



Northern Hemisphere atmospheric stilling accelerates lake thermal responses to a warming world

Article

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1 **Title**

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3 world

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21
22 **Key points**

- 23 1. Atmospheric stilling has resulted in an increase in lake surface temperature across the
24 Northern Hemisphere
25 2. A decrease in wind speed results in a lengthening of the stratified period and a
26 strengthening of lake stability
27 3. Shallow lakes and those situated at low-latitude are influenced most by atmospheric
28 stilling

29
30 **Abstract (<150 words)**

31 Climate change, in particular the increase in air temperature, has been shown to influence
32 lake thermal dynamics, with climatic warming resulting in higher surface temperatures,
33 stronger stratification, and altered mixing regimes. Less-studied is the influence on lake
34 thermal dynamics of atmospheric stilling, the decrease in near-surface wind speed observed
35 in recent decades. Here we use a lake model to assess the influence of atmospheric stilling, on
36 lake thermal dynamics across the Northern Hemisphere. From 1980-2016, lake thermal
37 responses to warming have accelerated as a result of atmospheric stilling. Lake surface
38 temperatures and thermal stability have changed at respective rates of 0.33 and 0.38°C
39 decade⁻¹, with atmospheric stilling contributing 15 and 27% of the calculated changes,
40 respectively. Atmospheric stilling also resulted in a lengthening of stratification, contributing
41 23% of the calculated changes. Our results demonstrate that atmospheric stilling has
42 influenced lake thermal responses to warming.

43
44 **Plain Language Summary**

45 Studies of climate change impacts on lakes typically consider projections of air temperature
46 over time. Such studies have demonstrated that a warming world will have numerous
47 repercussions for lake ecosystems. Climate, however, is much more than temperature. In
48 lakes, changes in near-surface wind speed play an important role. Here, using a lake model to

49 simulate the thermal behaviour of lakes across the Northern Hemisphere, we show that lake
50 warming has accelerated as a result of atmospheric stilling, the decrease in near-surface wind
51 speed observed in recent decades. Specifically, as a result of atmospheric stilling, lake surface
52 temperatures have increased at a faster rate since 1980. Atmospheric stilling also resulted in a
53 lengthening and strengthening of stratification, which is important for lake ecology and has
54 numerous implications for lake ecosystems. Our results demonstrate that atmospheric stilling
55 has influenced lake thermal responses to climatic warming and that future evolution of wind
56 speed is highly pertinent to assessment of future climate change impacts on lake ecosystems.

57 58 **1. Introduction**

59 Atmospheric stilling is the decrease of near-surface (~10 m) terrestrial wind speed observed
60 in recent decades [Roderick *et al.*, 2007; McVicar *et al.*, 2012]. This slowdown has had
61 impacts across the world, including regions where inland waters are present. Although the
62 exact cause is unknown, some of the hypothesised drivers of atmospheric stilling include a
63 reduction in the equatorial-polar thermal gradient [McVicar *et al.*, 2012], changes in mean
64 circulation [Lu *et al.*, 2007; Azorin-Molina *et al.*, 2014], and an increase in land-surface
65 roughness [Pryor *et al.*, 2009; Vautard *et al.*, 2010].

66 Wind speed is one of the most important drivers of physical processes within lakes.
67 Momentum and mechanical energy fluxes across the lake-air interface scale as the wind
68 speed squared and cubed, respectively [Wüest and Lorke, 2003]. Modest fractional reductions
69 in wind speed may cause substantial changes in stratification and mixing dynamics. Studies
70 suggest that increasing air and, in turn, lake surface temperature typically, although not
71 always [Tanentzap *et al.*, 2008], leads to a strengthening of stratification, as a result of an
72 increase in the temperature difference between surface and bottom waters. A concurrent
73 decrease in wind speed over lakes could reduce the magnitude of vertical mixing, leading to
74 less heat being mixed from the surface to greater depths, and subsequently leading to an
75 increase in surface temperature, a decrease in bottom temperature, and a strengthening of
76 stratification. Such a process could accelerate the expected thermal impacts on lakes of
77 climatic warming [Woolway *et al.*, 2017a; Magee *et al.*, 2017].

78 Alterations to temperature and stratification have profound effects on lake
79 ecosystems. Increased surface temperature and more stable and longer stratification can
80 favour bloom-forming cyanobacteria [Paerl and Huisman, 2009] and influence lake
81 productivity [Verburg *et al.*, 2003; O'Reilly *et al.*, 2003]. Moreover, when a lake stratifies the
82 deep water becomes decoupled from the atmospheric supply of oxygen and the longer the
83 stratification lasts the more the oxygen becomes depleted due to in-lake respiration [Rippey
84 and McSorley, 2009], resulting in anoxic conditions and the formation of deep-water dead
85 zones [North *et al.*, 2014; Del Giudice *et al.*, 2018]. This not only limits fish habitat for most
86 species [Regier *et al.*, 1990] but also alters the water chemical balance, promoting the
87 production of methane [Borrel *et al.*, 2011].

88 Despite the potentially large decrease in wind mixing energy as a result of
89 atmospheric stilling, the majority of climate change studies on lakes have ignored this
90 influence, in part owing to an implicit assumption that surface air temperature is the dominant
91 factor impacting lake thermal responses to climate change [O'Reilly *et al.*, 2015; Woolway *et al.*,
92 2017b; Winslow *et al.*, 2018]. In this study, we aim to address this research gap by
93 analysing lake thermal responses to atmospheric stilling. We use a one-dimensional,
94 numerical lake model to study the influence of atmospheric stilling on lake surface and
95 bottom water temperatures, water column stability, and the number of stratified days per year
96 in lakes situated across the Northern Hemisphere.

