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

Article

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1 **Title**
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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*
92   *al.*, 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**

99
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 km^2) [*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*
126 *al*., 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*
133 *al*., 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 0.75º. 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 'stilling' and 'no-stilling' 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 'stilling' minus 'no-stilling' 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 'stilling' minus 'no-stilling' 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) ms^{-1} 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) m s^{-1} 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) °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) °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) °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) °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   °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   °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
263   **4. Discussion**
264   Previous studies have discussed the effects of climatic warming on lake temperature and
265   stratification dynamics [*Kraemer et al.*, 2015; *Woolway et al.*, 2017b]. The focus on air
266   temperature change has drawn attention away from the possible influences of other aspects of
267   climate change, such as atmospheric stilling. A few studies that have investigated the
268   response of lake thermal dynamics to changes in wind speed have demonstrated the important
269   effect of this long-term change on the physical environment of lakes [*Magee et al.*, 2016;
270   *Magee et al.*, 2017; *Woolway et al.*, 2017a; *Deng et al.*, 2018]. However, the majority of these
271   previous studies have focussed on local and/or regional changes and, in particular, the
272   influence of a decrease in wind speed on individual systems. Prior to this investigation, no
273   known previous studies have investigated the influence of atmospheric stilling on
274   temperature and stratification dynamics in lakes situated across the Northern Hemisphere. In
275   this study, we demonstrate that the decrease in wind speed has resulted in less heat being
276   mixed from the lake surface to greater depths and, consequently, resulted in a warming of
277   surface waters and a cooling of bottom water temperature. In turn, the thermal stability and
278   the number of stratified days in the lakes studied has increased, on average, as a result of
279   atmospheric stilling.
280   While atmospheric stilling influenced lake thermal dynamics in many of the studied
281   sites, our investigation demonstrated that shallow lakes and those situated at low-latitude
282   experienced the greatest response. We found mean depth and latitude to be important
283   predictors of the sensitivity of the studied lakes to atmospheric stilling in terms of lake
284   surface temperature. A decline in wind speed can influence lake surface temperature in many
285   ways [*Edinger et al.*, 1968]. The most important is, arguably, through its influence on the
286   mixing depth and, in turn, the volume of water that is influenced directly by atmospheric
287   forcing. A shoaling of the upper mixed layer over time (e.g. due to less wind mixing), can
288   lead to a stronger trend in lake surface temperature than would be expected from changes in
289   air temperature alone. Atmospheric stilling can also influence lake surface temperature via its
290   effect on the turbulent fluxes at the air-water interface, where a decrease in wind speed will
291   result in less latent and sensible heat loss, and thus a warming at the lake surface. This is
292   particularly important for low-latitude lakes. The latent heat flux is a greater contributor of
293   total turbulent heat loss in the tropics, compared to lakes situated in other climate zones as a
294   result of the increase in the air-water humidity difference, to which the latent heat flux is
295   proportional, with decreasing latitude [*Woolway et al.*, 2018a]. Fractional reductions in wind
296   speed as a result of atmospheric stilling can therefore have a greater influence on the surface
297   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*
312   *al*., 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 ms^{-1} $decade^{-1}$) [*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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Acknowledgements

