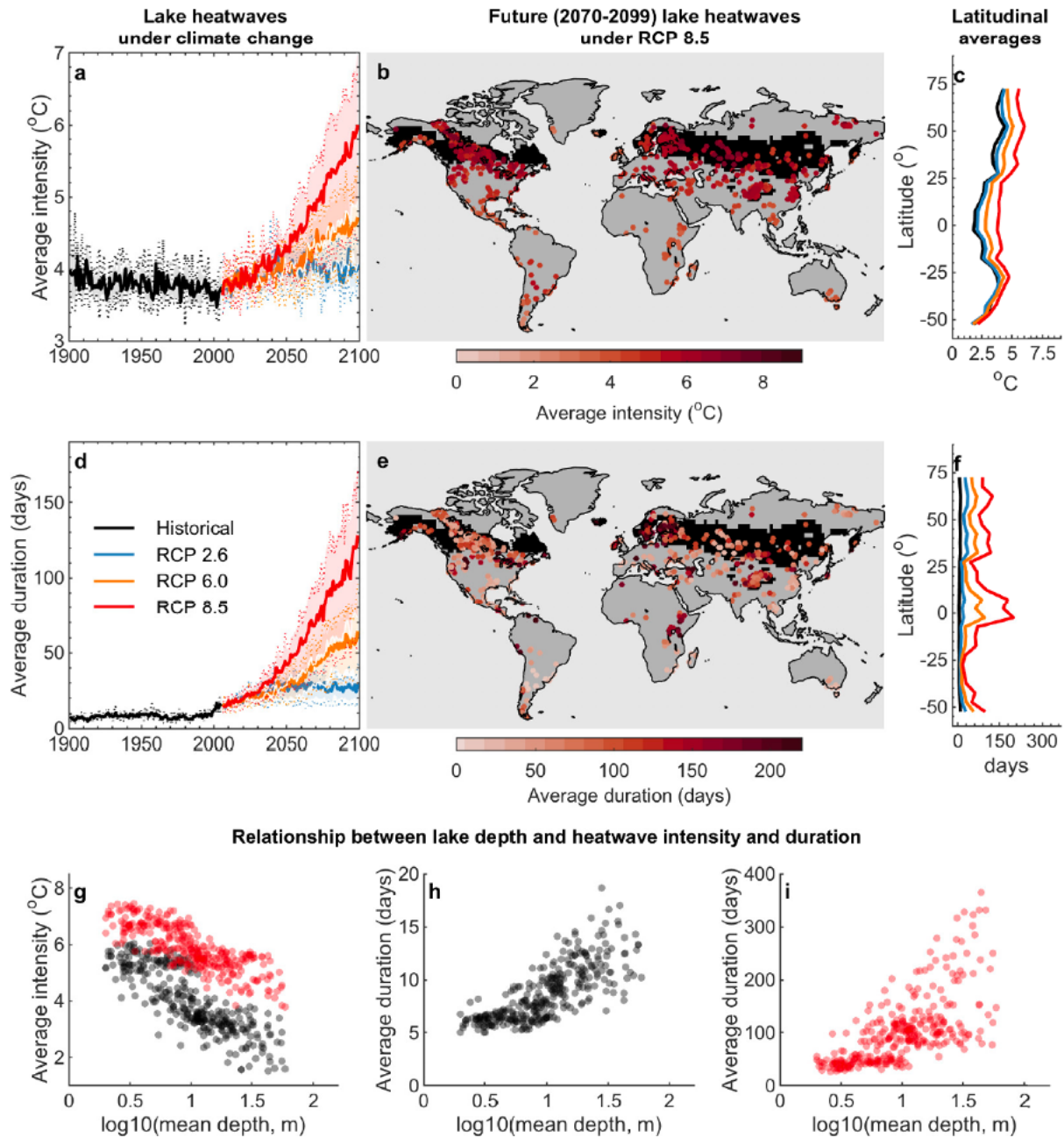
Fig. 1 | Historical and future projections of the intensity and duration of lake heatwaves. Temporal and spatial patterns in the average **(a-c)** intensity and **(d-f)** duration of lake heatwaves. Shown are **(a, d)** the temporal changes in lake heatwaves from 1901 to 2099 under historical and future climate forcing (RCP 2.6, 6.0, 8.5). The thick lines show the mean across all studied lakes, the shaded regions represent the standard deviation, and the dashed lines represent the range across the lake-climate model ensembles. Panels **b** and **e** show the average intensity and duration of lake heatwaves in each lake by the end of the 21st century (averaged for all years from 2070 to 2099) under RCP 8.5. Panels **c** and **f** show the latitudinal averages (5° bins) of the lake heatwave metrics under historical (1970-1999) and future (2070-2099) forcing. Panels **g-i** demonstrate the relationship between lake heatwaves and average lake depth

(log$_{10}$), under historic (black) and future (red; RCP 8.5) forcing for lakes situated in the
Northern Cool thermal region (shown as black regions in panels **b** and **e**; relationships for other
thermal regions are shown in Extended Data Fig. 4-6). All results are based on the average
simulations from the lake model driven by the four climate models.
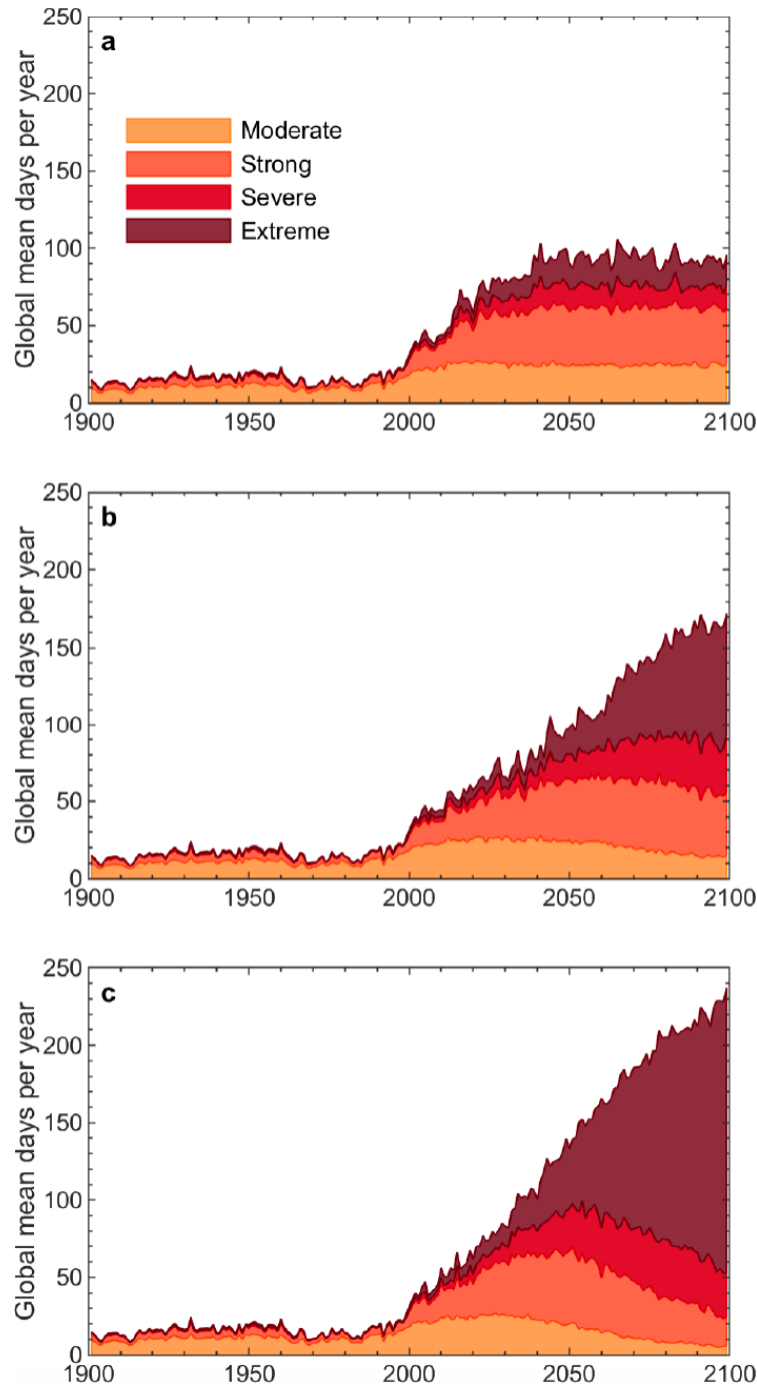
Fig. 2 | Historical and future projections of global lake heatwave strength. Time series of
the global annual mean count of Moderate (light orange), Strong (orange), Severe (red), and
Extreme (dark red) simulated lake heatwave days under historical and future climate forcing.
Future projections are subject to three different greenhouse gas emission scenarios: **(a)** RCP
2.6, **(b)** RCP 6.0, and **(c)** RCP 8.5. The total stacked amount in each panel is equivalent to the

