

Geophysical Research Letters

RESEARCH LETTER

10.1029/2019GL082752

Key Points:

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

Supporting Information:

- Supporting Information S1

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Citation:



Woolway, R. I., Merchant, C. J., Van Den Hoek, J., Azorin-Molina, C., Nöges, P., Laas, A., et al. (2019). Northern Hemisphere atmospheric stilling accelerates lake thermal responses to a warming world. *Geophysical Research Letters*, 46. <https://doi.org/10.1029/2019GL082752>

Received 9 MAR 2019

Accepted 3 SEP 2019

Accepted article online 12 SEP 2019

Northern Hemisphere Atmospheric Stilling Accelerates Lake Thermal Responses to a Warming World

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

Plain Language Summary Studies of climate change impacts on lakes typically consider projections of air temperature over time. Such studies have demonstrated that a warming world will have numerous repercussions for lake ecosystems. Climate, however, is much more than temperature. In lakes, changes in near-surface wind speed play an important role. Here, using a lake model to simulate the thermal behavior of lakes across the Northern Hemisphere, we show that lake warming has accelerated as a result of atmospheric stilling, the decrease in near-surface wind speed observed in recent decades. Specifically, as a result of atmospheric stilling, lake surface temperatures have increased at a faster rate since 1980. Atmospheric stilling also resulted in a lengthening and strengthening of stratification, which is important for lake ecology and has numerous implications for lake ecosystems. Our results demonstrate that atmospheric stilling has influenced lake thermal responses to climatic warming and that future evolution of wind speed is highly pertinent to assessment of future climate change impacts on lake ecosystems.

1. Introduction

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

Wind speed is one of the most important drivers of physical processes within lakes. Momentum and mechanical energy fluxes across the lake-air interface scale as the wind speed squared and cubed, respectively (Wüest & Lorke, 2003). Modest fractional reductions in wind speed may cause substantial changes in stratification and mixing dynamics. Studies suggest that increasing air and, in turn, lake surface temperature typically, although not always (Tanentzap et al., 2008), leads to a strengthening of stratification, as a result of an increase in the temperature difference between surface and bottom waters. A concurrent decrease in wind

speed over lakes could reduce the magnitude of vertical mixing, leading to less heat being mixed from the surface to greater depths, and subsequently leading to an increase in surface temperature, a decrease in bottom temperature, and a strengthening of stratification. Such a process could accelerate the expected thermal impacts on lakes of climatic warming (Magee & Wu, 2017; Woolway, Meinson, et al., 2017).

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

Despite the potentially large decrease in wind mixing energy as a result of atmospheric stilling, the majority of climate change studies on lakes have ignored this influence, in part owing to an implicit assumption that surface air temperature is the dominant factor impacting lake thermal responses to climate change (O'Reilly et al., 2015; Winslow et al., 2018; Woolway, Dokulil, et al., 2017; Woolway et al., 2019). In this study, we aim to address this research gap by analyzing lake thermal responses to atmospheric stilling. We use a one-dimensional, numerical lake model to study the influence of atmospheric stilling on lake surface and bottom water temperatures, water column stability, and the number of stratified days per year in lakes situated across the Northern Hemisphere.

2. Methods

2.1. Study Sites

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

2.2. Canopy Height Estimation

The mean sheltering height of each lake was computed according to the land cover type within 250 m of a given lake perimeter following Van Den Hoek et al. (2015), where the lake shoreline polygons were extracted from Messenger et al. (2016). Sheltering height was based on global canopy height data collected in 2005 using the Geoscience Laser Altimeter System (GLAS) lidar aboard the National Aeronautics and Space Administration (NASA) ICESat (Friedl & Sulla-Menashe, 2015). Land cover type was based on the 2005 MCD12Q1 V6 Annual IGBP land cover classification product, derived from data collected by the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) satellite (Simard et al., 2011). All data used to measure the mean sheltering height are open-access, and calculations were performed using Google Earth Engine.

