

Impact of the 2018 European heatwave on lake surface water temperature

Article

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1 **Title**

2 Impact of the 2018 European heatwave on lake surface water temperature

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11

12 **Abstract**

13 In 2018 Europe experienced the warmest May-October (Northern Hemisphere Warm
14 Season) since air temperature records began. In this study, we ran model simulations
15 for 46,557 lakes across Europe to investigate the influence of this heatwave on surface
16 water temperature. We validated the model with satellite-derived lake surface
17 temperatures for 115 lakes from 1995 to 2018. Using the validated model, we
18 demonstrated that, during May-Oct 2018, mean and maximum lake surface
19 temperatures were 1.5°C and 2.4°C warmer than the base-period average (1981-
20 2010). A lake model experiment demonstrated that, on average, the increase in air
21 temperature was the dominant driver of surface water temperature change. However,
22 in some lake regions, other meteorological forcing had a greater influence. Notably,
23 higher than average solar radiation and lower than average wind speed exacerbated
24 the influence of the heatwave on lake surface temperature in many regions,
25 particularly Fennoscandia and Western Europe. To place our results in the context of
26 projected 21st century climate change, we then ran the lake model with input data
27 from state-of-the-art climate model projections under three emissions scenarios.
28 Under the scenario with higher emissions (Representative Concentration Pathway
29 8.5), we demonstrated that by the end of the 21st century, the lake surface
30 temperatures that occurred during the heatwave of 2018 will become increasingly
31 common across many lake regions in Europe.

32

33 **Keywords**

34 Climate change; Limnology; Modelling; Climate projections; Extreme; FLake

35 **1. Introduction**

36 Directional climate change is increasingly evident from a wide variety of observations
37 (Hulme 2016; Roe et al. 2017; Rogora et al. 2018). Increasing air temperature is one
38 of the clearest consequences of global change with robust evidence for climatic
39 warming over the last century (Hansen et al. 2010). Parallel to further projected
40 increases in global average air temperature, climate models indicate an increase in the
41 frequency and severity of extreme heat (IPCC, 2014; Meehl and Tebaldi 2004;
42 Christidis et al. 2015). There is evidence that this may already be taking place, with
43 air temperature extremes becoming more frequent at both regional and global scales
44 in recent decades (Beniston 2004; Stott et al. 2004; Rahmstorf and Coumou 2011;
45 Russo et al. 2015).

46 Extreme heat can affect lake ecosystems via its influence on the lake surface
47 energy budget and, in turn, surface water temperature (Edinger et al. 1968; Woolway
48 et al. 2015). Temperature is a fundamental lake property that can influence many lake
49 processes including mixing patterns, phenology, and the structure of biotic
50 communities (Adrian et al. 2009; Thackeray et al. 2016; Woolway and Merchant
51 2019). Previous studies have demonstrated that heatwaves can affect lake thermal and
52 oxygen dynamics (Jankowski et al. 2006), lead to changes in phytoplankton
53 communities and the occurrence of cyanobacteria blooms (Jöhnk et al. 2008; Rasconi
54 et al. 2017), and affect greenhouse gas emissions from lakes (Bartosiewicz et al. 2016;
55 Audet et al. 2017). Understanding the thermal response of lakes to extreme heat is
56 therefore critical for predicting biotic change and for anticipating the repercussions of
57 climatic variations on lakes and their associated ecosystems (Woodward et al. 2010;
58 Piccolroaz et al., 2018).

59 During spring/summer of 2018 many parts of Europe experienced record-
60 breaking temperatures (Toreti et al. 2019) which were caused, in part, by an
61 anomalously stationary north-south meander of the jet stream, a phenomenon often
62 referred-to as atmospheric blocking (Nakamura and Huang 2018). As the jet stream
63 stalled over Europe, it trapped many regions of high pressure with lower than average
64 near-surface wind speed and cloud cover (thus higher solar radiation), and higher than
65 average air temperature. These atmospheric variables have a considerable influence
66 on lake surface temperature. Recent studies have shown an amplified response of lake
67 surface water temperature to an increase in air temperature (O'Reilly et al. 2015;
68 Piccolroaz et al. 2015; Zhong et al. 2016; Woolway and Merchant 2017), a decrease
69 in near-surface wind speed (Woolway et al. 2019), and an increase in solar radiation
70 (Schmid and Köster 2016).

71 In this contribution, we investigate the influence of the 2018 European
72 heatwave on lake surface temperature across the continent. We hypothesised that the
73 increase in air temperature at this time would have resulted in a continental-scale
74 increase in lake surface temperature. We also hypothesised that lake surface
75 temperatures during the 2018 European heatwave were higher than expected as a
76 result of the decrease in near-surface wind speed and the increase in solar radiation,
77 potentially leading to optimum atmospheric conditions for extraordinary lake surface
78 warming in some regions. To place this event in the context of projected future

79 changes, a numerical lake model driven by climate projections was used to compare
80 lake surface temperatures during the 2018 heatwave to those predicted by the end of
81 the 21st century.

82

83 **2. Methods**

84

85 *2.1. Study sites* - The lakes investigated in this study were selected based on
86 the availability of mean depth information for lakes in Europe (Messenger et al. 2016).
87 Of these lakes ($n = 100,481$), not all were suitable for inclusion in this investigation.
88 Lakes were only included if their approximate residence time was greater than six
89 months ($n = 55,083$). This criterion was selected to ensure that the entire lake volume
90 was not replaced during the study period (i.e., May-Oct 2018) and that any climatic
91 signal would be present in the lake surface water temperature time series. In addition,
92 lakes were only included if their mean depth was less than 60m, which follows the
93 recommendations of Balsamo et al. (2012) when using the selected lake temperature
94 model (see below) across a wide-spectrum of lakes. In total 46,557 lakes were
95 included in this study. The lakes that were investigated range in altitude between 35
96 and 2,822 m above sea level, in surface area between 0.1 and 9,961 km², and in mean
97 depth between 2.1 and 59.6 m.