Figures and legends

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

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

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

Figure 4. The influence of atmospheric stilling on the thermal response of lakes to climate change. Shown are the contributions (demonstrated via the rate of change) of atmospheric stilling to long-term changes in (a) lake surface temperature, (b) lake bottom temperature, (c) thermal stability, and (d) the duration of thermal stratification. Also shown are (e) changes in the Northern Hemisphere average anomalies (relative to 1981-2010) of the lake thermal metrics as a result of atmospheric stilling. A linear fit to the data is also shown. The influence of atmospheric stilling on each thermal metric was evaluated by calculating the trend in the time series of 'stilling' minus 'no-stilling' model outputs (see Methods). Statistically significant trends are shown with circles and non-significant trends are shown with squares.
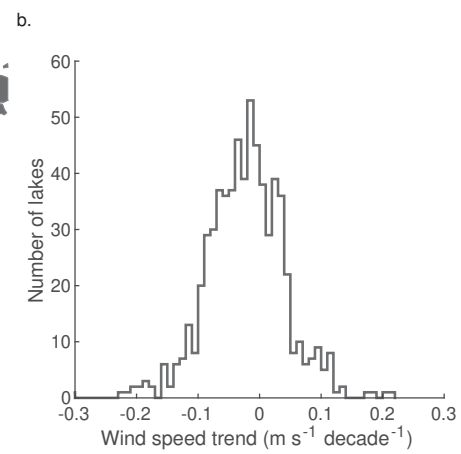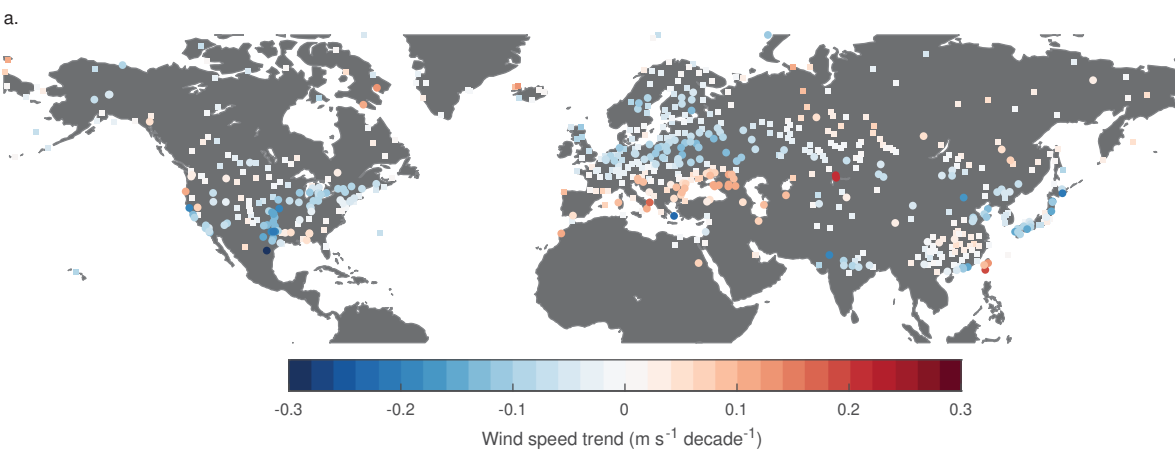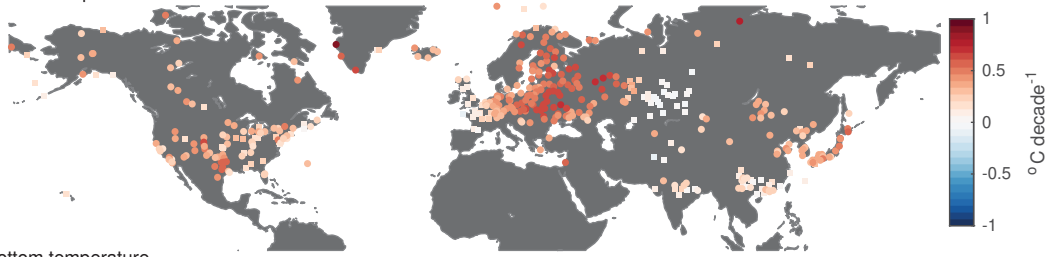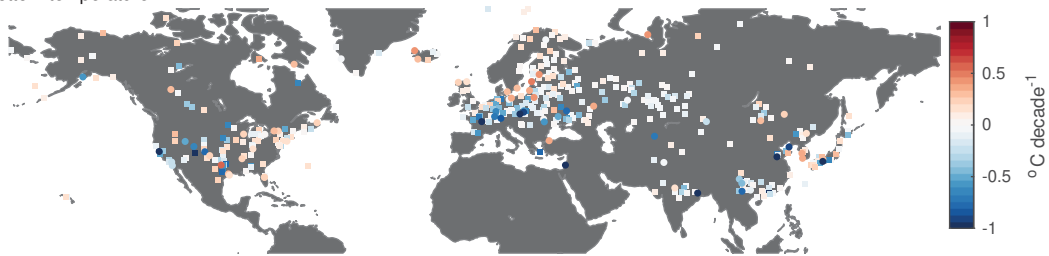
Figure 1.

a.

b.