97 98 **2. Methods**

100 2.1. *Study sites* – The studied lakes were selected based on the availability of mean
 101 depth information as well as wind speed observations near lakes worldwide. Of the 1.4
 102 million lakes globally (larger than 0.1 km²) [Messager *et al.*, 2016], only those situated
 103 within 10 km of a meteorological station were included in this study ($n = 2,063$). The
 104 majority of these lakes were situated in the Northern Hemisphere ($n = 1,924$), and thus we
 105 restrict our study sites to this region. Of these 1,924 Northern Hemisphere lakes, not all were
 106 suitable for inclusion in this study. Lakes were deemed suitable if the lake surface area was
 107 considered large enough for the influence of terrestrial sheltering (e.g., tall tree canopy) on
 108 over-lake wind speeds to be considered negligible, which depends on lake area and the
 109 sheltering height (e.g., local canopy height). According to field and wind tunnel experiments
 110 [Markfort *et al.*, 2010], if the radius of the lake is 50 times greater than the average sheltering
 111 height [Read *et al.*, 2012], we can expect terrestrial sheltering to have less influence on over-
 112 lake wind conditions. In total, 1,123 lakes met this criteria. In addition, as we were interested
 113 in changes in thermal stability, lakes were only included if they stratified at any point
 114 seasonally, as determined from the lake model (see below). Following the recommendations
 115 of Balsamo *et al.*, [2012] when using the selected model (see below) across a wide-spectrum
 116 of lakes, we only included lakes in the analysis if their mean depth was less than 60m. This
 117 resulted in 650 lakes for the analysis.

118
 119 2.2. *Canopy height estimation* - The mean sheltering height of each lake was
 120 computed according to the land cover type within 250 meters of a given lake perimeter
 121 following Van Den Hoek *et al.*, [2015], where the lake shoreline polygons were extracted
 122 from Messager *et al.*, [2016]. Sheltering height was based on global canopy height data
 123 collected in 2005 using the GLAS lidar aboard NASA ICESat [Friedl and Sulla-Menashe,
 124 2015]. Land cover type was based on the 2005 MCD12Q1 V6 Annual IGBP land cover
 125 classification product, derived from data collected by the NASA MODIS satellite [Simard *et al.*,
 126 2011]. All data used to measure the mean sheltering height are open-access, and
 127 calculations were performed using Google Earth Engine.

128
 129 2.3. *Lake temperature model* - To simulate lake thermal responses to climate change,
 130 we used the one-dimensional Freshwater lake (FLake) model [Mironov, 2008; Mironov *et al.*,
 131 2010]. FLake has been tested extensively in past studies. It has been used for simulating the
 132 vertical temperature profile as well as the mixing regime of lakes [Kirillin, 2010; Shatwell *et al.*,
 133 2016; Woolway and Merchant, 2019], and has been shown to reproduce accurately
 134 bottom water temperatures as well as temporal changes to the depth of the upper mixed layer
 135 and thermocline [Thiery *et al.*, 2014; Thiery *et al.*, 2015]. The meteorological variables
 136 required to drive FLake are air temperature at 2 m, wind speed at 10 m, surface solar and
 137 thermal radiation, and specific humidity. The forcing data used by FLake were from ERA-
 138 Interim [Dee *et al.*, 2011], available at a latitude-longitude resolution of 0.75°. Time series
 139 data were extracted for the grid point situated closest to the lake centre [Carrea *et al.*, 2015].
 140 A set of lake specific parameters are also needed to drive FLake, including fetch (m), which
 141 we fix in this study to the square root of lake surface area; mean depth; lake-ice albedo,
 142 which was assumed to be 0.6 [Mironov, 2008]; and the light attenuation coefficient (K_d , m⁻¹),
 143 which was set to 1 m⁻¹.

144
 145 2.4. *Near-surface wind speed observations* - To ensure that ERA-Interim wind speeds
 146 were comparable to those observed in-situ, we compared these data with observations from
 147 within 10 km of each lake (Fig. S3), available from HadISD [Dunn *et al.*, 2012]. In addition
 148 to the quality control applied by Dunn *et al.*, [2012], we performed a more robust

149 homogenization method following *Azorin-Molina et al.*, [2018a], using the R [*R Core Team*,
150 2018] package HOMER [*Mestre et al.*, 2013].

151

152 *2.5. Lake thermal metrics* – We investigated changes in lake surface and bottom water
153 temperature, and thermal stability in each of the studied lakes. These were calculated only
154 during July–September, in order to avoid the period of ice-cover in some lakes [*O’Reilly et*
155 *al.*, 2015; *Woolway and Merchant*, 2017]. The thermal stability of each lake was calculated as
156 the top (defined as 0.1m below the lake surface) minus bottom (defined as the deepest point
157 of the lake) temperature difference. We also calculated the change in the number of positively
158 stratified (i.e., excluding inverse stratification) days per year (not limited to July–September).
159 To capture all stratification periods in this study, we use a top-bottom density difference of
160 0.05 kg m^{-3} to define a stratified day.