98

99 *2.2. Lake temperature model* – To simulate the surface water temperature of
100 each studied lake, we used the one-dimensional thermodynamic lake model FLake
101 (Mironov 2008; Mironov et al. 2010). FLake has been tested extensively in previous
102 studies, including detailed validations across a spectrum of lake contexts (Woolway
103 and Merchant 2019). The meteorological variables required to drive FLake are air
104 temperature at 2 m, wind speed at 10 m, surface solar and thermal radiation, and
105 specific humidity. The forcing data used by FLake in the current study were from
106 ERA-Interim (Dee et al. 2011), available at a latitude-longitude resolution of 0.75°
107 from 1979 to 2018. Time series data were extracted for the grid point situated closest
108 to the centre of each lake, defined as the point on the lake most distant from land
109 (Carrea et al. 2015).

110 In order to initialize FLake from physically reasonable fields, we initialized
111 runs from a perpetual-year solution for the lake state. To find this solution for the
112 initialization state, the model parameters are set as follows: mean depth was extracted
113 from the Hydrolakes database (Messenger et al. 2016); the light attenuation coefficient
114 (K_d) was set to 1 m⁻¹ (Woolway et al. 2019); lake ice albedo was set to 0.6 (Mironov
115 2008), and fetch was estimated as the square root of lake surface area (Messenger et al.
116 2016). The perpetual-year solution is obtained by repeating the forcing from a
117 representative year (in this case data from 1979) and running FLake until the annual
118 cycle in modelled lake state stabilized. As we initialize FLake using a perpetual year
119 solution, we ignore the first year of simulations in this study. Therefore, in this study
120 we investigate lake surface temperatures from the period 1980 to 2018.

121

122 2.3. *Lake surface temperature observations* – Modelled lake surface water
123 temperatures were validated in this study with satellite-derived lake surface water
124 temperatures (1995 to 2016) from Carrea and Merchant (2019), and extended until
125 2018 with data from the Copernicus Climate Change Service. These observations
126 were generated using data from the ATSR (Along Track Scanning Radiometer) series
127 including ATSR-2 (1995-2003) and the Advance ATSR (AATSR) (2002-2012), from
128 MetOp-A AVHRR (Advanced Very High Resolution Radiometer) (2007-2018) and
129 from MetOp-B AVHRR (2017-2018). Lake surface temperature observations were
130 retrieved following the methods of MacCallum and Merchant (2012) on image pixels
131 filled with water according to both the inland water dataset of Carrea et al. (2015) and
132 a reflectance-based water detection scheme. Lake-mean surface temperature time-
133 series were obtained by averaging across the surface area of each lake. Lake-mean
134 surface temperatures are used in this study in order to average across the intra-lake
135 heterogeneity of surface water temperature responses to climate change (Woolway
136 and Merchant 2018; Zhong et al. 2019) and to correspond to the lake-mean model
137 used. In total, 115 of the studied lakes had satellite-derived surface water temperature
138 observations from 1995 to 2018 (Fig. S1). These 115 lakes are all included within the
139 Globolakes database (Carrea and Merchant 2019), which include data from 1000
140 lakes worldwide. The selection process for these 1000 lakes is described by Politi et
141 al. (2016). The 115 lakes are relatively well distributed across the continent but, given
142 the preponderance of lakes in high, northern latitudes (Verpoorter et al. 2014), there
143 were more lakes with satellite data situated in northern Europe. The 115 lakes with
144 satellite-derived surface temperature data range in altitude between -22 and 834 m
145 above sea level, in surface area between 9.22 and 17,444 km², and in mean depth
146 between 0.3 and 52.9 m.

147

148 2.4. *Lake model experiments* - To investigate the influence on lake surface
149 water temperatures of air temperature, wind speed, and solar radiation, each of which
150 experienced anomalous conditions during the 2018 European heatwave, we performed
151 a lake model experiment, similar to that of Zhong et al. (2016). Firstly, we ran FLake
152 with the meteorological data from ERA-Interim and calculated the 2018 May-Oct
153 mean and maximum lake surface temperature in each studied lake. We then
154 performed three additional model runs where, during each simulation, the seasonal
155 cycle of the meteorological variable was maintained at its long-term mean (1981-
156 2010) during 2018. For example, when investigating the sole influence of wind speed
157 on lake surface water temperature in 2018, we compared the first model run with
158 model outputs where the 2018 wind speed was replaced by its long-term mean. Then,
159 by calculating the average difference between the May-Oct mean and maximum lake
160 surface temperatures of these two model outputs, the sole influence of wind speed can
161 be estimated. This was repeated for different meteorological variables (air
162 temperature and solar radiation). The meteorological variable that was considered to
163 have the greatest impact on surface water temperature in a given lake during the 2018
164 heatwave was selected according to the greatest lake surface temperature difference.
165 We note that replacing a year of driver data with that of the long-term mean will

166 influence the natural variability of the climatic drivers, which will also be different
167 from one driver to another. In addition, momentum and mechanical energy fluxes
168 across the lake-air interface scale as the wind speed squared and cubed, respectively.
169 Thus, small changes in wind speed can have a relatively large influence on lake
170 thermal dynamics (Woolway et al. 2019).