total lake heatwave days under that particular forcing scenario. All results are based on the average simulations from the lake model driven by the four climate models.
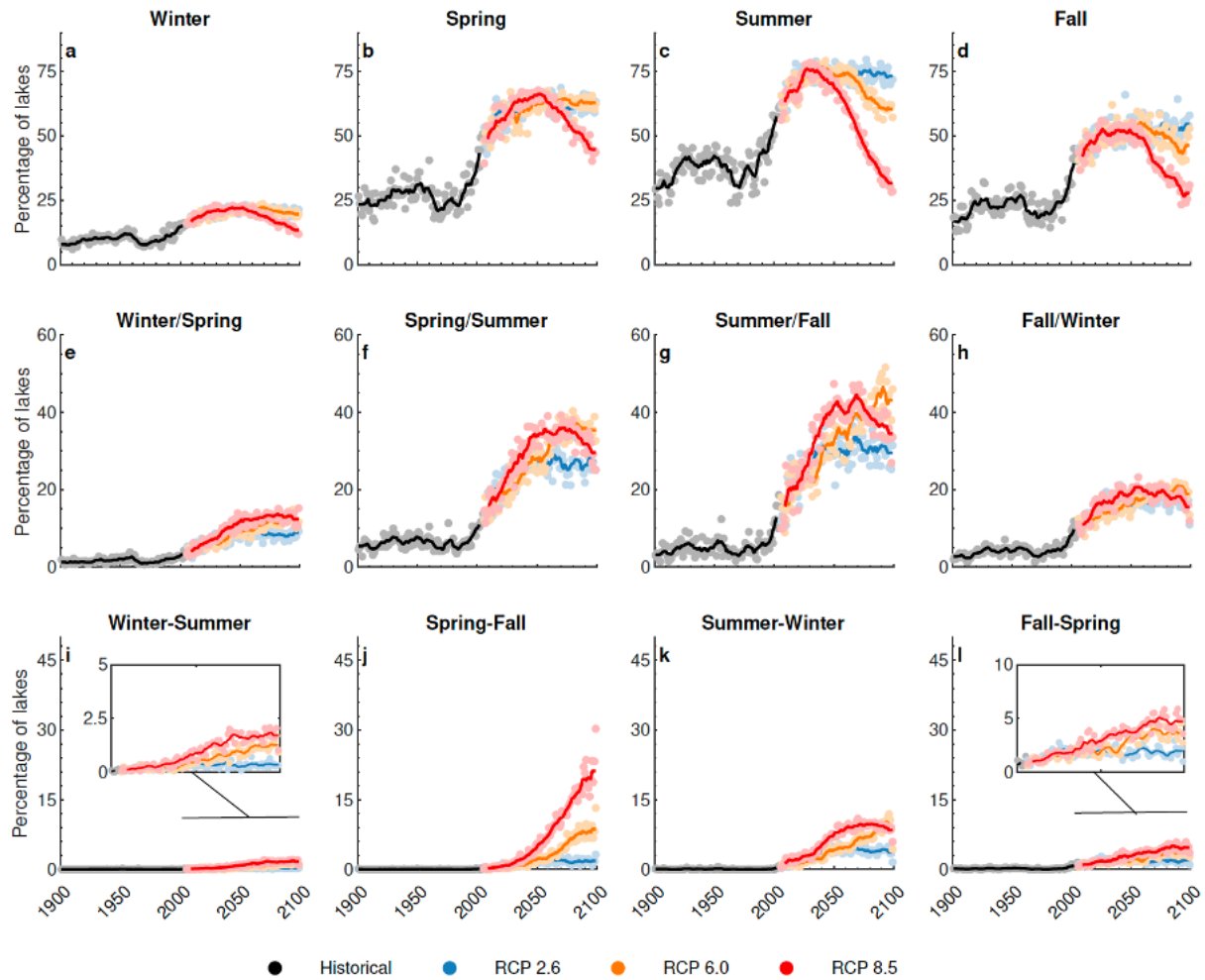
Fig. 3 | Seasonal variations in lake heatwave occurrence under historical and future climate change. Temporal changes in the season(s) during which the simulated lake heatwaves occur under historic (1901-2005) and future (2006-2099) climate forcing. Future projections are subject to three different greenhouse gas emission scenarios (RCP 2.6, 6.0, 8.5). Shown are the percentage of studied lakes which experience a heatwave during **(a-d)** a single season (Winter, Spring, Summer, Fall) only, and/or experience a heatwave which extended across **(e-h)** two or **(i-l)** three seasons. Note the different axis limits in panels **a-d**, **e-h**, and **i-l**. Each point represents the percentage of lakes globally during each year, and the solid line represents a 7-year moving average (included for illustration). The decline in panels **a-d** toward the end of the 21st century is due to fewer lakes experiencing heatwaves that are only maintained for a single season. Insets in panels **i** and **l** show the same data on an expanded scale. All results are based on the average simulations from the lake model driven by the four climate models. June is used to define the start of Boreal summer and December as the start of Austral summer.
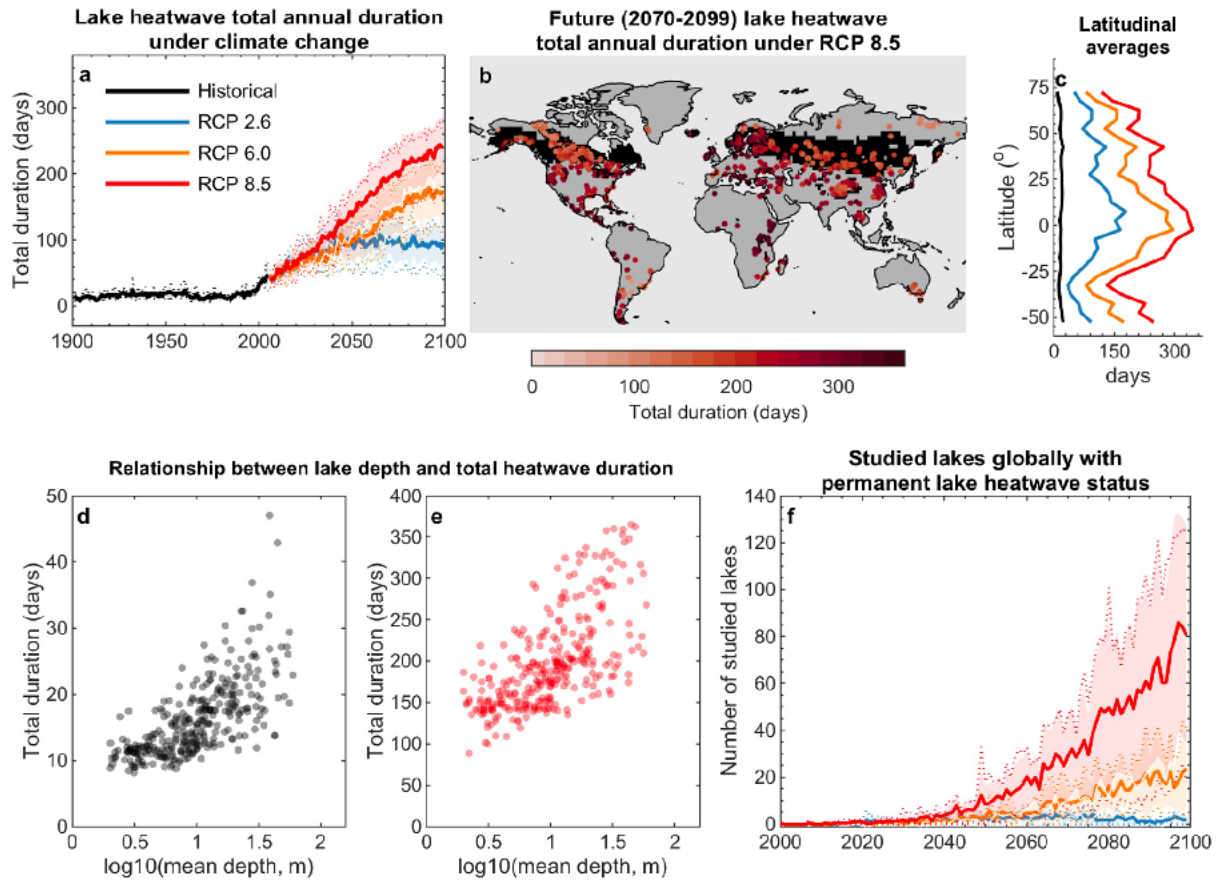
Fig. 4 | Total heatwave duration and the emergence of a permanent heatwave state in lakes globally. (a, b) Temporal and spatial patterns in the total annual duration of lake heatwaves per year under 20th and 21st century climate change. Time series are shown from 1901 to 2099 under historic and future climate forcing (RCP 2.6, 6.0, 8.5). The thick lines demonstrate the mean across all studied lakes, the shaded regions represent the standard deviation, and the dashed lines represent the range across the lake-climate model ensembles. Panel **b** shows the total duration of simulated lake heatwaves per year by the end of the 21st century (averaged for all years from 2070 to 2099) under RCP 8.5. **(c)** The latitudinal averages (5° bins) of the lake heatwave duration under historical (1970-1999) and future (2070-2099) forcing. **(d-e)** The relationship between heatwave duration and average lake depth (log10), under historic (black) and future (red; RCP 8.5) climate change for lakes situated in the Northern Cool thermal region (shown as black regions in panel **b**; relationships for other thermal regions are shown in Extended Data Fig. 7-8). **(f)** The number of studied lakes worldwide that will experience a permanent lake heatwave state under RCP 2.6, 6.0, and 8.5. All results are based on the average simulations from the lake model driven by the four climate models.