161

162 *2.6. Lake model validation* – To validate the simulated lake surface temperatures from
163 FLake, we use lake surface temperatures from the ARC-Lake dataset [*MacCallum and*
164 *Merchant*, 2012]. Daily lake-mean time-series were obtained from the spatially-resolved
165 satellite data by averaging across the lake area. Lake-mean surface temperatures are used, as
166 these have been shown to give a more representative picture of lake temperature responses to
167 climate change compared to single-point measurements [*Woolway and Merchant*, 2018], and
168 also correspond better to the lake-mean model used. Fourteen lakes simulated in this study
169 were included in the ARC-Lake dataset (Fig. S1; Table S3). Modelled summer average lake
170 surface temperatures were also compared with in-situ summer-average lake surface
171 temperatures ($n = 4$) from *Sharma et al.*, [2015] (Fig S1; Table S2). To verify that FLake was
172 able to simulate lake stability, we compared these simulations with calculated stability from
173 22 lakes, in which high-resolution lake temperature observations were available (Fig. S2;
174 Table S4).

175

176 *2.7. Lake model experiments* - To investigate the influence of atmospheric stilling on
177 lake thermal dynamics, we performed two model experiments. Firstly, the thermal metrics
178 were calculated from the lake model temperature profiles generated using the atmospheric
179 forcing data over the study period. These model runs were then repeated, but with a
180 detrended near-surface wind speed. Near-surface wind speed was detrended in each site while
181 maintaining the inter-annual variability by first calculating the rate of change, keeping the
182 wind speed for the first simulation year unchanged, and removing the trend from the
183 following years. We then calculated the difference between the annually (or July–September)
184 averaged ‘stiling’ and ‘no-stiling’ model runs for each thermal metric across the lakes. The
185 influence of atmospheric stilling on each thermal metric was evaluated by calculating the
186 trend in the time series of ‘stiling’ minus ‘no-stiling’ model outputs. Trends were calculated
187 using ordinary least squares linear regression models, and the 5% to 95% confidence intervals
188 were also calculated. To determine if any lake specific characteristics influenced the
189 sensitivity of different lake thermal metrics to atmospheric stilling, we used the computed
190 trend from the ‘stiling’ minus ‘no-stiling’ time series within a multiple linear regression
191 model. Lake area, depth, altitude, latitude, and the trend in wind speed were used as
192 predictors in the model (*Woolway et al.*, 2017c).

193

194 **3. Results**

195

196 *3.1. Change in near-surface wind speed* - Among the studied lakes, the average rate
197 of change in wind speed was -0.07 (95% CI: $-0.07, -0.06$; $p < 0.01$) $\text{ms}^{-1} \text{ decade}^{-1}$, but with
198 considerable across-lake variability (Fig. 1; $n = 650$). Almost two-thirds of the sites ($n = 422$)

199 investigated experienced a decrease in wind speed. The average rate of change among these
200 sites was -0.09 (95% CI: $-0.09, -0.08$; $p < 0.01$) $\text{m s}^{-1} \text{decade}^{-1}$. The largest and most
201 consistent area of atmospheric stilling occurs in central and northern Europe (Fig. 1). Sites in
202 north-eastern and south-central USA, India, and some regions of east Asia also experience a
203 substantial decline in near-surface wind speed from 1980-2016.
204

205 *3.2. Lake thermal responses to climate change* - As the objective of this study was to
206 investigate the influence of atmospheric stilling on lake thermal dynamics, we focus on the
207 large majority of lakes which experienced a decline in near-surface wind speed from 1980-
208 2016. Among these 422 sites, lake surface temperature and thermal stability demonstrate a
209 clear response to climate change (Fig. 2). In terms of lake surface temperature, the average
210 rate of change over all sites was 0.33 (95% CI: $0.16, 0.50$; $p < 0.01$) $^{\circ}\text{C decade}^{-1}$. The
211 confidence interval in 74% of lakes did not include zero. The average rate of change in
212 bottom water temperatures was -0.07 (95% CI: $-0.11, -0.03$; $p = 0.07$) $^{\circ}\text{C decade}^{-1}$. The
213 confidence interval in 61% of lakes did not include zero. As a result of greater warming at the
214 lake surface compared to bottom waters, lake thermal stability increased in 82% of lakes (Fig.
215 2) and the confidence interval did not include zero in 67% of lakes. The top-bottom
216 temperature difference increased at an average rate of 0.38 (95% CI: $0.34, 0.42$; $p < 0.01$) $^{\circ}\text{C}$
217 decade^{-1} . The number of stratified days also increased, at an average rate of 4.13 (95% CI:
218 $3.72, 4.54$; $p < 0.01$) days decade^{-1} (Fig. 3). The confidence interval in 68% of lakes did not
219 include zero.
220

221 *3.3. Influence of atmospheric stilling on lake thermal dynamics* - To investigate only
222 the influence of atmospheric stilling on lake thermal dynamics, we removed the decrease in
223 wind speed and repeated the lake model runs (see Methods). Our results demonstrate that
224 atmospheric stilling accelerated the response of lake surface temperature to climatic warming
225 (Fig. 4). The average rate of change in lake surface temperature from the ‘no-stilling’ model
226 run was 0.28 (95% CI: $0.26, 0.30$; $p < 0.01$) $^{\circ}\text{C decade}^{-1}$, 15% lower than the model run
227 where the influence of atmospheric stilling was present. The average rate of change in lake
228 bottom temperature from the ‘no-stilling’ model run was 0.03 (95% CI: $-0.01, 0.07$; $p > 0.1$)
229 $^{\circ}\text{C decade}^{-1}$, which was higher than the rate of change calculated when the influence of
230 atmospheric stilling was present. This demonstrates that atmospheric stilling is having a
231 cooling influence on lake bottom temperature. The thermal stability of the lakes is also
232 influenced considerably. When the decline in wind speed was removed from the model input
233 data, the average rate of change in thermal stability was 0.28 (95% CI: $0.24, 0.32$; $p < 0.01$)
234 $^{\circ}\text{C decade}^{-1}$, ~27% lower than when the influence of atmospheric stilling was present.
235 Atmospheric stilling also influenced the number of stratified days per year, contributing 23%
236 of the changes observed across the Northern Hemisphere. The number of stratified days in
237 the ‘no-stilling’ model run changed at an average rate of 3.08 (95% CI: $2.67, 3.49$; $p < 0.01$)
238 days decade^{-1} , which is lower than calculated by the model where the influence of
239 atmospheric stilling was included. Thus, atmospheric stilling resulted in a lengthening of the
240 thermally stratified period. From the stilling minus no-stilling model runs, we calculate that
241 79%, 52%, 57%, and 61% of the confidence intervals of the calculated trends do not include
242 zero with regards to lake surface temperature, lake bottom temperature, lake thermal stability,
243 and the number of stratified days, respectively.
244