171

172 *2.5. Climate model projections* – To simulate lake surface temperature towards
173 the end of the 21st century, we drove our lake model with bias-corrected climate
174 projections from the Inter-Sectoral Impact Model Intercomparison Project
175 (ISIMIP2b). Specifically, we used projections from HadGEM2-ES during the historic
176 (1981-1999) and future (2081-2099) periods under three emissions scenarios:
177 Representative Concentration Pathway (RCP) 2.6, 6.0, and 8.5. We downloaded the
178 data needed to drive FLake from ISIMIP2b (<https://www.isimip.org>), which were
179 available at a daily time step and at a grid resolution of 0.5°. The relevant data for
180 each lake were extracted for the grid point situated closest to each lake centre (Carrea
181 et al. 2015). We validated the FLake modelled temperatures when forced by
182 HadGEM2-ES climate data during the period 1995-2005, the period during which
183 both the satellite data and the climate projections were available.

184

185 **3. Results**

186

187 *3.1. Surface air temperature* – In 2018 Europe experienced the warmest May-
188 Oct since air temperature records began in 1880, with a mean air temperature anomaly
189 of +1.97°C (Fig. S2) (GISTEMP Team 2016; Hansen et al. 2010). This was
190 considerably warmer than the May-Oct average air temperatures observed during the
191 European heatwaves of 2003 (+1.28°C) and 2006 (+1.52°C). However, we must note
192 that the severity of heatwaves is also related to their duration and spatial extent, which
193 was different during the time periods mentioned above (i.e., 2003, 2006, 2018), and
194 not evaluated in this study. Also, as one would expect, we note that averaging over the
195 entire continent and over a long time period can reduce the quantitative severity of a
196 given heatwave, but locally the thermal extremes experienced are severe. For
197 example, across Europe the mean air temperature anomaly varied considerably during
198 May-Oct 2018 and was highest in central Europe (Fig. 1a). The maximum air
199 temperature anomaly exceeded 4°C in several countries (e.g., in Western Europe and
200 Fennoscandia), and was noticeably higher in western regions (Fig. 1b).

201

202 *3.2. Lake surface temperature response to the 2018 heatwave* – The lake
203 surface temperature model simulated accurately the thermal response of 115 European
204 lakes to the 2018 heatwave, with minimal identified bias (Fig. S3). The mean absolute
205 difference between the modelled and satellite-derived lake surface water temperature
206 anomalies (relative to the 1981 to 2010 average) in 2018 was 0.18°C and the root
207 mean square difference was 0.23°C. The difference between the modelled and
208 observed maximum lake surface water temperature anomalies was 0.13°C (Fig. S3)
209 and the root mean square difference between the maximum temperatures was 0.23°C.

210 Using the validated model, we simulated the surface temperature of 46,557
211 lakes across Europe (Fig. 2). The modelled lake surface water temperatures
212 demonstrated anomalous conditions throughout most of the continent. The mean and
213 maximum lake surface temperatures were, on average, 1.5°C and 2.4°C warmer than
214 the base-period average. Ninety-eight percent of lakes experienced positive mean lake
215 surface temperature anomalies (Fig. 2b). Fifty-seven percent of lakes experienced a
216 mean lake surface temperature anomaly that exceeded 1.5°C. The highest and most
217 consistent areas of anomalously warm May-Oct mean lake surface temperatures
218 included central Europe and southern parts of Fennoscandia, where lake surface
219 temperature anomalies were often greater than 2°C. Maximum lake surface water
220 temperatures were also exceptionally high during May-Oct 2018 in the studied lakes,
221 with surface water temperatures in many regions exceeding 30°C (Fig. 2c). The
222 maximum surface water temperature anomaly exceeded 4°C in a number of the
223 studied lakes, such as those in Fennoscandia and Ireland, but was also anomalously
224 low in others (Fig. 2d).

225

226 *3.3. Attribution of lake surface temperature response to the 2018 heatwave –*
227 In addition to the anomalously high air temperatures observed during May-Oct 2018
228 (Fig. 1), higher than average solar radiation and lower than average near-surface wind
229 speed also occurred in many regions (Fig. 3). Most noticeable was the higher than
230 average solar radiation in eastern and western Europe, in addition to numerous
231 regions in Fennoscandia. Some lake regions experienced solar radiation that was
232 greater than 30 Wm⁻² higher than the long-term average. There were also clear lower
233 than average near-surface wind speeds over central and western Europe, whereas
234 northern regions experienced higher than average wind speeds (as well as higher solar
235 radiation). Some regions of Ireland and the United Kingdom, for example,
236 experienced near-surface wind speeds that were up to 1 ms⁻¹ lower than the long-term
237 average.

238 To investigate the influence of air temperature, solar radiation, and wind speed
239 on the anomalous lake surface water temperatures, we conducted a model experiment
240 (see Methods). To omit from this analysis lakes that did not experience exceptionally
241 warm surface water temperature during May-Oct 2018, we selected only lakes with
242 maximum surface temperature anomalies for that period that were greater than the
243 90th percentile, relative to all May-Oct temperatures from 1980-2018 ($n = 42,011$).
244 Our model experiment demonstrated that air temperature had the greatest influence on
245 the maximum surface water temperature anomalies in 60% of the lakes studied.
246 However, solar radiation and near-surface wind speed were the most important
247 contributors in other lakes (28% and 12% of lakes, respectively), but in differing
248 regions (Fig. 4). This analysis was also repeated for the May-Oct mean lake surface
249 temperatures and demonstrate similar regional patterns (Fig. S4), although only
250 30,710 lakes experienced anomalous conditions according to mean lake temperatures.
251 For both the maximum and mean May-Oct lake surface temperatures, the influence of
252 solar radiation was particularly strong in some parts of Norway but was also
253 important in other lake regions (Finland, Swedish mid-latitudes and parts of Central

254 Europe). Wind speed influenced considerably the maximum lake surface temperature
255 in the United Kingdom and Ireland, where the maximum lake surface temperatures
256 would have been 0.8°C cooler had there not been a decrease in near-surface wind
257 speed at this time.