Author contributions: RIW conceived the work, developed the concept of the study, performed the numerical modelling, completed the data analysis, and wrote the manuscript with input from SCM. All authors edited and revised the manuscript. TS performed the 3-hour FLake simulations and led the light attenuation analysis, as used in the global simulations. EJ performed the statistical analyses. MG and DP assisted with the large-scale computations and data handling.

Methods

Study sites - The lakes investigated in this study (n = 702) were selected based on the availability of satellite-derived lake surface temperature observations worldwide, in addition to the availability of mean depth information for lakes globally. The studied lakes vary in their geographic and morphological characteristics (Extended Data Fig. 2a-c).

Observed lake surface temperatures – In this study, we utilize lake surface temperatures generated by ref. 44 using data from the ATSR (Along Track Scanning Radiometer) series of sensors including ATSR-2 (1995-2003) and the Advance ATSR (AATSR) (2002-2005). Lake surface temperature observations were retrieved following the methods of ref. 45 on image pixels filled with water according to both the inland water dataset of ref. 46 and a reflectance-based water detection scheme. The data (v4.0) are available at daily resolution from https://catalogue.ceda.ac.uk/uuid/76a29c5b55204b66a40308fc2ba9cdb3. Lake-mean surface temperature time-series were obtained by averaging across the surface area of each lake. Lake-mean surface temperatures were used in this study in order to average across the intra-lake heterogeneity of surface water temperature responses to climate change[47] and to correspond to the lake-mean model used (see below). In the case of satellite-derived lake surface temperatures, the obtained value is sensitive to the skin temperature of the water, which is the temperature of a layer <0.1 mm thick from which thermal radiation is emitted by the lake. Thus, the satellite data is an estimate of this skin temperature which may differ from the temperature as measured by a thermometer a few centimeters below the water-air interface. Typically, the temperature difference between skin and sub-skin lake surface temperature is of order 0.2 °C. However, the difference depends on meteorological conditions (e.g., wind speed). Although the skin effect is variable, the satellite lake surface temperature is nonetheless tightly coupled to the lake surface temperature as measured conventionally. Satellite lake surface temperatures have been used to quantify worldwide aspects of lake thermal dynamics such as seasonal cycles[8], onset of summer stratification[47], lake mixing dynamics[7], and over-turning behavior[48]. As an additional validation, we also compared the simulated lake surface temperatures with those available from the European Space Agency's (ESA) CCI Lakes project (http://cci.esa.int/lakes) which provides daily observations of lake surface temperature at a grid resolution of 1/120° for 250 lakes worldwide, following the procedure used by ref. 34.

Simulated lake surface temperatures - The surface temperature (and ice cover) of lakes (notably the temperature of the upper well-mixed layer, the depth of which is defined according to the maximum vertical density difference) globally were simulated in this study via the Freshwater Lake model, FLake[49,50], which has been tested extensively in past studies. FLake is used widely both for research and as a component in numerical weather prediction[51-54]. FLake is particularly suitable for global lake modelling as it is based on the concept of self-similarity of the temperature-depth curve, which results in low computational cost. Moreover, it contains few lake-specific model parameters and does not require extensive calibration. The model has been shown to provide accurate representation of the evolving temperature cycle of lakes worldwide. The performance of FLake has been tested across a spectrum of lake contexts and validated simulations of lake thermal responses to climate change as well as extreme

479 atmospheric events[7,55]. It has also been compared with other more sophisticated, but
480 computationally expensive, models and these studies demonstrate that FLake can consistently
481 simulate accurately lake surface water temperatures with comparable skill and good agreement
482 with observations[56]. In brief, FLake is based on a two-layer parametric representation of the
483 time-evolving temperature profile and on the integral budgets of heat and kinetic energy. The
484 integrated approach implemented in FLake allows a realistic representation of the major
485 physics behind turbulent and diffusive heat exchange in lakes; it includes an ice module, and a
486 module to describe the vertical temperature structure of the thermally active layer of bottom
487 sediments, as well as its interaction with the water column above. FLake was developed to
488 simulate the thermal dynamics of lakes shallower than approximately 60m (see for example
489 ref. 53), and thus when selecting the studied lakes this depth limitation was considered.
490 Therefore, the deepest lakes included in this study have an average depth of ~60m. In this study
491 we also set a lower limit of 2m for the selected lakes, as FLake has been shown previously to
492 produce a considerable bias in surface temperature during summer in very shallow systems.
493 FLake was also developed to simulate the thermal dynamics of freshwater lakes. Thus, hyper-
494 saline lakes were not included in this study. However, previous studies have demonstrated the
495 ability of the model to simulate accurately the surface conditions of lakes along salinity
496 gradients[8,53,57-59] and FLake is even used in numerical weather prediction models to simulate
497 shallow coastal waters (e.g., ECMWF's Integrated Forecasting System)[53]. Thus, while we
498 caution against the use of FLake for simulating the thermal dynamics of brackish lakes,
499 particularly without modifying the model source code[60], we include some brackish lakes here
500 as validation data was available, and the model performed well when compared to observations
501 of both surface temperature and the lake heatwave metrics investigated.