2.3. Lake Temperature Model

To simulate lake thermal responses to climate change, we used the one-dimensional Freshwater lake (FLake) model (Mironov, 2008; Mironov et al., 2010). FLake has been tested extensively in past studies. It

has been used for simulating the vertical temperature profile as well as the mixing regime of lakes (Kirillin, 2010; Shatwell et al., 2016; Woolway & Merchant, 2019) and has been shown to reproduce accurately bottom water temperatures as well as temporal changes to the depth of the upper mixed layer and thermocline (Thiery et al., 2014). The meteorological variables required to drive FLake are air temperature at 2 m, wind speed at 10 m, surface solar and thermal radiation, and specific humidity. The forcing data used by FLake were from ERA-Interim (Dee et al., 2011), available at a latitude-longitude resolution of 0.75° . Time series data were extracted for the grid point situated closest to the lake centre (Carrea et al., 2015). A set of lake specific parameters are also needed to drive FLake, including fetch (m), which we fix in this study to the square root of lake surface area; mean depth; lake-ice albedo, which was assumed to be 0.6 (Mironov, 2008); and the light attenuation coefficient (K_d , m^{-1}), which was set to 1 m^{-1} .

2.4. Near-Surface Wind Speed Observations

To ensure that ERA-Interim wind speeds were comparable to those observed in situ, we compared these data with observations from within 10 km of each lake (Figure S3 in the supporting information), available from HadISD (Dunn et al., 2012). In addition to the quality control applied by Dunn et al. (2012), we performed a more robust homogenization method following Azorin-Molina et al. (2018), using the R (R Core Team, 2018) package HOMER (Mestre et al., 2013).

2.5. Lake Thermal Metrics

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

2.6. Lake Model Validation

To validate the simulated lake surface temperatures from FLake, we use lake surface temperatures from the ARC-Lake dataset (MacCallum & Merchant, 2012). Daily lake-mean time-series were obtained from the spatially resolved satellite data by averaging across the lake area. Lake-mean surface temperatures are used, as these have been shown to give a more representative picture of lake temperature responses to climate change compared to single-point measurements (Woolway & Merchant, 2018), and also correspond better to the lake-mean model used. Fourteen lakes simulated in this study were included in the ARC-Lake dataset (Figure S1 and Table S3 in the supporting information). Modeled summer average lake surface temperatures were also compared with in situ summer-average lake surface temperatures ($n = 4$) from Sharma et al. (2015) (Figure S1 and Table S2). To verify that FLake was able to simulate lake stability, we compared these simulations with calculated stability from 22 lakes, in which high-resolution lake temperature observations were available (Figure S2 and Table S4).

2.7. Lake Model Experiments

To investigate the influence of atmospheric stilling on lake thermal dynamics, we performed two model experiments. Firstly, the thermal metrics were calculated from the lake model temperature profiles generated using the atmospheric forcing data over the study period. These model runs were then repeated, but with a detrended near-surface wind speed. Near-surface wind speed was detrended in each site while maintaining the interannual variability by first calculating the rate of change, keeping the wind speed for the first simulation year unchanged, and removing the trend from the following years. We then calculated the difference between the annually (or July–September) averaged “stilling” and “no-stilling” model runs for each thermal metric across the lakes. 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. Trends were calculated using ordinary least squares linear regression models, and the 5 to 95% confidence intervals were also calculated. To determine if any lake specific characteristics influenced the sensitivity of different lake thermal metrics to atmospheric stilling, we used the computed trend from the stilling minus no-stilling time series within a multiple linear regression model. Lake area, depth, altitude, latitude, and the trend in wind speed were used as predictors in the model (Woolway, Verburg, et al., 2017).

3. Results

3.1. Change in Near-Surface Wind Speed

Among the studied lakes, the average rate of change in wind speed was -0.07 (95% CI: -0.07 , -0.06 ; $p < 0.01$) $\text{m} \cdot \text{s}^{-1} \cdot \text{decade}^{-1}$, but with considerable across-lake variability (Figure 1; $n = 650$). Almost two thirds of the sites ($n = 422$) investigated experienced a decrease in wind speed. The average rate of change among these sites was -0.09 (95% CI: -0.09 , -0.08 ; $p < 0.01$) $\text{m} \cdot \text{s}^{-1} \cdot \text{decade}^{-1}$. The largest and most consistent area of atmospheric stilling occurs in central and northern Europe (Figure 1). Sites in north-eastern and south-central United States, India, and some regions of East Asia also experience a substantial decline in near-surface wind speed from 1980 to 2016.