258

259 *3.4. Future projections of lake surface water temperature* – The lake model
260 driven by climate projections from HadGEM2-ES simulated accurately the surface
261 temperature of the 115 validation lakes during the period 1995-2005 (the years in
262 which both satellite data and climate projections were available). The mean absolute
263 difference between the modelled and satellite-derived lake surface water temperatures
264 was 0.35°C and the root mean square difference was 0.67°C (Fig. S5). Mean May-Oct
265 lake surface temperatures in the studied lakes were projected to be 2.9°C, 4.5°C, and
266 6.5°C warmer by 2081-2099 compared to the historic (1981-1999) period under RCPs
267 2.0, 6.0 and 8.5, respectively (Fig. 5). Under each of these climate change scenarios,
268 every studied lake will have higher mean temperatures compared to those during the
269 2018 heatwave. Under RCPs 6.0 and 8.5, mean lake temperatures will be at least 2°C
270 warmer than the 2018 temperatures in every studied lake by the end of the century. In
271 terms of maximum surface water temperature, lakes in the studied region will be
272 2.3°C, 4.3°C, and 7.3°C warmer, on average, by 2081-2099 under RCPs 2.0, 6.0 and
273 8.5 respectively (Fig. 6), although with some intra-continental differences. Ninety-
274 two, ninety-eight, and ninety-nine percent of the studied lakes will experience
275 maximum lake surface temperatures that exceed those observed in 2018 by the end of
276 the century under RCPs 2.0, 6.0 and 8.5, respectively. Under RCP 8.5, ninety-five
277 percent of lakes will experience maximum lake surface temperatures that are at least
278 3°C warmer than observed in 2018.

279

280 **4. Discussion**

281 In this study, we investigated the influence of the 2018 European heatwave on lake
282 surface water temperature. Lake surface temperature responses to extreme heat events
283 have been investigated previously (Jankowski et al. 2006; Jöhnk et al. 2008), but our
284 study is the first to demonstrate the simulated response of thousands of lakes to a
285 specific heatwave at a continental scale. In addition, our study is one of the first to
286 investigate the response of lake surface temperature to different meteorological
287 forcing during an extreme event. Most other studies have investigated only the
288 influence of air temperature change during a heatwave (Jankowski et al. 2006), in part
289 owing to an implicit assumption that surface air temperature is the dominant factor
290 impacting lake surface temperature. Importantly, our study shows that the increase in
291 solar radiation and the decrease in wind speed had a considerable influence on lake
292 surface temperature in many regions, including Norway and the United Kingdom and
293 Ireland, respectively.

294

295 Solar radiation is one of the most important components of the lake surface
296 energy budget, and thus one of the key drivers of lake surface temperature change.
297 Previous studies have shown that solar radiation can contribute substantially to long-
term surface water temperature change (Fink et al. 2014; Schmid and Köster 2016)

298 and can contribute to average lake surface temperature being higher than over-lake air
299 temperature (Woolway et al. 2017b). Near-surface wind speed is also an important
300 driver of lake thermal dynamics. A decline in wind speed can influence lake surface
301 temperature in many ways. The most important is, arguably, through its influence on
302 the mixing depth and, in turn, the volume of water that is influenced directly by
303 atmospheric forcing. A shoaling of the upper mixed layer due to reduced wind mixing
304 can lead to warmer surface waters. That is, lake surface temperatures increase more
305 rapidly when the volume of water that participates directly in the air-water surface
306 heat exchange is smaller, as is common in shallow lakes (Toffolon et al. 2014). A
307 decline in wind speed over lakes can also result in less heat being mixed from the lake
308 surface to greater depths, and subsequently lead to an increase in surface temperature
309 and thermal stability (Magee et al. 2016; Woolway et al. 2017a; Mi et al. 2018;
310 Woolway et al. 2019). In addition to the well-documented increase in air temperature
311 during May-Oct in 2018, changes in solar radiation and wind speed resulted in
312 optimum conditions for extraordinary lake warming, where the mean and maximum
313 May-Oct temperatures were, on average, 1.5°C and 2.4°C warmer than the base-
314 period. We demonstrated that by the end of the 21st century, May-Oct mean and
315 maximum lake surface temperatures will increase considerably in Europe, and that the
316 lake temperatures observed during May-Oct 2018 will become increasingly common.