503 The meteorological variables required to drive FLake are air temperature at 2 m, wind speed
504 at 10 m, surface solar and thermal radiation, atmospheric pressure, and specific humidity.
505 These atmospheric drivers were downloaded for this study from four bias-corrected (to the
506 EWEMBI reference dataset[61,62]) climate model projections from the Inter-Sectoral Impact
507 Model Intercomparison Project phase 2b (ISIMIP2b), HadGEM2-ES, GFDL-ESM2M, IPSL-
508 CM5A-LR, and MIROC5, for the historic and future periods under three climate change
509 scenarios: RCP 2.6, RCP 6.0, and RCP 8.5. These data were available at a daily time step and
510 at a grid resolution of 0.5°x0.5°. Time series data were extracted for the grid point situated
511 closest to the centre of each studied lake, defined as the maximum distance to land[46]. As the
512 bias-corrected climate projections were available at a daily timestep, the lake temperature
513 simulations from FLake in this study were also generated at a daily resolution. However, an
514 important consideration in lake modelling is that the timestep chosen to run a model can
515 influence the accuracy of the simulations due to, for example, the importance of diurnal forcing
516 and the description of within-lake turbulence. These features can only be resolved fully when
517 using high (e.g., sub-hourly) temporal resolution data, and some studies have shown improved
518 lake model performance when using sub-daily (compared to daily) data over short time
519 periods[63]. However, for long-term global lake-climate projections, the temporal resolution of
520 the input data (hourly vs daily) has been shown to have relatively minimal influence, at least
521 in one case study site[64]. In this study, we investigate the influence of model timestep in
522 simulating lake heatwaves by comparing, for three case study sites (Extended Data Fig. 10),

523   modelled lake heatwave intensity and duration by the end of the 21st century. Specifically, we
524   compare the heatwave metrics from the original daily FLake simulations to those driven by the
525   climate model projections which we temporally disaggregated, following the methods of ref.
526   65, to a 3-hour timestep. The results demonstrate only minor differences between the model
527   simulations across the case study sites thus suggesting, for this study, that daily data is
528   sufficient and can simulate lake heatwave responses to climate change.

530   Lake specific parameters must be set to simulate individual lakes optimally in FLake. These
531   parameters comprise fetch (m), which we fix in this study to the square root of lake surface
532   area, lake depth, lake ice albedo and the light attenuation coefficient (K_d, m^{-1}). The prognostic
533   variables needed to initialize FLake simulations include (i) mixed layer temperature, (ii) mixed
534   layer depth, (iii) bottom temperature, (iv) temperature at the ice (if present) upper surface and
535   (v) ice thickness (if present). In order to initialise the model runs from physically reasonable
536   fields, we initialise runs from a perpetual-year solution for the lake state. To find this solution
537   for the initialisation state, the model parameters are set as follows: mean depth was extracted
538   from the Hydrolakes database[21], and lake ice albedo was set to 0.6 (ref. 50). The Hydrolakes
539   data (specifically those for lake depth) have been extensively validated by ref. 21, including
540   detailed validations using ~12,000 records of observations. The atmospheric forcing data to
541   derive the initialization conditions are from the ERA5 reanalysis product[66], available at a
542   latitude and longitude resolution of 0.25°. To optimize FLake simulations for each lake, and to
543   approximate K_d, we use the model-tuning algorithm of ref. 67. Prior to running the model-
544   tuning algorithm we first approximate K_d for each study site according to $K_d = 5.681 \times \text{depth}^{-0.795}$
545   ($R^2_{adj} = 0.51$, df=1256). This relationship was derived from Secchi depth (Z_{secchi})
546   measurements in 1183 lakes in the US-EPA's National Lakes Assessment[68] and 75 lakes from
547   the World Lake Database. Secchi depth was converted to extinction coefficients with the
548   standard relationship of $K_d = 1.7 / Z_{secchi}$ (ref. 69). These initial K_d values were then used as an
549   initialization value within the tuning algorithm. The optimization routine estimates K_d to
550   closely reproduce the observed seasonal and inter-annual surface temperature dynamics (1995
551   to 1999), specifically by minimizing the mean square differences between the model and
552   satellite-derived surface water temperatures described above, in simulations initialized from
553   the perpetual-year solution. The lake-specific parameters for the model are thus set without
554   reference to any of the climate model forcing fields used for the historical-period simulation
555   and future projections. A 51-year spin-up period (1850-1900) for each lake was also used in
556   this study. As there is no water balance equation in FLake, lake depth and surface area are
557   constant in time. While this is common in global lake modelling[24,53], the dynamic
558   representation of lakes within the Earth system is a priority for future research.

560   In this study, the 'snow block' of FLake was not used, thus the simulated ice cover dynamics
561   of some lakes might be over or underestimated, due to the lack of snow on ice. Specifically,
562   greater snow cover can delay or hasten ice breakup, respectively, through higher albedo
563   (positive feedback) or greater insulation (negative or positive feedback, depending on the
564   season). However, the model has been used previously to estimate successfully the ice cover
565   dynamics of lakes globally, and been extensively validated with data from, for example, the

566   National Snow and Ice Data Center and from the Interactive Multisensor Snow and Ice
567   Mapping System[53].

568

569   *Lake heatwave definitions* - Lake heatwave intensity and duration were calculated from daily
570   lake surface temperature time series following the methods described by ref. 19 for defining
571   heatwaves in marine environments. Specifically, the R package 'heatwaveR'[70] was used for
572   these calculations. Lake heatwaves were identified as when daily lake surface temperatures,
573   specifically the average temperature of the upper mixed layer (which has a more direct
574   influence on the ecosystem compared to, for example, the upper 1m), were above a local and
575   seasonally varying 90th percentile threshold (Extended Data Fig. 1). These anomalies were
576   calculated for each calendar day using the daily temperatures within an 11-day window
577   centered on the date across all years within the climatological period (1970-1999) and
578   smoothed by applying a 31-day moving average[19]. An 11-day window and a 31-day moving
579   average were selected to ensure a sufficient sample size for percentile estimation as well as a
580   smooth climatological mean[13,19]. In addition, the 90th percentile threshold had to be exceeded
581   for at least five consecutive days to be considered a lake heatwave event, and two events with
582   a break of less than three days were considered as a single event. Ideally, this definition should
583   be relevant to ecological processes and thresholds (e.g., based on evidence of impact on specific
584   species). However, for this global-scale analysis, we follow the recommendations of ref. 19 of
585   a five-day exceedance condition. Future studies should investigate thermal extreme indicators
586   based on, for example, thermal tolerance limits of individual species. A statistical percentile-
587   based threshold is useful as lake ecosystems are, to some degree, adapted to their own climate;
588   thus, a statistical extreme is likely also to be an extreme in ecosystem functioning. In addition,
589   the use of a percentile-based and seasonally varying threshold allows quantification of lake
590   heatwaves across locations that differ in variability and mean conditions (Extended Data Fig.
591   2d-g) and to identify anomalously warm events at any time of the year, rather than events only
592   during the warmest month. An absolute threshold would only be relevant in terms of impacts
593   in some regions and seasons but not others (e.g., due to species acclimation).