245 *3.4. Lake characteristics influence their sensitivity to atmospheric stilling* - Multiple
246 linear regression models were used to determine how lake location and different lake
247 attributes, influence the response of lake thermal dynamics to atmospheric stilling. We find
248 that, for both lake surface temperature and the number of stratified days, lake depth as well as

249 the trend in near-surface wind speed are statistically significant predictors in the model
250 (Table S5). In addition, our results demonstrate that while many of the lakes studied
251 experienced an increase in surface temperature and the number of stratified days as a result of
252 atmospheric stilling, shallow lakes were most affected. Latitude was also a statistically
253 significant predictor in the model with regards to lake surface temperature, demonstrating
254 that surface temperatures in low-latitude lakes experienced a greater increase as a result of
255 atmospheric stilling (Table S5). None of the predictor variables tested were statistically
256 significant with regards to their influence on the role of atmospheric stilling on lake bottom
257 temperature and thermal stability. The magnitude of atmospheric stilling was the only
258 statistically significant predictor in the model (Table S6). This illustrates that lake bottom
259 temperature and thermal stability of the lakes studied are sensitive to the influence of
260 atmospheric stilling, if a sufficient decline in near-surface wind speed occurs, but none of the
261 tested lake specific characteristics had an influence on this response.

262 4. Discussion

263 Previous studies have discussed the effects of climatic warming on lake temperature and
264 stratification dynamics [Kraemer *et al.*, 2015; Woolway *et al.*, 2017b]. The focus on air
265 temperature change has drawn attention away from the possible influences of other aspects of
266 climate change, such as atmospheric stilling. A few studies that have investigated the
267 response of lake thermal dynamics to changes in wind speed have demonstrated the important
268 effect of this long-term change on the physical environment of lakes [Magee *et al.*, 2016;
269 Magee *et al.*, 2017; Woolway *et al.*, 2017a; Deng *et al.*, 2018]. However, the majority of these
270 previous studies have focussed on local and/or regional changes and, in particular, the
271 influence of a decrease in wind speed on individual systems. Prior to this investigation, no
272 known previous studies have investigated the influence of atmospheric stilling on
273 temperature and stratification dynamics in lakes situated across the Northern Hemisphere. In
274 this study, we demonstrate that the decrease in wind speed has resulted in less heat being
275 mixed from the lake surface to greater depths and, consequently, resulted in a warming of
276 surface waters and a cooling of bottom water temperature. In turn, the thermal stability and
277 the number of stratified days in the lakes studied has increased, on average, as a result of
278 atmospheric stilling.

279 While atmospheric stilling influenced lake thermal dynamics in many of the studied
280 sites, our investigation demonstrated that shallow lakes and those situated at low-latitude
281 experienced the greatest response. We found mean depth and latitude to be important
282 predictors of the sensitivity of the studied lakes to atmospheric stilling in terms of lake
283 surface temperature. A decline in wind speed can influence lake surface temperature in many
284 ways [Edinger *et al.*, 1968]. The most important is, arguably, through its influence on the
285 mixing depth and, in turn, the volume of water that is influenced directly by atmospheric
286 forcing. A shoaling of the upper mixed layer over time (e.g. due to less wind mixing), can
287 lead to a stronger trend in lake surface temperature than would be expected from changes in
288 air temperature alone. Atmospheric stilling can also influence lake surface temperature via its
289 effect on the turbulent fluxes at the air-water interface, where a decrease in wind speed will
290 result in less latent and sensible heat loss, and thus a warming at the lake surface. This is
291 particularly important for low-latitude lakes. The latent heat flux is a greater contributor of
292 total turbulent heat loss in the tropics, compared to lakes situated in other climate zones as a
293 result of the increase in the air-water humidity difference, to which the latent heat flux is
294 proportional, with decreasing latitude [Woolway *et al.*, 2018a]. Fractional reductions in wind
295 speed as a result of atmospheric stilling can therefore have a greater influence on the surface
296 energy budget, and thus surface temperature, at low latitudes.