317 The lake model used in this study was able to predict accurately the surface
318 temperature of 115 lakes with validation data. In terms of the root mean square
319 difference between observed and modelled temperature anomalies, FLake was able to
320 simulate the surface temperature of many lakes to less than 1°C. A root mean square
321 difference of 1°C is similar to that achieved by other lake model studies (Stefan et al.
322 1998; Piccolroaz et al. 2013; Bruce et al. 2018). However, there are some limitations
323 to consider in this study. Specifically, our validation dataset of 115 lakes does not
324 cover the range of lake surface temperatures in which our model is applied. For
325 example, within the validation set, the model was tested on lakes with average
326 temperature anomalies ranging from -1 to 1.5°C, whereas over half of the lakes within
327 the full suite (i.e., 46,557 lakes) had a mean anomaly that exceeded 1.5°C. Thus, the
328 model was not validated over the entire range of simulated temperatures across
329 Europe, and thus not validated for very extreme temperature anomalies. These
330 limitations should also be considered when interpreting our simulations. Furthermore,
331 future projections of maximum lake temperature is very sensitive to how well the
332 climate projections can predict the peak phase of extreme heatwaves, which is
333 particularly important for shallow lakes that have a lower thermal inertia (Toffolon et
334 al., 2014). Our future projections are based on the assumption that the climate models
335 can adequately capture these climatic extremes, and we presume that for all lakes the
336 peak temperature occurs in May-Oct. In addition, in this study we calculate the
337 maximum temperature based on all temperatures within May-Oct, and when
338 evaluating the ability of the model to capture this extreme we are not evaluating the
339 timing of the seasonal peaks, which could be different between the observations and
340 simulations.

341 Some lake specific processes were not considered in our simulations which
342 may influence the thermal response of lakes to thermal extremes, such as the
343 temperature of influent water (Vinnå et al. 2018). Also, given the lack of light
344 attenuation data available for such a large number of lakes, we applied a single light
345 attenuation for all sites. Although this is common in global lake simulations (Balsamo
346 et al. 2012; Le Moigne et al. 2016), it does likely introduce some bias. Specifically,
347 water clarity can influence how solar radiation is absorbed in the water column
348 (Persson and Jones 2008), and studies have shown that lower water clarity can
349 contribute to warmer surface waters (Rinke et al. 2010; Rose et al. 2016). Thus, a
350 higher light attenuation coefficient could result in higher thermal extremes. However,
351 we demonstrated that the value chosen worked well for the 115 lakes with validation
352 data. Despite these limitations we believe that given the large-scale scope of our
353 study, the model adequately captures the dominant drivers of lake surface temperature
354 change across the study sites and provides insight into how lakes can respond
355 differently to heatwaves.

356 An increase in temperature can have numerous implications for lake ecology.
357 Temperature can control a wide range of ecological states and processes in lakes such
358 as, among other things, species distribution (Comte and Olden 2017), food web
359 interactions (Norris et al. 2013), and phenology (Thackeray et al. 2016). One of the
360 most concerning consequences of lake warming in terms of water quality is the
361 potential increase in the occurrence of toxin-producing cyanobacteria, which are
362 known to respond positively to temperature (Reynolds 2006; Jöhnk et al. 2008; Paerl
363 and Huisman 2008; Mantzouki et al. 2018). During May-Oct 2018, higher lake
364 surface temperatures potentially resulted in optimum conditions for the development
365 of cyanobacteria blooms in many lakes across Europe, but these were not investigated
366 in this study. The next logical step is to investigate biological, chemical, and
367 ecological processes so that water managers can use this information and the true
368 environmental and socio-economic cost of climate change, including the occurrence
369 of extreme events, can be considered. Understanding, predicting and quantifying the
370 response of lakes to extreme events is critical for future decision-making involving
371 water resource management policies and to understand how ecosystems will respond
372 in the future. If drastic changes in ecosystem functionality are to be avoided, aquatic
373 ecosystems may have to adapt to not only gradual changes in water temperature as
374 climate change progresses, but also to the increased occurrence of extremes.

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539 Service will be made available in 2020 on the **Copernicus Climate Data Store**
540 (<https://cds.climate.copernicus.eu/#!/home>).

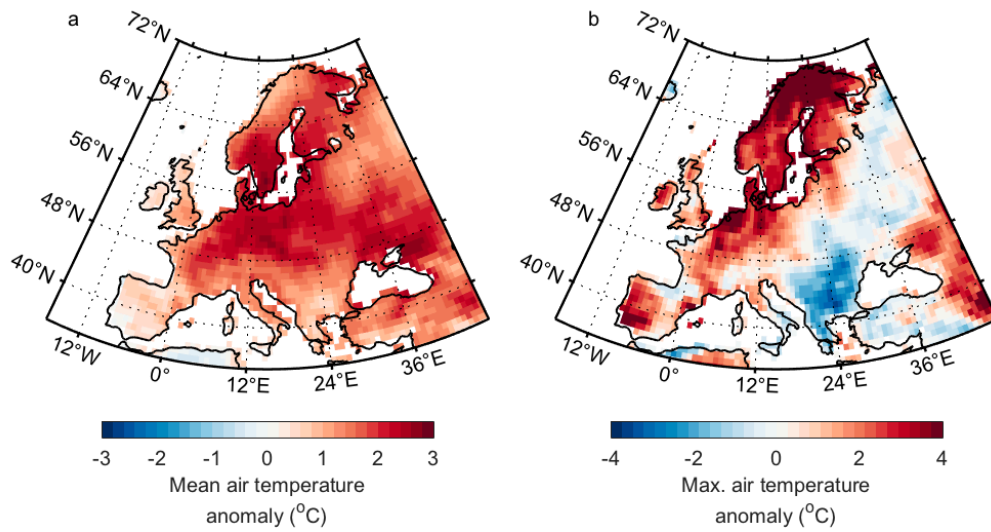
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542 **Competing interests**