594

595   In this study we investigated lake heatwave metrics related to their duration and intensity. We
596   also use an intensity-based lake heatwave category to define the strength of lake heatwaves.
597   Each lake heatwave event was classified as being Moderate, Strong, Severe, or Extreme. These
598   categories are defined by the maximum intensity of the event scaled by the threshold
599   temperature anomaly exceeding the climatological mean[20]. For example, Moderate events are
600   those with lake temperature anomalies that exceed the identified threshold but are less than 2
601   times that threshold value; Strong, Severe, and Extreme events are then identified according to
602   anomalies that exceed 2, 3, and 4 times the threshold, respectively (Extended Data Fig. 1). The
603   season(s) during which lake heatwaves occur are also investigated in this study. June is used
604   as the start of Boreal summer and December as the start of Austral summer. When calculating
605   the time series of annual average intensity and average duration of lake heatwave events, we
606   separated heatwaves into two events if they lasted over December 31. Thus, the maximum
607   duration of a lake heatwave in this study is 366 days.

608

609   In this study, following ref. 15 we also calculate lake heatwaves based on detrended lake
610   surface temperature anomalies (Extended Data Fig. 9d-f) in order to illustrate the influence on
611   lake heatwaves of mean lake temperature change vs changes in variance, both of which are
612   considered important for the future occurrence of heatwaves events. However, we do stress
613   that by detrending the lake surface temperature anomalies, one is no longer explicitly analyzing
614   lake heatwaves, at least according to the definitions commonly used for marine heatwaves[12-14,
615   16-17, 19]. To compare heatwaves across realms (e.g., ocean vs lakes), a consistent methodology
616   (to the extent possible) should be adopted.

617

618   *Validation of simulated lake heatwaves* – Due to the dearth of long term in situ high resolution
619   data available for lakes[71], the simulated intensity and duration of lake heatwaves could not be
620   validated with in-situ observations. However, the ability of the model to simulate lake
621   heatwave events can be evaluated by comparing the simulations with those identified from the
622   satellite observations. An issue when using satellite observations to identify lake heatwaves is
623   that these data often contain gaps due to, for example, the presence of clouds which will
624   undoubtedly influence the identification of lake heatwaves. Some lakes do contain sufficient
625   data to identify lake heatwaves at certain times of the year (e.g., Jul-Sep), and thus to compare
626   with the simulated heatwaves in some years. Specifically, in lakes with less than 3 consecutive
627   days of missing data in a given time period, the temporal threshold used for determining if a
628   heatwave is considered a single event or multiple shorter events, we can estimate lake
629   heatwaves from the satellite data. In our dataset, 190 globally distributed lakes have sufficient
630   data for such comparisons (Extended Data Fig. 3). For these lakes, we compare the observed
631   and simulated average intensity and duration of lake heatwaves during Jul-Sep (or Jan-Mar;
632   see below), the time of year in which most cloud-free satellite retrievals are available. By
633   following the definitions of refs 1, 72, we selected temperatures for a 3-month period. For lakes
634   situated in the Northern Hemisphere we used the period of 1 July—30 September (JAS);
635   whereas, in the Southern Hemisphere, we used 1 January—31 March (JFM). Exceptions were
636   latitudes less than 23.5°, for which the JAS metric was used south of the equator and the JFM
637   metric was used north of the equator. This was done in order to avoid the cloudy wet season in
638   the tropics and instead collect data during the dry season, which allows for an increased number
639   of cloud-free satellite observations[72]. We selected data from these months to define lake
640   heatwaves. For this model validation, the climatological mean was calculated over the satellite
641   period (1995-2005). To compare with the simulated lake heatwaves, we calculated the
642   heatwave metrics from the average lake-climate model ensembles from 2000 to 2005 (i.e., the
643   years which were not used in the optimization of the model parameters). Good agreement is
644   obtained between simulations and observations of lake heatwaves (Extended Data Fig. 3).

645

646   *Statistical methods* - To investigate the influence of lake depth on the average intensity and
647   duration of lake heatwaves we first separated the studied lakes into the thermal regions in which
648   they are located, following the definitions of ref. 8. The thermal regions had been produced
649   objectively using b-spline modelling and K-means clustering of satellite-derived seasonal lake
650   surface water temperature data, for lakes globally over a period of 16 years. Within each lake
651   thermal region, relationships between the response variables (heatwave duration and heatwave
652   intensity) and the independent variable (mean depth; log_{10} transformed) were assessed using

653 generalized additive modelling (GAM) with a cubic regression spline using cross validation to
654 optimize k, the number of knots in R[73-75]. The sequence of the analysis was guided by the
655 protocol of ref. 76. The residuals from each GAM were first checked for any breach of
656 assumptions. A variance structure was added to the models to account for unequal variance in
657 residuals where appropriate. Where the estimated degrees of freedom (edf) were = 1, the GAM
658 was compared to a linear model and the optimum model was selected based on the Akaike
659 information criterion (AIC). The p value presented is defined as the probability of getting a
660 value of the test statistic that is at least as favorable to the alternative hypothesis as one actually
661 observed if the null hypothesis is true[73]. For linear regression models we used a threshold for
662 significance of $p < 0.05$. For generalized additive models we used a more conservative
663 threshold of $p < 0.001$ (ref. 73, 76).

664

665 *In situ observations of lake heatwaves* – In this study, we also calculate the intensity and
666 duration of lake heatwaves in lakes where long-term *in situ* surface water temperature data are
667 available. Specifically, by analyzing published daily data from two European lakes[77], Lake
668 Vättern, Sweden (58.321 °N, 14.467 °E) and Wörthersee, Austria (46.628° N, 14.127° E), we
669 investigate lake heatwave variability from 1960 to 2017. Although lake surface temperature
670 measurements from these lakes are not directly comparable to those simulated in this study,
671 given that they were either measured at a lake level gauging station (Wörthersee) or from a
672 drinking water intake point (Vättern), they are useful to explore historical changes in lake
673 heatwaves. Following the same definitions as above for defining simulated lake heatwaves, we
674 demonstrate a considerable increase in heatwave duration in both lakes from 1960 to 2017. An
675 increase in lake heatwave intensity is also calculated for Lake Vättern since 1960, but not in
676 Wörthersee (Extended Data Fig. 1).

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Extended Data

Extended Data Fig. 1 | Definitions and examples of lake heatwaves. Shown are examples of **(a)** the method used to define a lake heatwave event (light orange) from lake surface temperatures (black) and **(b)** the categorization scheme used for defining the severity of lake heatwaves. Lake heatwave categories are defined according to multiples of the 90th percentile differences (1, 2, 3, 4 x threshold) relative to a 30-year (1970-1999) climatological mean (blue) and are described as Moderate (light orange), Strong (orange), Severe (red), or Extreme (dark red). Also shown are examples of historical lake heatwave **(c, d)** intensity and **(e, f)** duration in **(c, e)** Lake Vättern (Sweden) and **(d, f)** Wörthersee (Austria), where observational data are available from 1960 to 2017.

Extended Data Fig. 2 | Specific characteristics of the studied lakes. Shown are histograms of **(a)** surface area (log10, km^2), **(b)** average depth (log10, m), and **(c)** elevation (m) of the studied lakes as well as **(d-g)** the lake thermal regions in which they reside. We also show, for illustration, **(d)** the global distribution of lake thermal regions, **(e)** their climatological seasonal cycle, **(f)** a map of studied lakes categorized by thermal region, and **(g)** the number of studied lakes (points) as well as the number of lakes globally (information from the Hydrolakes database) situated within each lake thermal region (line).