3.2. Lake Thermal Responses to Climate Change

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

3.3. Influence of Atmospheric Stilling on Lake Thermal Dynamics

To investigate only the influence of atmospheric stilling on lake thermal dynamics, we removed the decrease in wind speed and repeated the lake model runs (see section 2). Our results demonstrate that atmospheric stilling accelerated the response of lake surface temperature to climatic warming (Figure 4). The average rate of change in lake surface temperature from the no-stilling model run was 0.28 $^{\circ}\text{C}/\text{decade}$ (95% CI: 0.26 , 0.30 ; $p < 0.01$), 15% lower than the model run where the influence of atmospheric stilling was present. The average rate of change in lake bottom temperature from the no-stilling model run was 0.03 $^{\circ}\text{C}/\text{decade}$ (95% CI: -0.01 , 0.07 ; $p > 0.1$), which was higher than the rate of change calculated when the influence of atmospheric stilling was present. This demonstrates that atmospheric stilling is having a cooling influence on lake bottom temperature. The thermal stability of the lakes is also influenced considerably. When the decline in wind speed was removed from the model input data, the average rate of change in thermal stability was 0.28 $^{\circ}\text{C}/\text{decade}$ (95% CI: 0.24 , 0.32 ; $p < 0.01$), $\sim 27\%$ lower than when the influence of atmospheric stilling was present. Atmospheric stilling also influenced the number of stratified days per year, contributing 23% of the changes observed across the Northern Hemisphere. The number of stratified days in the no-stilling model run changed at an average rate of 3.08 days per decade (95% CI: 2.67 , 3.49 ; $p < 0.01$), which is lower than calculated by the model where the influence of atmospheric stilling was included. Thus, atmospheric stilling resulted in a lengthening of the thermally stratified period. From the stilling minus no-stilling model runs, we calculate that 79%, 52%, 57%, and 61% of the confidence intervals of the calculated trends do not include zero with regard to lake surface temperature, lake bottom temperature, lake thermal stability, and the number of stratified days, respectively.

3.4. Lake Characteristics Influence Their Sensitivity to Atmospheric Stilling

Multiple linear regression models were used to determine how lake location and different lake attributes influence the response of lake thermal dynamics to atmospheric stilling. We find that for both lake surface temperature and the number of stratified days, lake depth, and the trend in near-surface wind speed are statistically significant predictors in the model (Table S5). In addition, our results demonstrate that while many of the lakes studied experienced an increase in surface temperature and the number of stratified days as a result of atmospheric stilling, shallow lakes were most affected. Latitude was also a statistically significant predictor in the model with regard to lake surface temperature, demonstrating that surface temperatures in low-latitude lakes experienced a greater increase as a result of atmospheric stilling (Table S5). None of