543 The authors declare that there are no competing interests.

544 **List of Figures**

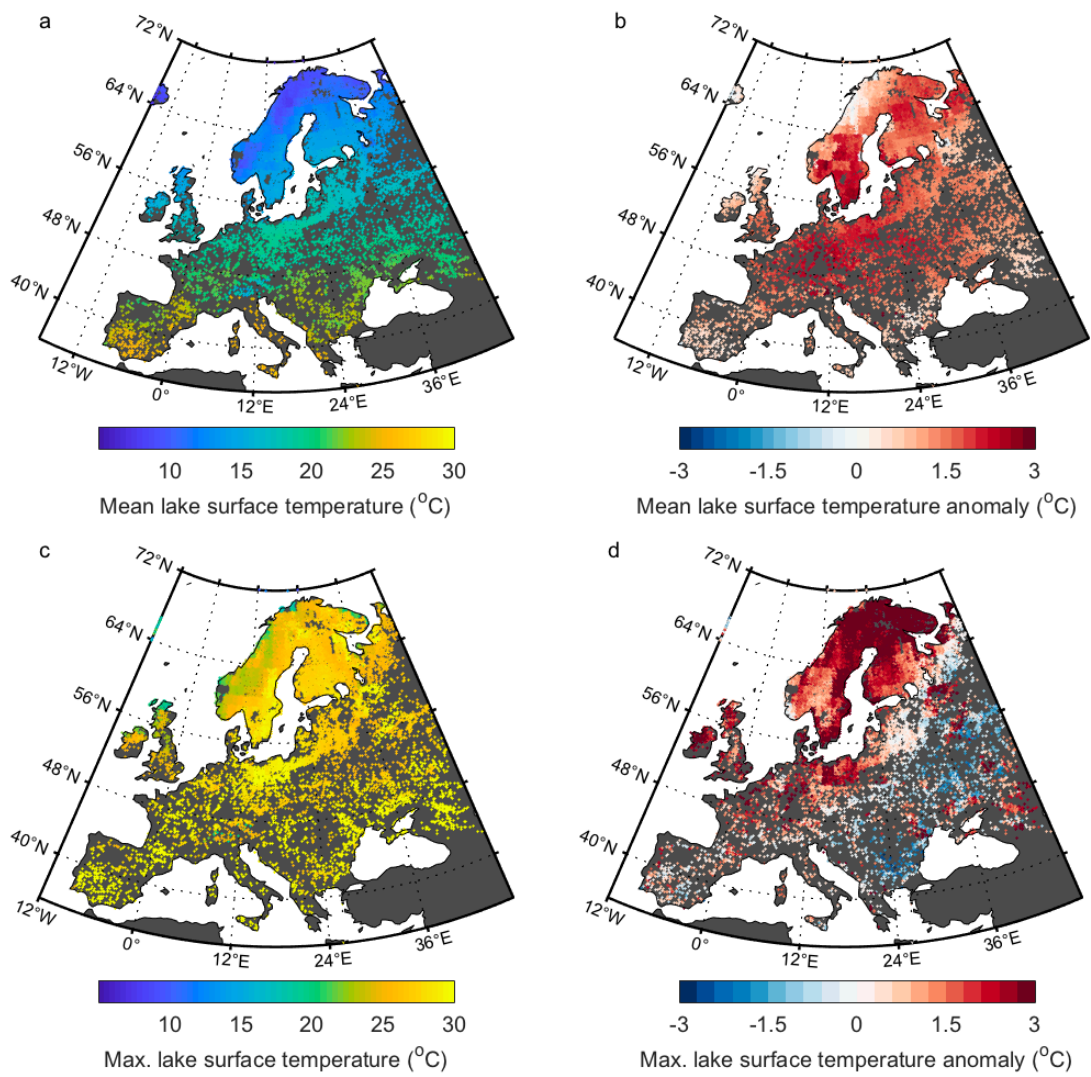
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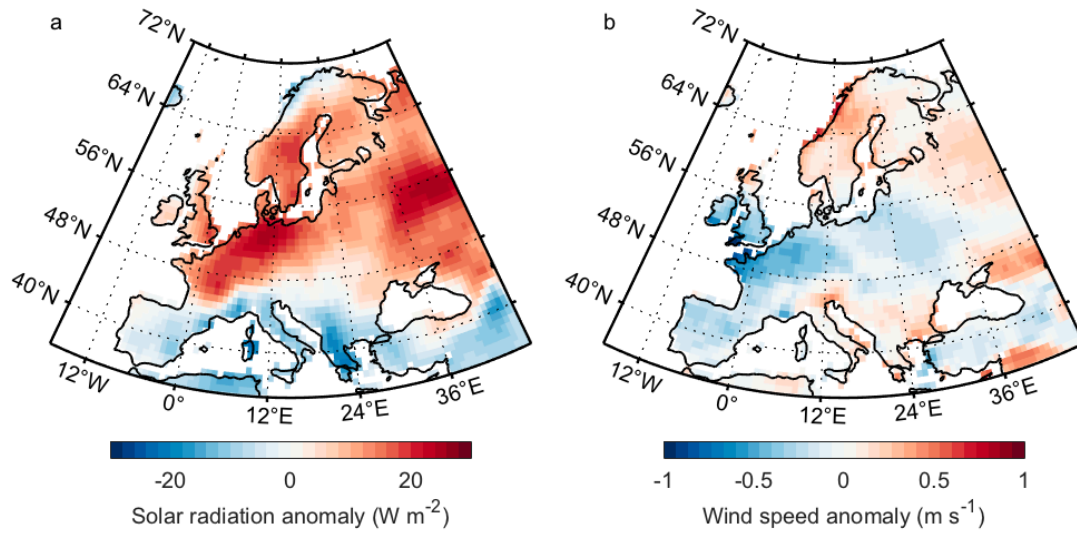
548 **Figure 1.** May-Oct 2018 surface air temperature anomalies (relative to the 1981-2010
549 average) in Europe, showing the (a) mean and (b) maximum temperatures. Air
550 temperature data are from ERA-Interim (Dee et al. 2011).