Extended Data Fig. 3 | Validation of simulated lake temperatures and heatwave characteristics. Comparison of modelled and satellite-derived **(a-b)** lake surface water temperatures for the studied lakes in which satellite data were available; and lake heatwave **(c-d)** duration and **(e-f)** intensity for lakes with sufficient data to identify lake heatwaves from 2000 to 2005 (see Methods). Simulated results are based on the average simulations from the lake model driven by the four climate models.

Extended Data Fig. 4 | Relationship between average lake depth and average heatwave intensity. Shown for each lake thermal region, is the relationship between lake depth and the average intensity of lake heatwave events during the historic period (averaged over all years from 1970 to 1999) and by the end of the 21st century (averaged over all years from 2070 to 2099) under RCP 2.6, 6.0, 8.5. The relationship between lake depth and the heatwave metrics (square = not significant; circle = significant) were calculated with a generalized additive model (see Methods).

Extended Data Fig. 5 | Relationship between average lake depth and average heatwave duration from 1970 to 1999. Shown for each lake thermal region, is the relationship between lake depth and the average duration of lake heatwave events during the historic period (averaged over all years from 1970 to 1999). The relationship between lake depth and the heatwave metrics (square = not significant; circle = significant) were calculated with a generalized additive model (see Methods).

Extended Data Fig. 6 | Relationship between average lake depth and average heatwave duration from 2070 to 2099. Shown for each lake thermal region, is the relationship between lake depth and the average duration of lake heatwave events by the end of the 21st century (averaged over all years from 2070 to 2099) under RCP 2.6, 6.0, 8.5. The relationship between lake depth and the heatwave metrics (square = not significant; circle = significant) were calculated with a generalized additive model (see Methods).
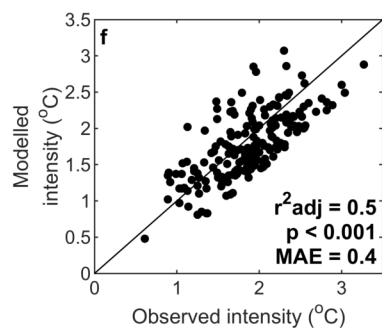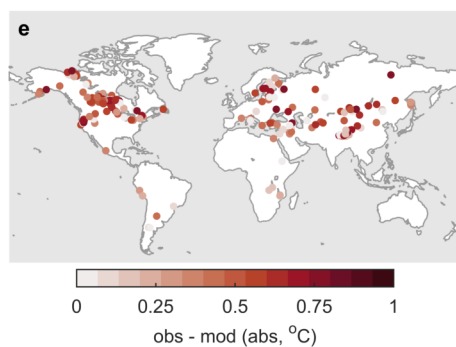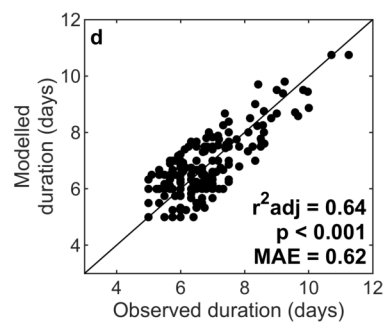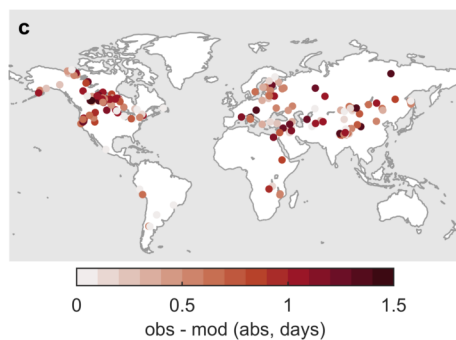
Extended Data Fig. 7 | Relationship between average lake depth and total heatwave duration from 1970 to 1999. Shown for each lake thermal region, is the relationship between lake depth and the total duration of lake heatwave events per year during the historic period (averaged over all years from 1970 to 1999). The relationship between lake depth and the heatwave metrics (square = not significant; circle = significant) were calculated with a generalized additive model (see Methods).

Extended Data Fig. 8 | Relationship between average lake depth and total heatwave duration from 2070 to 2099. Shown for each lake thermal region, is the relationship between lake depth and the total duration of lake heatwave events per year by the end of the 21st century (averaged over all years from 2070 to 2099) under RCP 2.6, 6.0, 8.5. The relationship between lake depth and the heatwave metrics (square = not significant; circle = significant) were calculated with a generalized additive model (see Methods).

Extended Data Fig. 9 | Lake thermal responses to climate change. Here we show the percentage of studied lakes which are projected to **(a)** experience annual ice cover, and **(b)** experience a permanent heatwave state during the 21st century (RCP 8.5). In panel **b**, percentages are calculated relative to the number of studied lakes that are projected to not experience annual ice cover by 2070-2099. Shown in panel **c** is a temporally varying (1-year shifting window) 30-year climatological mean, with temperatures plotted as anomalies relative to the historical climatological mean (1970 to 1999). We also demonstrate the future projections of lake heatwave **(d)** annually average intensity, **(e)** annually average duration, and **(f)** total duration during the 21st century (RCP 8.5) calculated after linearly detrending the lake surface temperature anomalies. All results are based on the average simulations from the lake model driven by the four climate models, the shaded regions represent the standard deviation, and the dashed lines represent the range across the lake-climate model ensembles.

Extended Data Fig. 10 | Comparison of simulated lake heatwaves from two models of different temporal resolution. Here we compare the simulated lake heatwave **(a)** intensity, and **(b)** duration by the end of the 21st century (averaged over all years from 2070 to 2099) from the FLake model driven at a temporal resolution of 3 and 24 hours for three case study lakes. All results are based on the average simulations from the FLake model driven by the four climate models.
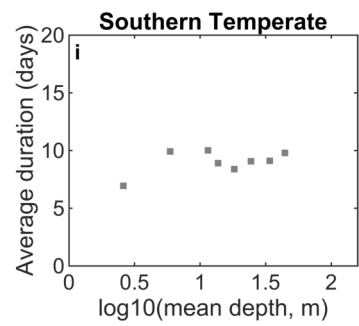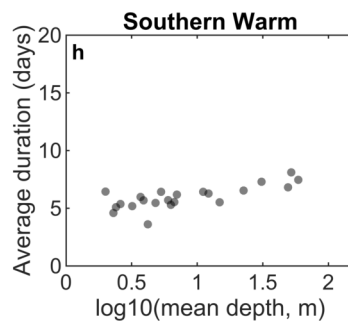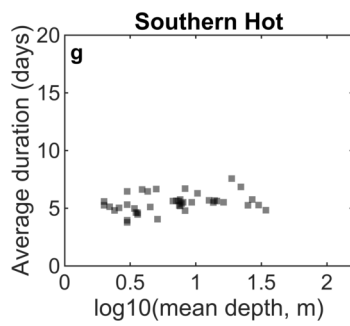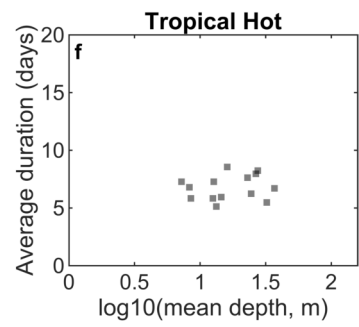
a