Figure 2.
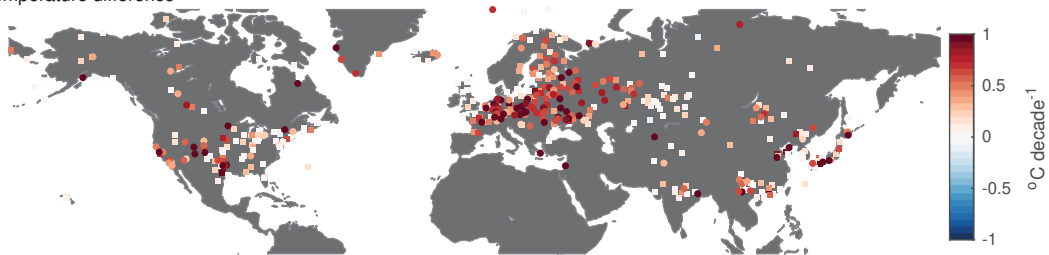
a. Surface temperature

b. Bottom temperature

c. Temperature difference

d.

Surface temperature; $r^2 = 0.60$, $p < 0.01$
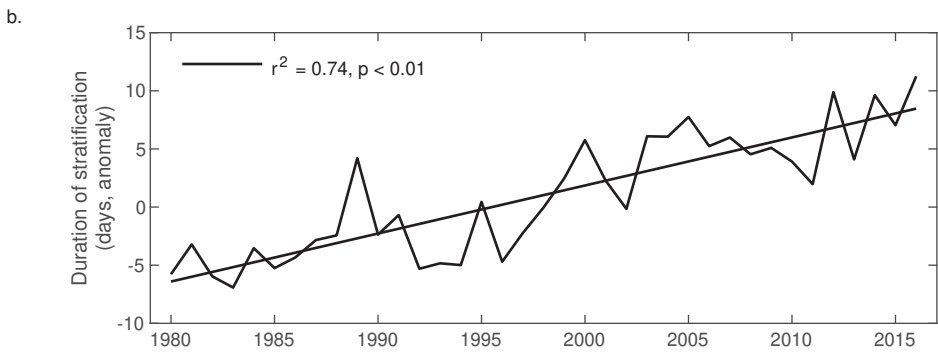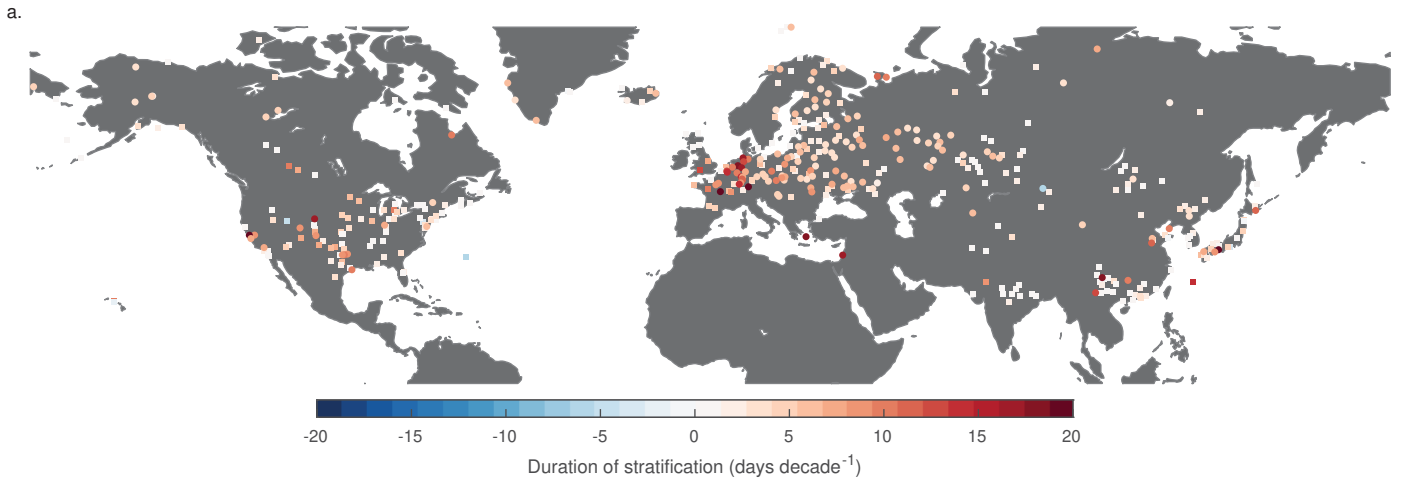