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554 **Figure 2.** Continental-scale variations in May-Oct 2018 (a) mean lake surface water
 555 temperature; (b) mean lake surface water temperature anomalies; (c) maximum lake
 556 surface water temperature; (d) maximum lake surface water temperature anomalies.
 557 Anomalies are shown relative to the 1981-2010 average.



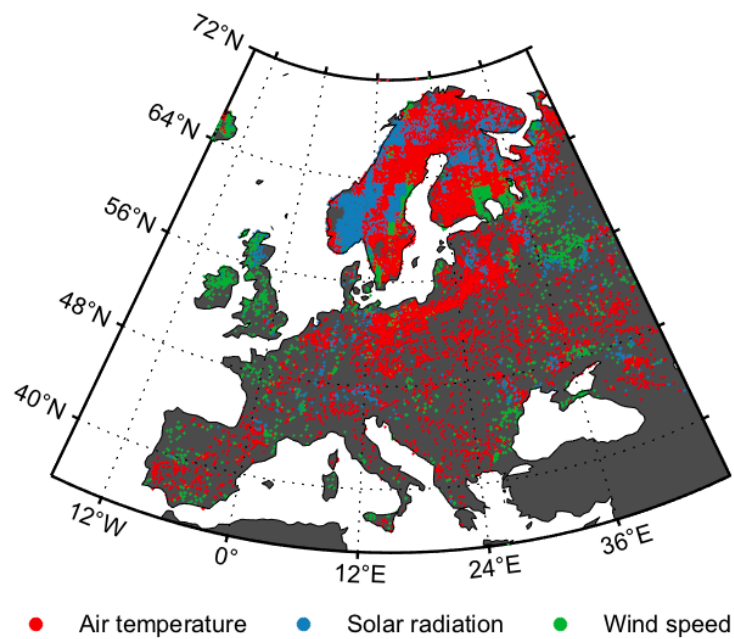
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560 **Figure 3.** May-Oct 2018 anomalies (relative to 1981-2010) in (a) solar radiation and

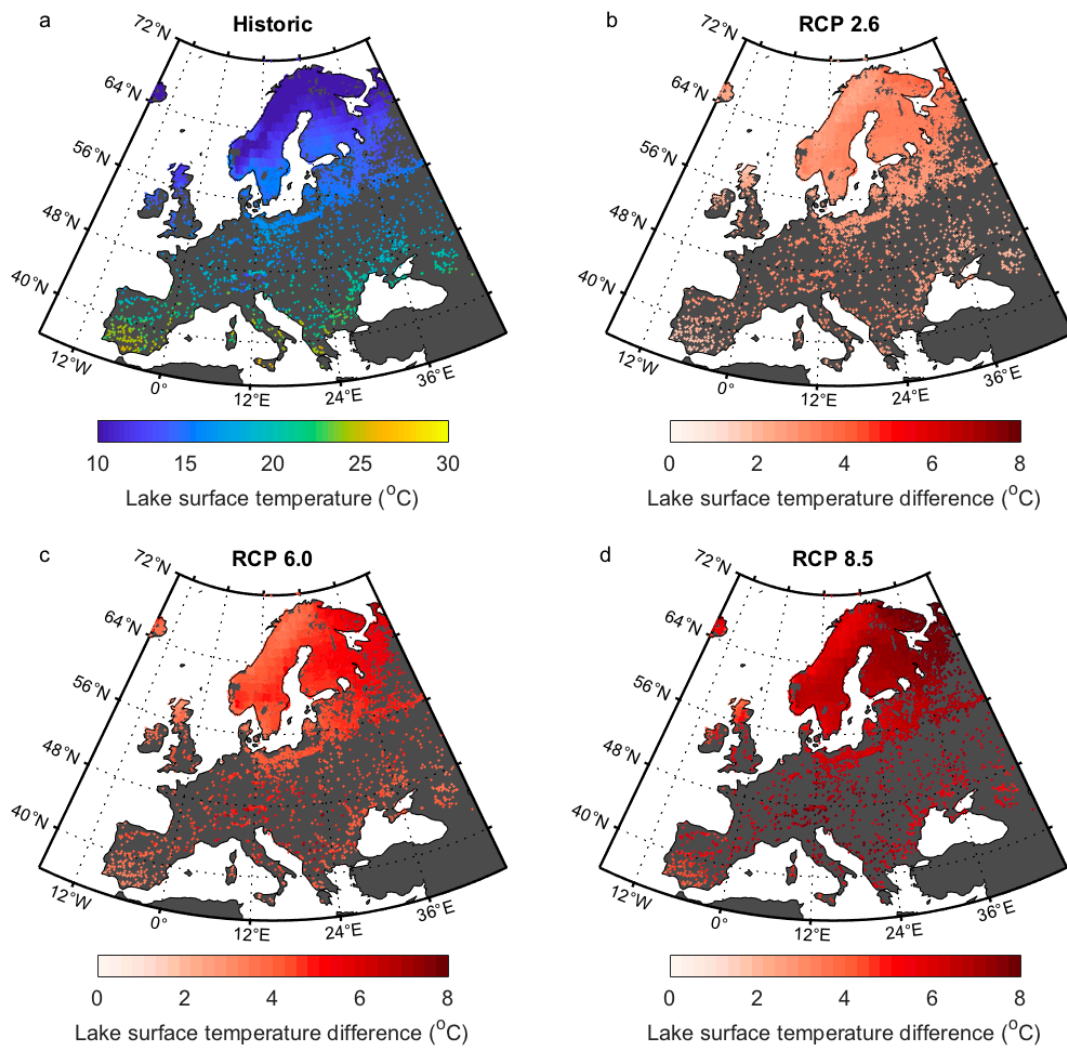
561 (b) near-surface wind speed. Data from ERA-Interim (Dee et al., 2011).