298 Mean depth was also an important predictor of the sensitivity of the studied lakes to
299 atmospheric stilling with regards to the number of stratified days per year. The number of
300 stratified days per year was influenced most by atmospheric stilling in shallow lakes. Unlike
301 deep lakes, which are often either monomictic (experiencing one mixing event in most years)
302 or dimictic (mixing twice per year), thus experiencing prolonged periods of stratification,
303 shallow lakes often mix frequently (i.e. polymictic), stratifying only during periods of calm
304 and/or warm weather. Previous studies have shown that atmospheric stilling can bring
305 shallow lakes towards a tipping point between never stratifying (i.e. continuous polymictic)
306 to experiencing prolonged periods of stratification (i.e. discontinuous polymictic) [Woolway
307 *et al.*, 2017a]. Although mixing regime shifts were not the focus of this study, and have been
308 investigated elsewhere [Woolway and Merchant, 2019], we found a prolonging effect of
309 atmospheric stilling on the duration of stratification across Northern Hemisphere lakes, which
310 was most apparent in shallow and, thus, more easily stratified systems. The ecological
311 implications of an increase in stratification duration, such as an increase in hypoxia [North *et al.*,
312 2014] and the occurrence of algal blooms [Paerl and Huisman, 2009], and/or a decrease
313 in lake productivity [O'Reilly *et al.*, 2003; Verburg *et al.*, 2003], will differ between lake
314 mixing types, and should be considered when interpreting our results. Specifically, the
315 ecological implications will be different between, for example, a dimictic lake where
316 stratification is lengthening, and a polymictic lake where a mixing regime alteration occurs.

317 The main limitation of our lake simulations is the one-dimensional assumption, as
318 lake temperature and stratification can often vary spatially within lakes [Woolway and
319 Merchant, 2018]. While these within-lake spatial variations were not captured in this
320 investigation, and can be extremely important for some large lakes, the modelling approach
321 used in this study is appropriate for a large-scale survey of lake responses, and likely captures
322 the dominant drivers of atmospheric stilling across the study sites. Other factors that were not
323 considered in this study can also influence the response of thermal dynamics to atmospheric
324 stilling or can complicate these relationships in some lakes. These include the influence of
325 groundwater inputs [Rosenberry *et al.*, 2015], the volume and temperature of influent water
326 [Vinnå *et al.*, 2018], and changes in lake transparency [Shatwell *et al.*, 2016]. Given the lack
327 of light attenuation data available, we applied a single light attenuation for all lakes, which is
328 common in global lake simulations [Balsamo *et al.*, 2012; Le Moigne *et al.*, 2016]. The value
329 chosen (i.e. 1m^{-1}) worked well for the multiple simulations (i.e. the simulated temperatures
330 reasonably well-matched temperature for lakes with validation data). While we expect the
331 light attenuation coefficient to influence the sensitivity of a given lake to atmospheric stilling,
332 for a study of multiple lakes the average response should be relatively insensitive to using a
333 single attenuation value.

334 Our results demonstrate that atmospheric stilling is an important driver of lake
335 thermal responses to climatic warming. However, the average rate of change in near-surface
336 wind speed among the lakes investigated is considerably less than the worldwide average ($-$
337 $0.14\text{ms}^{-1}\text{decade}^{-1}$) [McVicar *et al.*, 2012]. Therefore, at a global scale we anticipate the
338 influence of atmospheric stilling on lake thermal dynamics to be even greater. Future trends
339 in atmospheric stilling are unclear. If wind speeds continue to decrease, then atmospheric
340 stilling will exacerbate the impacts of climate warming on lakes through further increases in
341 lake surface temperature and thermal stability. The repercussions of changes to these
342 important thermal properties of lakes is fundamental as they influence not only physical, but
343 also chemical and biological processes. However, it is yet unclear if the atmospheric stilling
344 patterns observed in recent decades will continue. Some recent studies have suggested a
345 break in the negative tendency of near-surface wind speeds, with a recovering/strengthening
346 after the year ~ 2013 [Azorin-Molina *et al.*, 2018b]. An increase in near-surface wind speed,
347 which could be expected as a result of the projected increase in the frequency of extreme

348 weather [Woolway *et al.*, 2018b], could act to dampen lake thermal responses to climatic
349 warming, even resulting in a decrease in lake surface temperature and thermal stability in
350 lakes if large enough. It is as yet unclear if the physical environment of lakes will return to a
351 ‘pre-stilling’ state given recent changes. Either way, this study demonstrates that the
352 influence of long-term changes in near-surface wind speed needs to be taken into
353 consideration when assessing climate change impacts on lake ecosystems.

354

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488

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505 source code is available to download from <http://www.flake.igb-berlin.de/>.

506 **Figures and legends**

507

508 **Figure 1.** Observed mean wind speed changes across the Northern Hemisphere from 1980-
509 2016. Shown are (a) the July-September averaged wind speed trends in locations of the lakes
510 studied ($n = 650$), and (b) the frequency distribution of the calculated trends. Statistically
511 significant ($p < 0.05$) trends are shown with circles and non-significant trends ($p > 0.05$) are
512 shown with squares.

513

514 **Figure 2.** Thermal response of lakes to climate change. Shown are the changes in (a) surface
515 water temperature, (b) bottom water temperature, and (c) thermal stability across Northern
516 Hemisphere lakes from 1980-2016 ($n = 422$). Shown also are (d) the Northern Hemisphere
517 average anomalies, relative to 1981-2010, and (e) the frequency distribution of the calculated
518 trends in lake thermal metrics (as shown in panels a-c). Results are presented as July-
519 September averages. A linear fit to the average anomalies is also shown in panel d.
520 Statistically significant ($p < 0.05$) trends are shown with circles and non-significant trends (p
521 > 0.05) are shown with squares.

522

523 **Figure 3.** Changes in the number of stratified days per year across Northern Hemisphere
524 lakes from 1980-2016 ($n = 422$). Shown are (a) the trends in the duration of thermal
525 stratification per year, (b) the Northern Hemisphere average anomalies relative to 1981-2010,
526 and (c) the frequency distribution of the calculated trends in the number of stratified days per
527 year (as shown in panel a). A linear fit to the average anomalies is also shown in panel b.
528 Statistically significant ($p < 0.05$) trends are shown with circles and non-significant trends (p
529 > 0.05) are shown with squares.