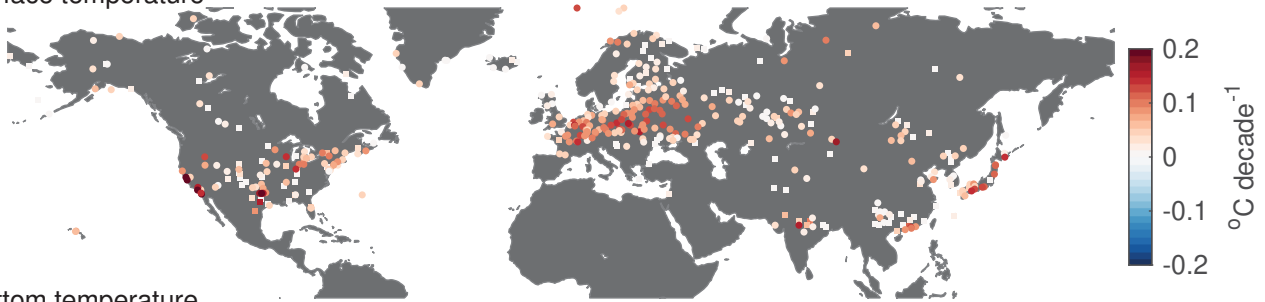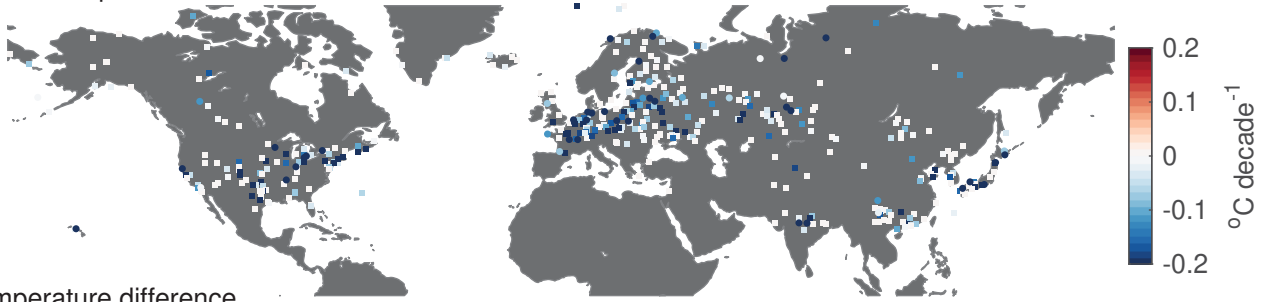Bottom temperature; $r^2 = 0.09$, $p = 0.07$
Temperature difference; $r^2 = 0.67$, $p < 0.01$

Temperature anomaly (°C)

°C decade^{-1}

e.