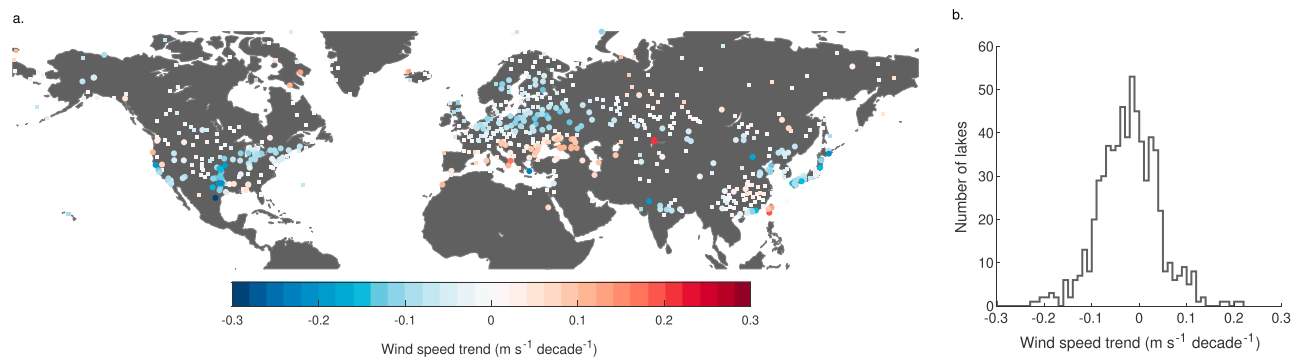


Figure 1. Observed mean wind speed changes across the Northern Hemisphere from 1980 to 2016. Shown are (a) the July–September averaged wind speed trends in locations of the lakes studied ($n = 650$) and (b) the frequency distribution of the calculated trends. Statistically significant ($p < 0.05$) trends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

the predictor variables tested were statistically significant with regard to their influence on the role of atmospheric stilling on lake bottom temperature and thermal stability. The magnitude of atmospheric stilling was the only statistically significant predictor in the model (Table S6). This illustrates that lake bottom temperature and thermal stability of the lakes studied are sensitive to the influence of atmospheric stilling, if a sufficient decline in near-surface wind speed occurs, but none of the tested lake specific characteristics had an influence on this response.