530

531 **Figure 4.** The influence of atmospheric stilling on the thermal response of lakes to climate
532 change. Shown are the contributions (demonstrated via the rate of change) of atmospheric
533 stilling to long-term changes in (a) lake surface temperature, (b) lake bottom temperature, (c)
534 thermal stability, and (d) the duration of thermal stratification. Also shown are (e) changes in
535 the Northern Hemisphere average anomalies (relative to 1981-2010) of the lake thermal
536 metrics as a result of atmospheric stilling. A linear fit to the data is also shown. The influence
537 of atmospheric stilling on each thermal metric was evaluated by calculating the trend in the
538 time series of 'stilling' minus 'no-stilling' model outputs (see Methods). Statistically
539 significant trends are shown with circles and non-significant trends are shown with squares.

Figure 1.

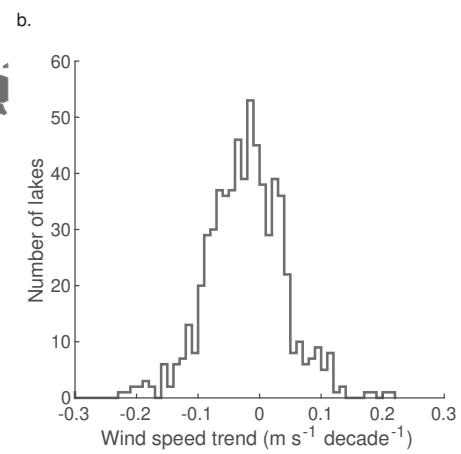
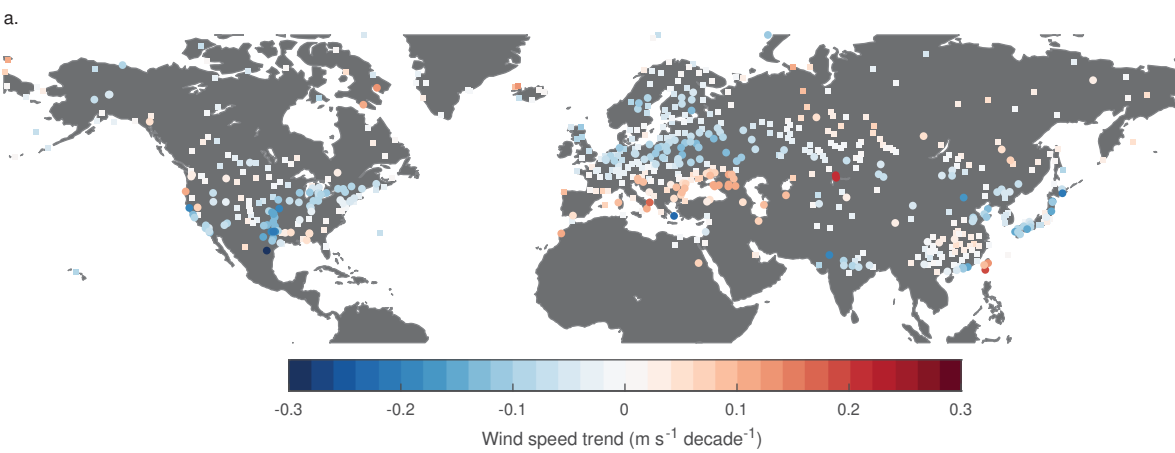
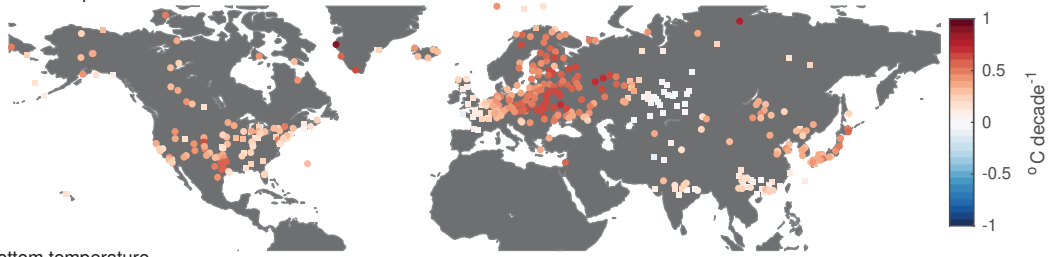
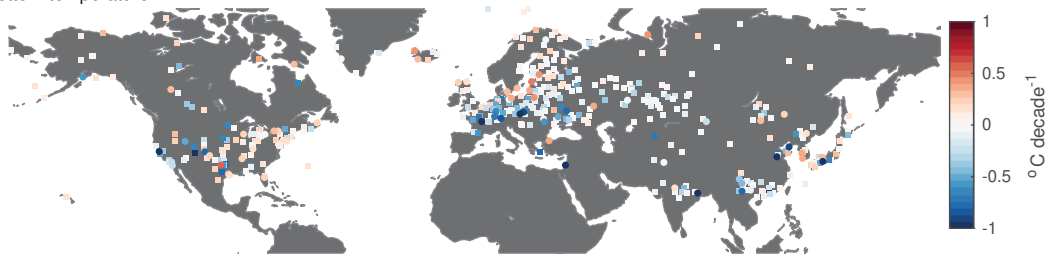


Figure 2.