Number of lakes

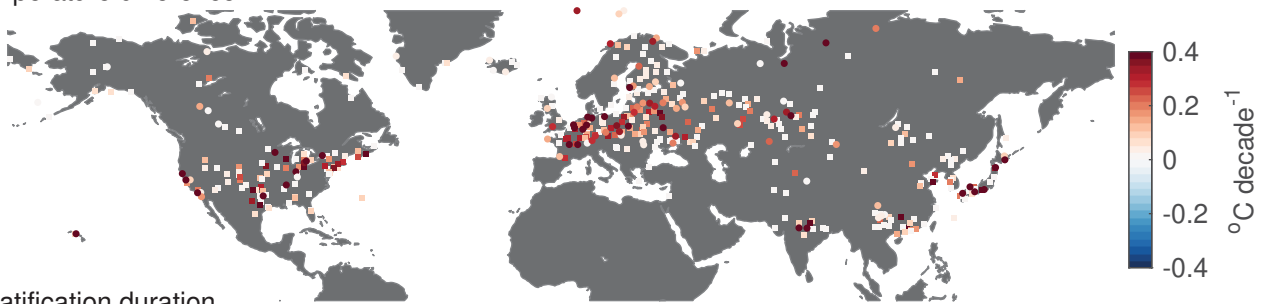°C decade^{-1}

Figure 3.

a.

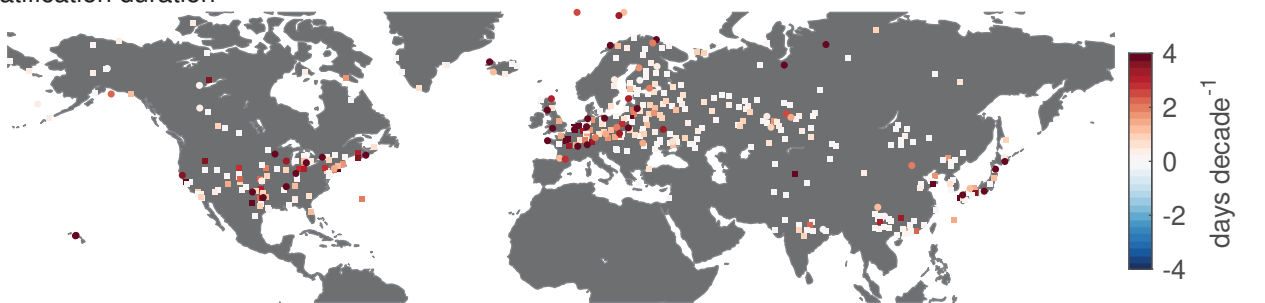b.

c.
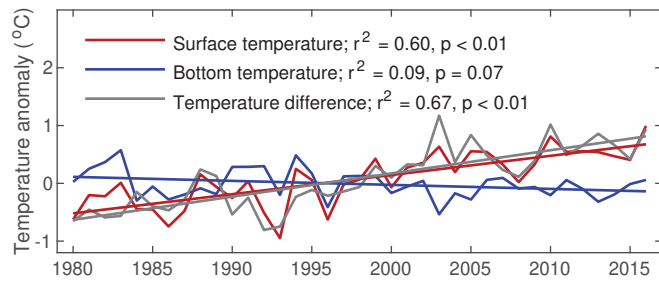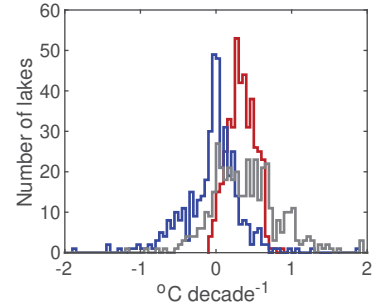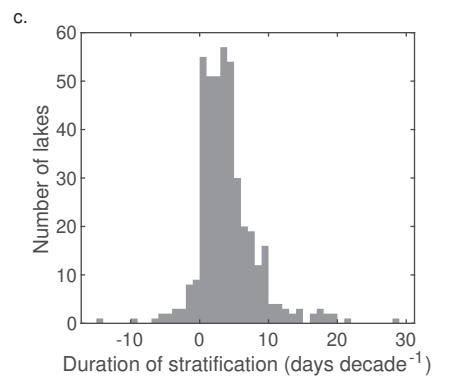
Figure 4.

a. Surface temperature

b. Bottom temperature

c. Temperature difference

d. Stratification duration

e.