4. Discussion

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

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

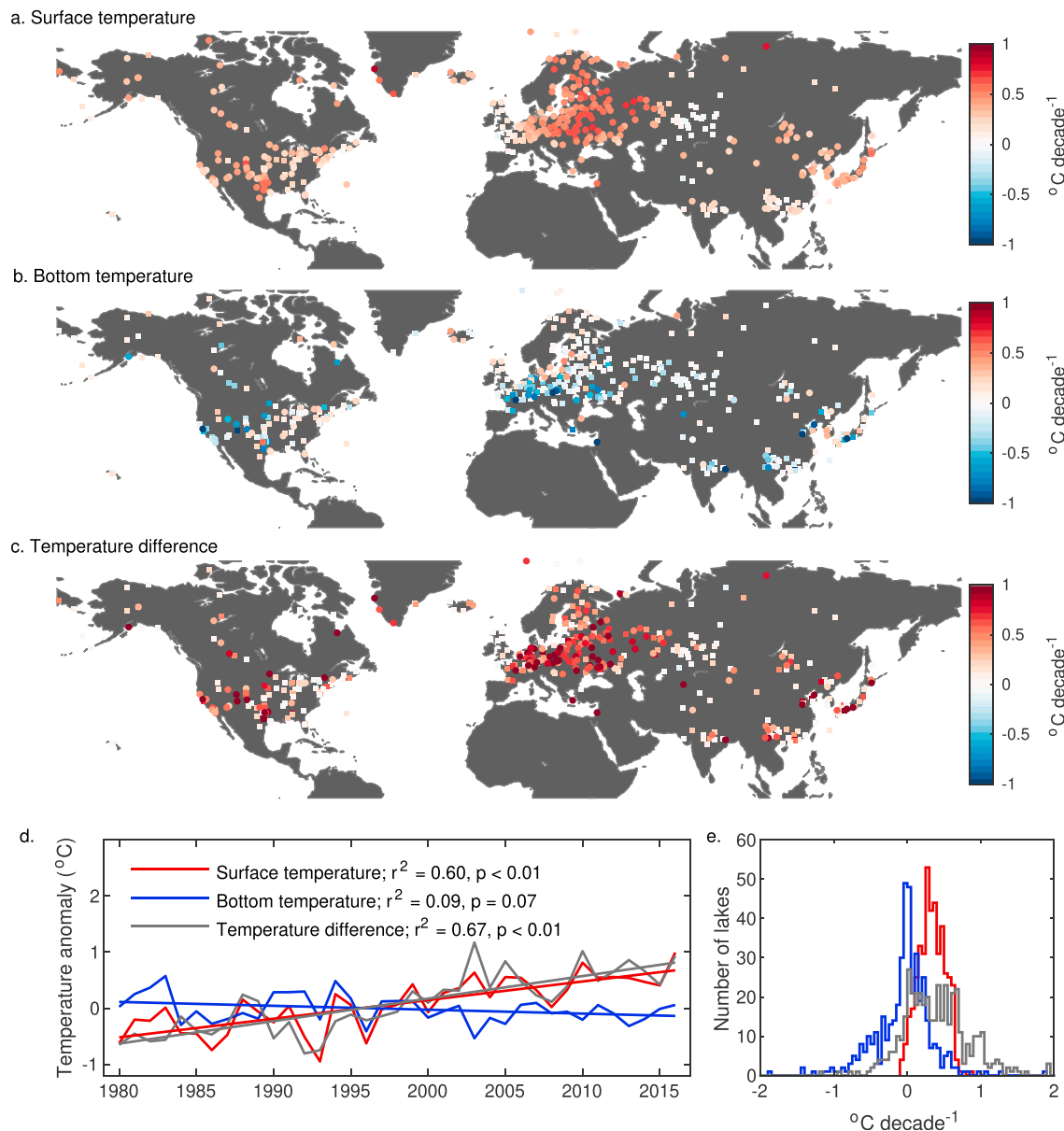


Figure 2. Thermal response of lakes to climate change. Shown are the changes in (a) surface water temperature, (b) bottom water temperature, and (c) thermal stability across Northern Hemisphere lakes from 1980 to 2016 ($n = 422$). Shown also are (d) the Northern Hemisphere average anomalies, relative 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.

Mean depth was also an important predictor of the sensitivity of the studied lakes to atmospheric stilling with regard to the number of stratified days per year. The number of stratified days per year was influenced most by atmospheric stilling in shallow lakes. Unlike deep lakes, which are often either monomictic (experiencing one mixing event in most years) or dimictic (mixing twice per year), thus experiencing prolonged periods of stratification, shallow lakes often mix frequently (i.e., polymictic), stratifying only during periods of calm and/or warm weather. Previous studies have shown that atmospheric stilling can bring shallow lakes toward a tipping point between never stratifying (i.e., continuous polymictic) to experiencing prolonged periods of stratification (i.e., discontinuous polymictic; Woolway, Meinson, et al., 2017). Although mixing regime shifts were not the focus of this study and have been investigated elsewhere (Woolway & Merchant, 2019), we found a prolonging effect of atmospheric stilling on the duration of stratification across Northern