b

c

d

e

f
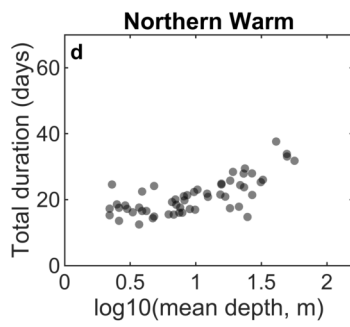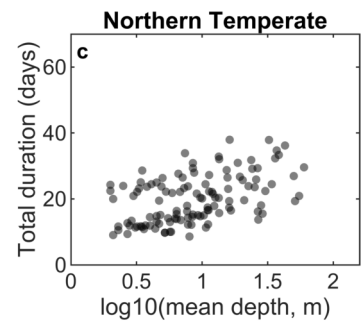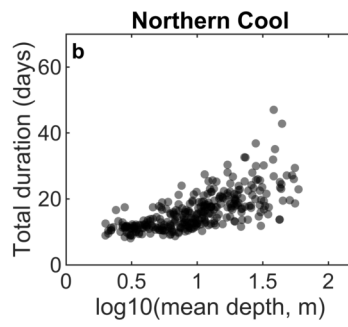
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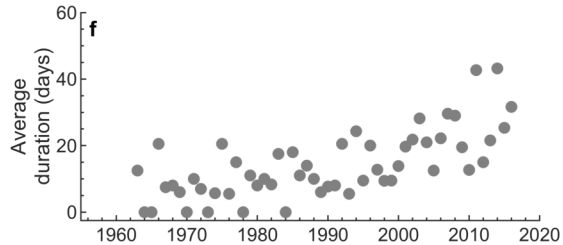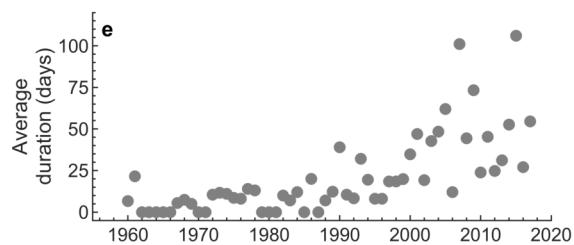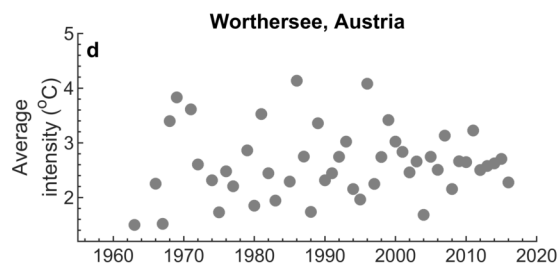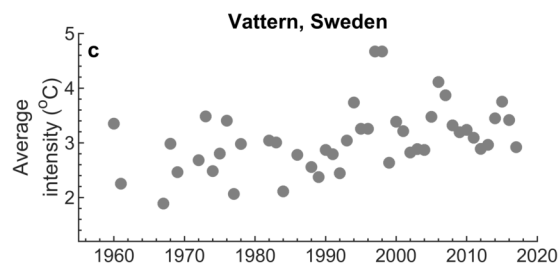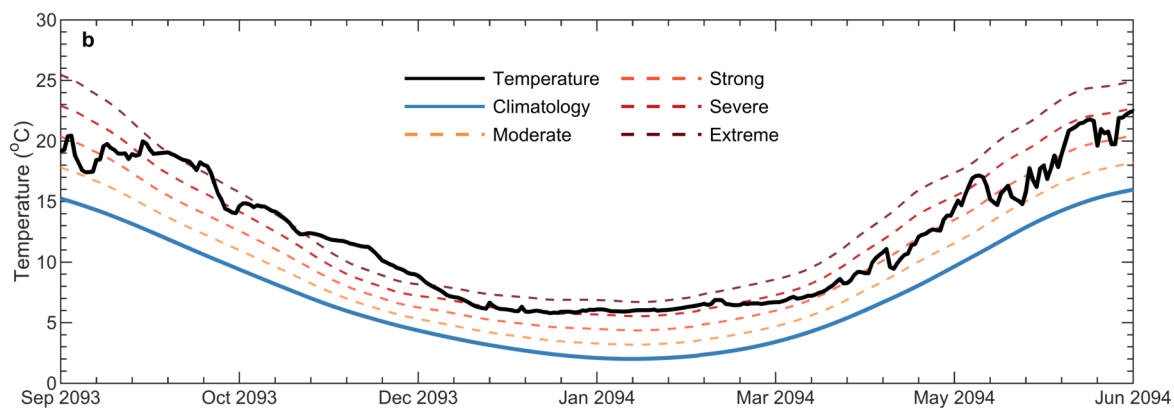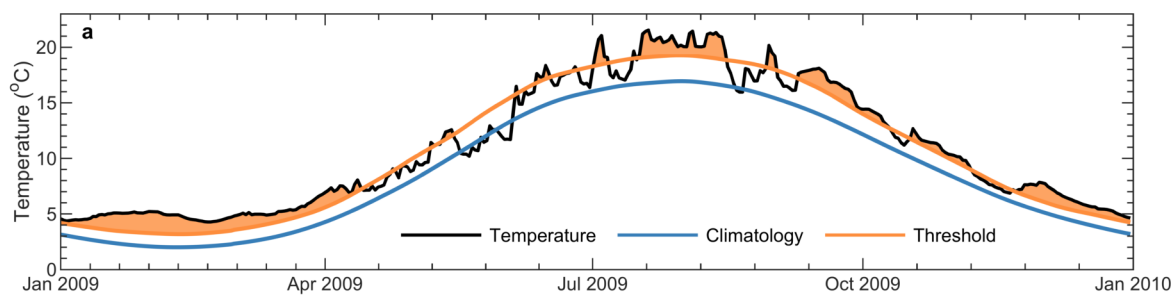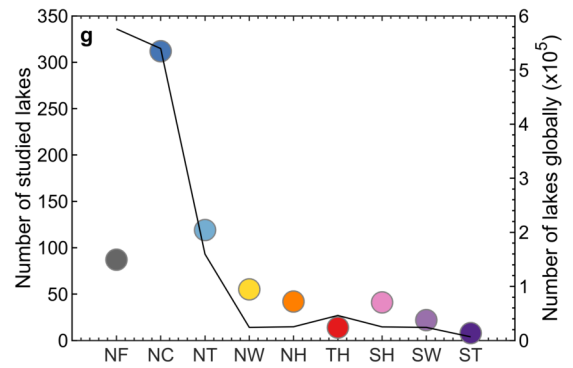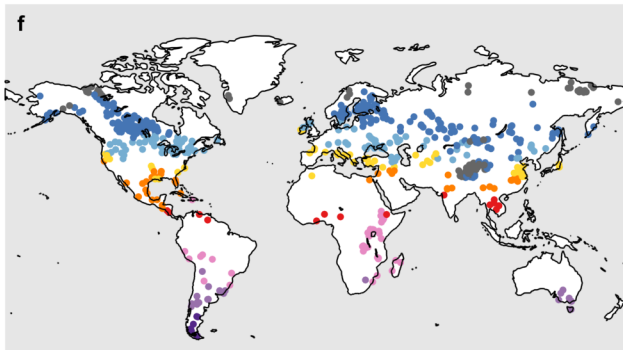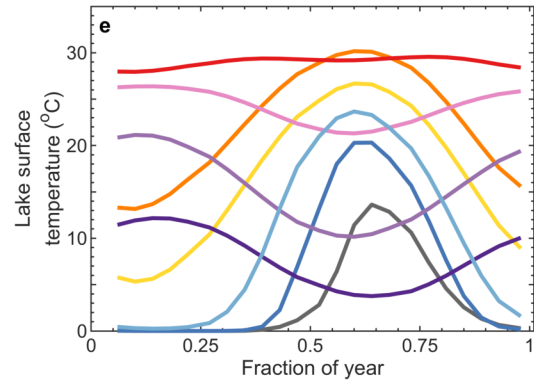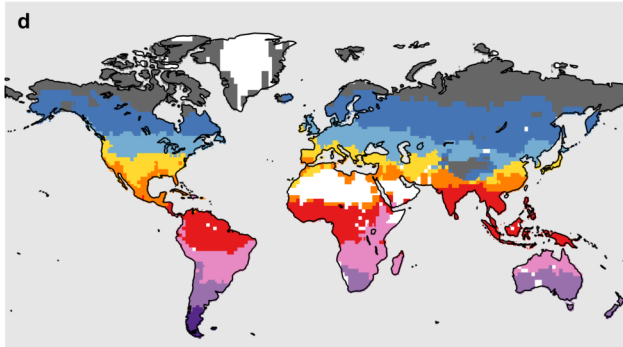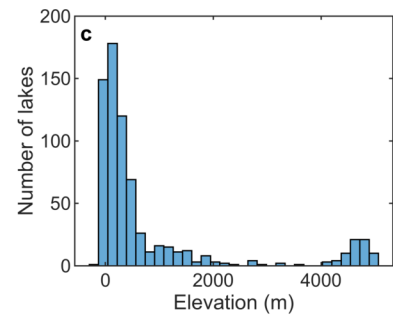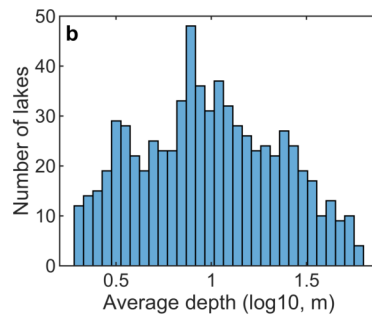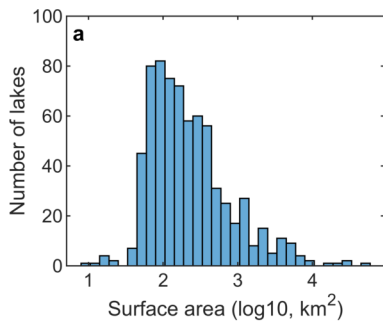
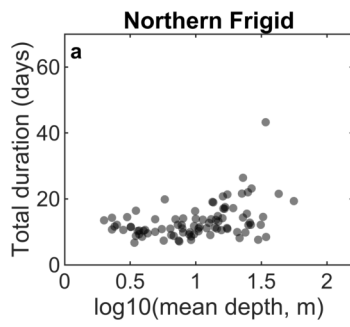NF - Northern Frigid   NW - Northern Warm   SH - Southern Hot