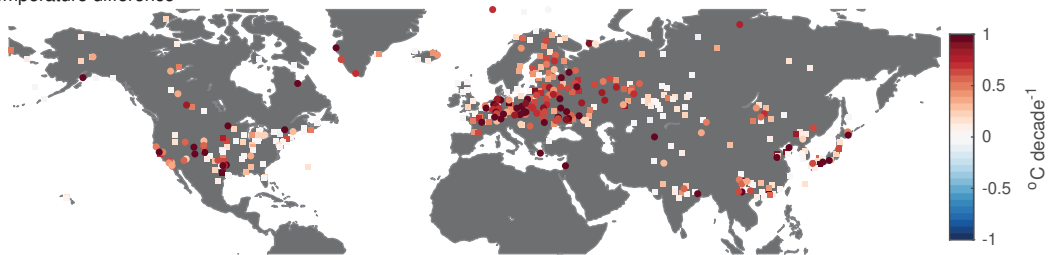
a. Surface temperature



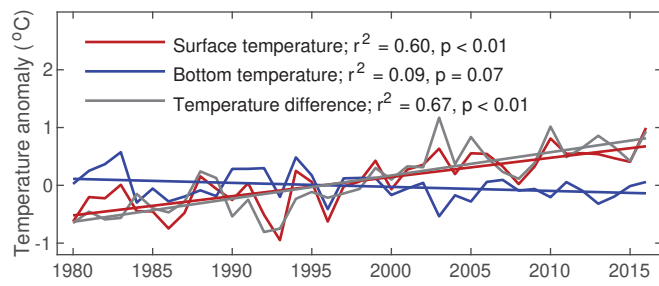
b. Bottom temperature



c. Temperature difference



d.



e.

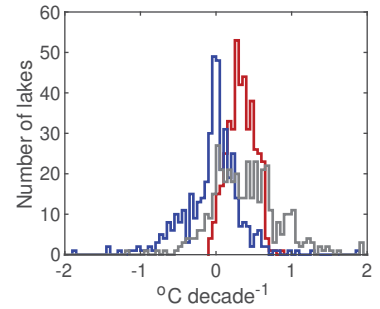


Figure 3.

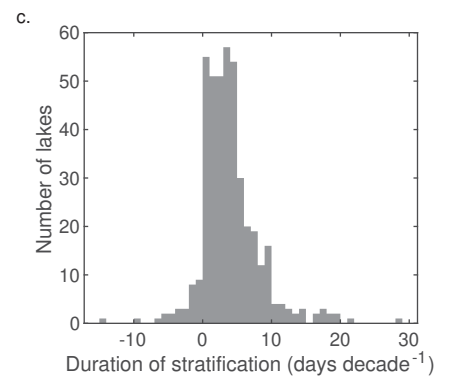
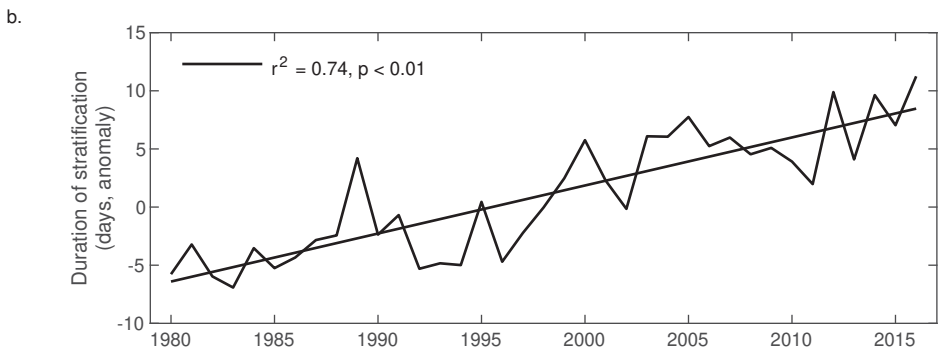
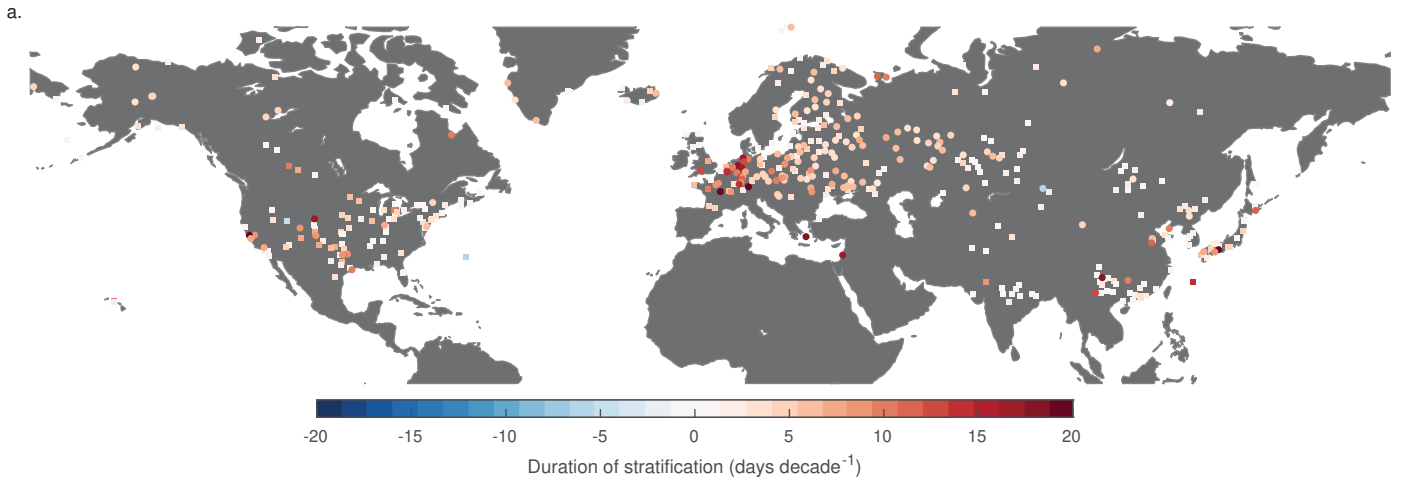
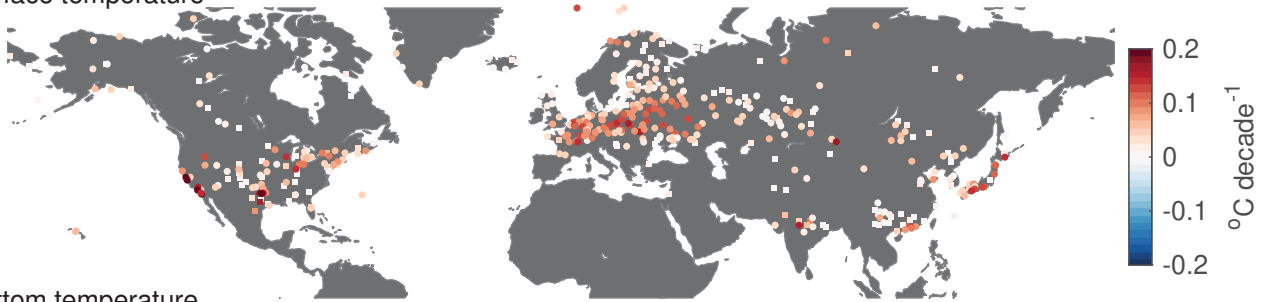
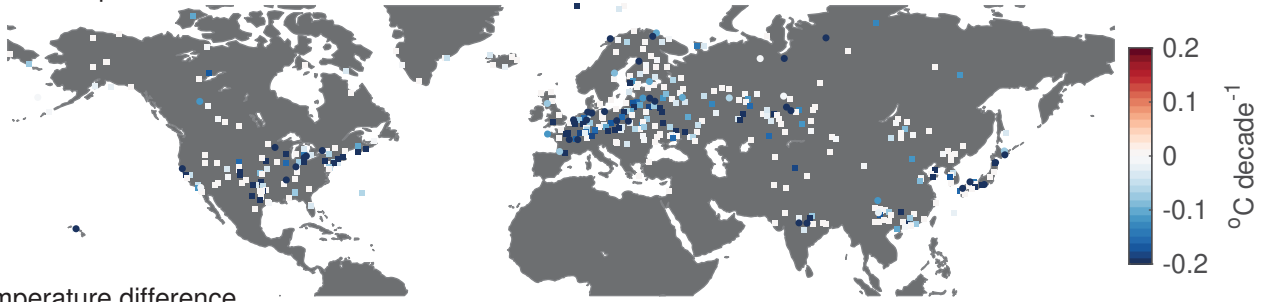