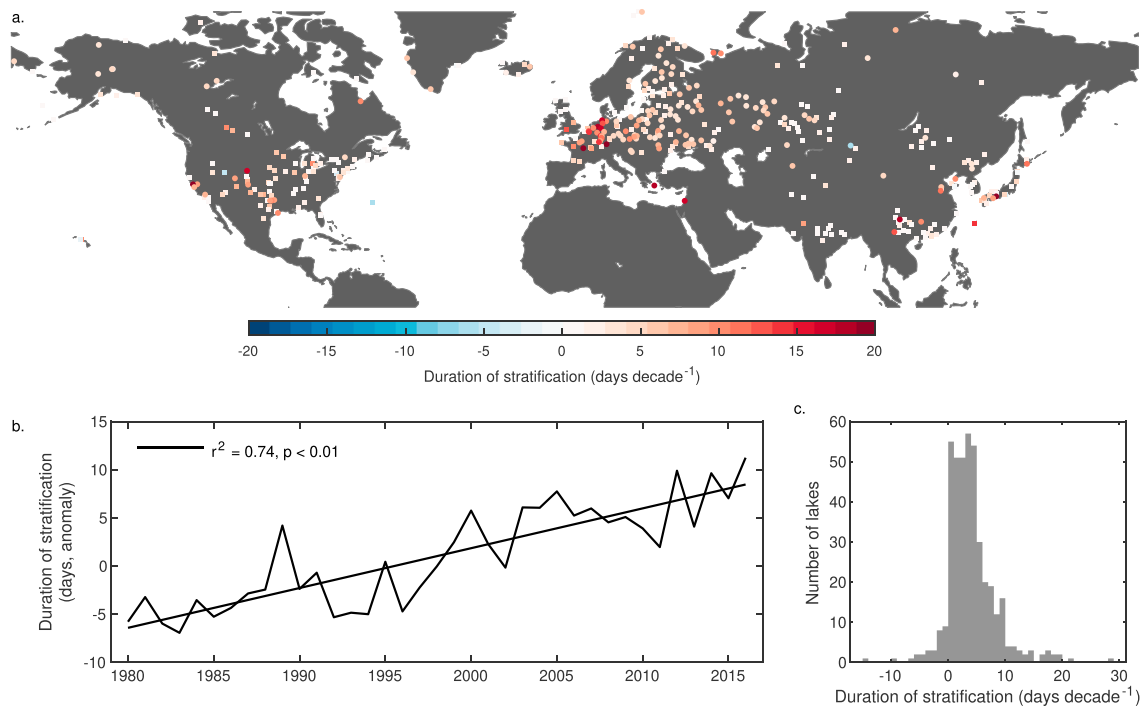


Figure 3. Changes in the number of stratified days per year across Northern Hemisphere lakes from 1980 to 2016 ($n = 422$). Shown are (a) the trends in the duration of thermal stratification per year, (b) the Northern Hemisphere average anomalies relative to 1981–2010, and (c) the frequency distribution 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 nonsignificant trends ($p > 0.05$) are shown with squares.

Hemisphere lakes, which was most apparent in shallow and, thus, more easily stratified systems. The ecological implications of an increase in stratification duration, such as an increase in hypoxia (North et al., 2014) and the occurrence of algal blooms (Paerl & Huisman, 2009), and/or a decrease in lake productivity (O'Reilly et al., 2003; Verburg et al., 2003), will differ between lake mixing types and should be considered when interpreting our results. Specifically, the ecological implications will be different between, for example, a dimictic lake where stratification is lengthening, and a polymictic lake where a mixing regime alteration occurs.

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

Our results demonstrate that atmospheric stilling is an important driver of lake thermal responses to climatic warming. However, the average rate of change in near-surface wind speed among the lakes investigated is considerably less than the worldwide average ($-0.14 \text{ m} \cdot \text{s}^{-1} \cdot \text{decade}^{-1}$; McVicar et al., 2012). Therefore, at a global scale we anticipate the influence of atmospheric stilling on lake thermal dynamics to be even