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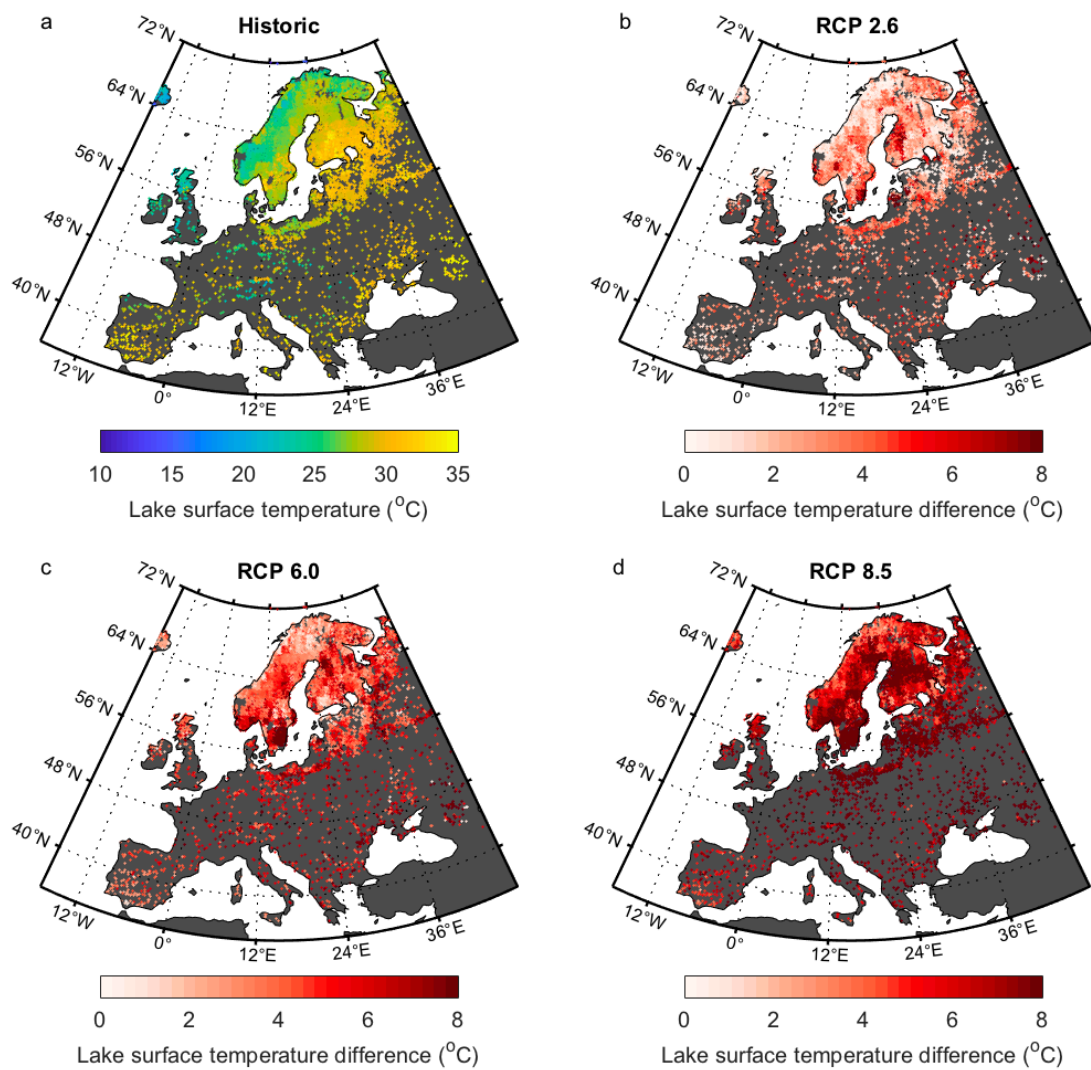
565 **Figure 4.** Attribution of lake surface temperature responses to the 2018 European
566 heatwave. Colors represent the meteorological variable which had the greatest
567 influence on maximum lake surface water temperature anomalies during May-Oct
568 2018. Only shown are lakes with maximum surface temperature anomalies that were
569 within the 90th percentile in 2018, relative to all May-Oct temperatures during the
570 study period (1980-2018).



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574 **Figure 5.** May-Oct mean lake surface temperatures shown for the (a) historic and (b-
 575 d) future periods. Future lake surface temperature projections are given for (b) RCP
 576 2.6, (c) RCP 6.0, (d) RCP 8.5. Lake temperature differences are given as the future
 577 minus historic temperatures.



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581 **Figure 6.** May-Oct maximum lake surface temperatures shown for the (a) historic and

582 (b-d) future periods. Future lake surface temperature projections are shown for (b)

583 RCP 2.6, (c) RCP 6.0, (d) RCP 8.5. Lake temperature differences are given as the

584 future minus historic temperatures.