Figure 4.

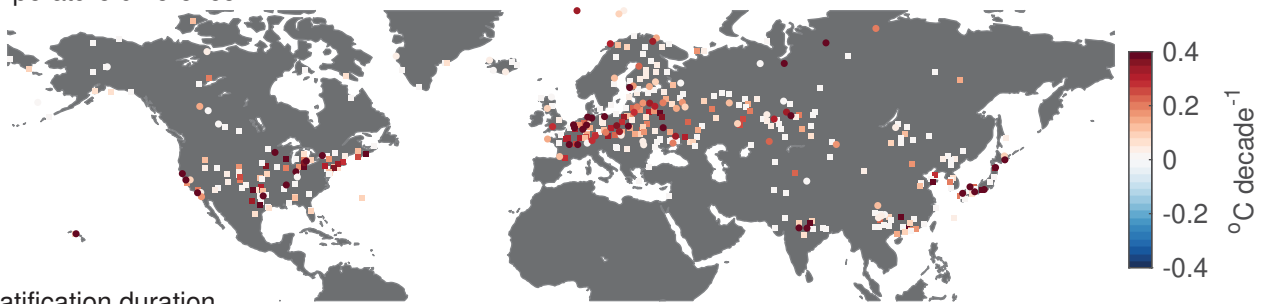
a. Surface temperature



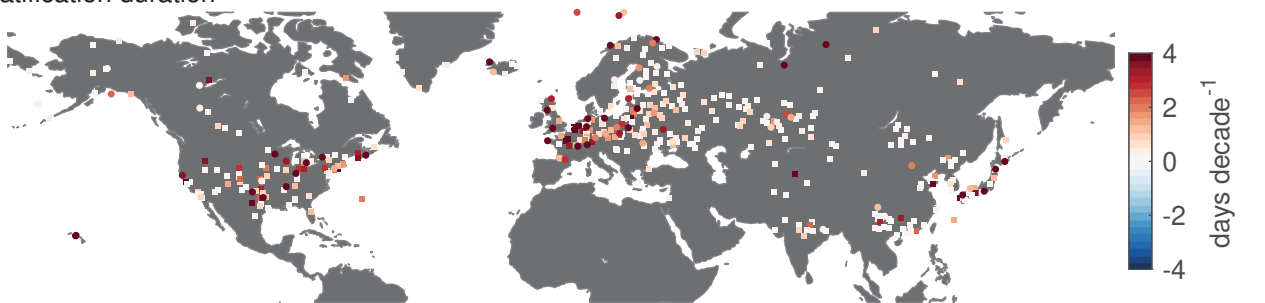
b. Bottom temperature



c. Temperature difference



d. Stratification duration



e.