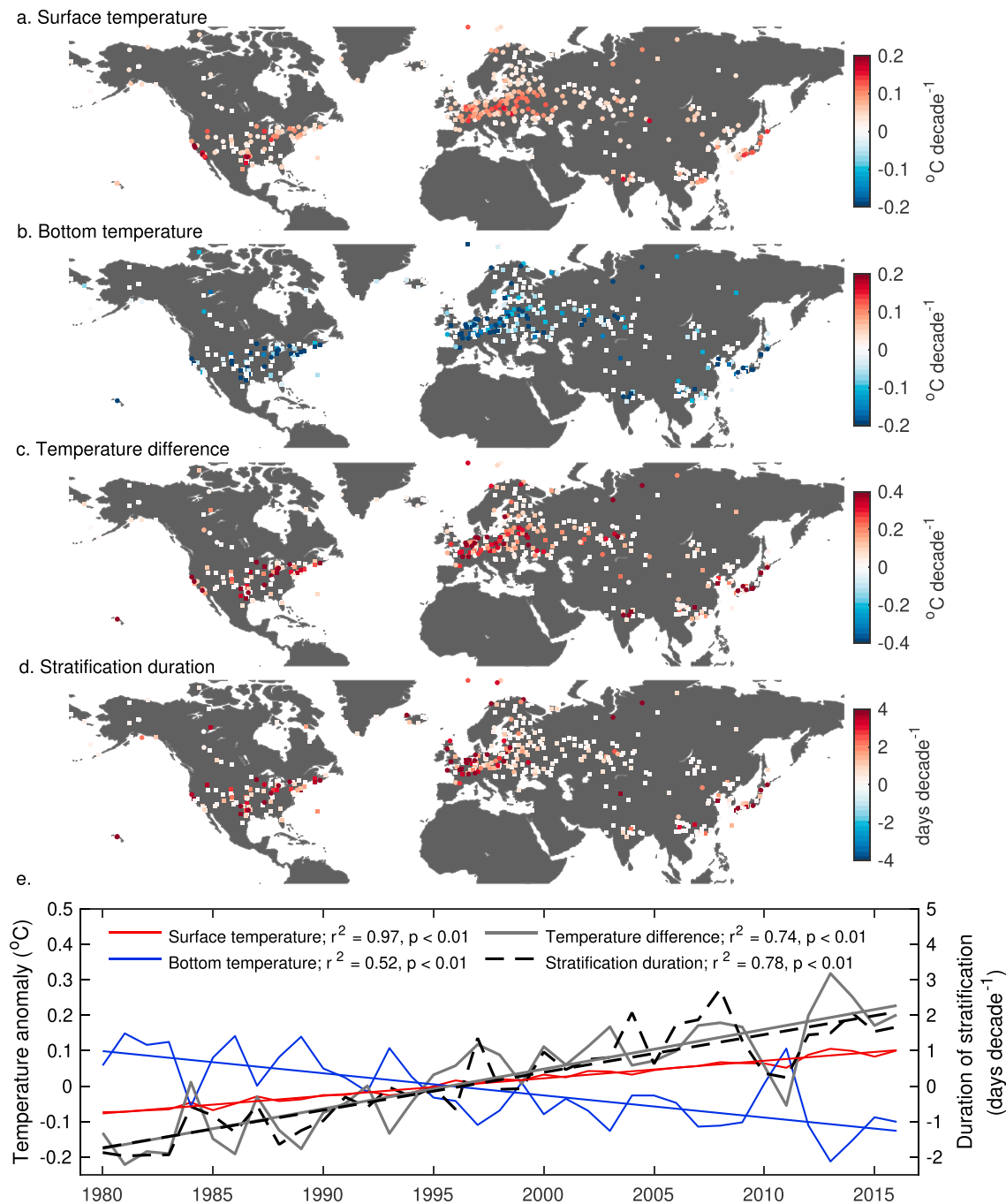


Figure 4. The influence of atmospheric stilling on the thermal response of lakes to climate change. Shown are the contributions (demonstrated via the rate of change) of atmospheric stilling to long-term changes in (a) lake surface temperature, (b) lake bottom temperature, (c) thermal stability, and (d) 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 section 2). Statistically significant trends are shown with circles, and nonsignificant trends are shown with squares.

greater. Future trends in atmospheric stilling are unclear. If wind speeds continue to decrease, then atmospheric stilling will exacerbate the impacts of climate warming on lakes through further increases in lake surface temperature and thermal stability. The repercussions of changes to these important thermal properties of lakes is fundamental as they influence not only physical but also chemical and biological processes. However, it is yet unclear if the atmospheric stilling patterns observed in recent decades will

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 791812. C. A.-M. received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie Grant agreement 703733. The authors acknowledge the European Space Agency funding of the ARC-Lake project. The authors would like to acknowledge the individuals who provided in situ lake data used in this study to validate the model outputs including Kevin Rose and Michael Vanni (Acton Lake), Evelyn Gaiser and Hilary Swain (Lake Annie), Peter Staehr (Castle Lake, Grib Soe, and Hampen Soe), Jake Zwart (Crampton Lake), Don Pierson (Lake Erken), Jim Rusak (Harp Lake), Bruce Hargreaves (Lacawac), and W. Reed Green (Mauumelle). We would also like to thank the North Temperate Lakes Long Term Ecological Research Network (NTL-LTER) who provided data from Crystal Lake, Lake Mendota, Sparkling Lake, South Trout Lake, Trout Bog, and Lake Wingra. This work benefited from participation in GLEON (Global Lake Ecological Observatory Network). Satellite lake temperature data are available at <http://www.laketemp.net>. Observed lake surface temperature data are available at <https://portal.lternet.edu/nis/mapbrowse?packageid=knblter-ntl.10001.3>. The lake model source code is available to download from <http://www.flake.igb-berlin.de/>.

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