NC - Northern Cool   NH - Northern Hot   SW - Southern Warm

NT - Northern Temperate   TH - Tropical Hot   ST - Southern Temperate

a

b

r²adj = 0.97
p < 0.001
MAE = 0.58

obs - mod (abs, °C)

c

d

r²adj = 0.64
p < 0.001
MAE = 0.62

obs - mod (abs, days)

e

f

r²adj = 0.5
p < 0.001
MAE = 0.4

obs - mod (abs, °C)

Northern Frigid

Northern Cool

Northern Temperate

Northern Warm

Northern Hot

Tropical Hot

Southern Hot

Southern Warm

Southern Temperate

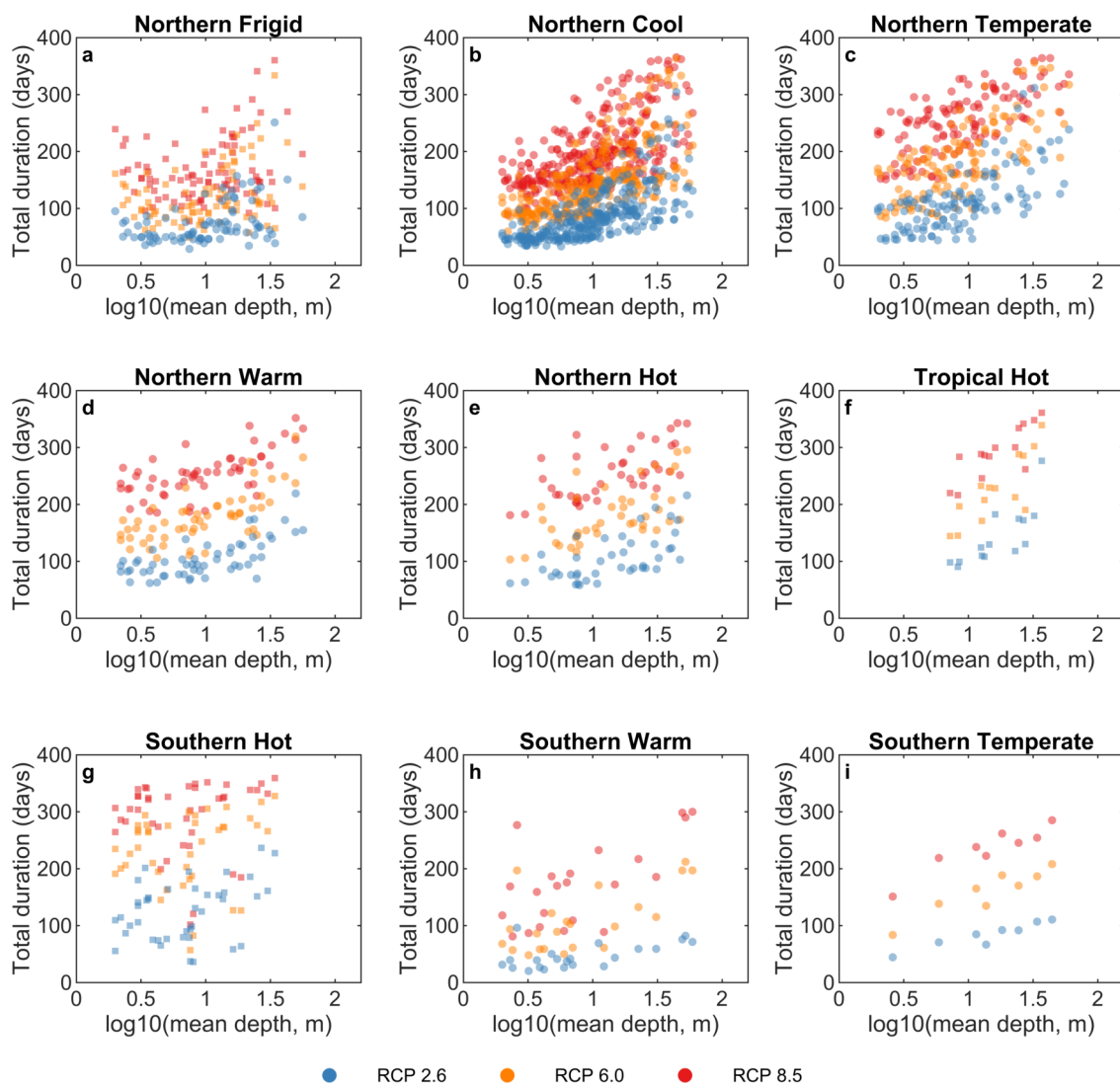Historical   RCP 2.6   RCP 6.0   RCP 8.5

a Studied lakes which freeze annually

b Studied lakes experiencing a permanent heatwave state

c Climatological mean lake surface temperature under climate change

d Average intensity of detrended lake heatwaves

e Average duration of detrended lake heatwaves

f Total duration of detrended lake heatwaves