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

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Key points

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

Abstract (<150 words)

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 1980-2016, 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^{-1}, 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 behaviour 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 [*Roderick et al*., 2007; *McVicar et al*., 2012]. This slowdown has had impacts across the world, including regions where inland waters are present. Although the exact cause is unknown, some of the hypothesised drivers of atmospheric stilling include a reduction in the equatorial-polar thermal gradient [*McVicar et al*., 2012], changes in mean circulation [*Lu et al*., 2007; *Azorin-Molina* et al., 2014], 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 and 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 [*Woolway et al*., 2017a; *Magee et al*., 2017].

Alterations to temperature and stratification have profound effects on lake ecosystems. Increased surface temperature and more stable and longer stratification can favour bloom-forming cyanobacteria [*Paerl and Huisman*, 2009] and influence lake productivity [*Verburg et al*., 2003; *O'Reilly 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 and McSorley*, 2009], resulting in anoxic conditions and the formation of deep-water dead zones [*North et al*., 2014; *Del Giudice et al*., 2018]. 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; *Woolway et al*., 2017b; *Winslow et al*., 2018]. In this study, we aim to address this research gap by analysing 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 km^2) [*Messager 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 this 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 meters of a given lake perimeter following *Van Den Hoek et al*., [2015], where the lake shoreline polygons were extracted from *Messager et al*., [2016]. Sheltering height was based on global canopy height data collected in 2005 using the GLAS lidar aboard NASA ICESat [*Friedl and 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 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 and 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; *Thiery et al*., 2015]. 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 0.75º. 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 (Fig. S3), 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*., [2018a], 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 and Merchant*, 2017]. The thermal stability of each lake was calculated as the top (defined as 0.1m 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 and 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 and 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 (Fig. S1; Table S3). Modelled summer average lake surface temperatures were also compared with in-situ summer-average lake surface temperatures (n = 4) from *Sharma et al*., [2015] (Fig S1; 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 (Fig. S2; 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 inter-annual 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 et al., 2017c).

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; $p < 0.01$) ms^{-1} $decade^{-1}$, but with considerable across-lake variability (Fig. 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; $p < 0.01$) m s^{-1} $decade^{-1}$. The largest and most consistent area of atmospheric stilling occurs in central and northern Europe (Fig. 1). Sites in north-eastern and south-central USA, India, and some regions of east Asia also experience a substantial decline in near-surface wind speed from 1980-2016.

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 1980-2016. Among these 422 sites, lake surface temperature and thermal stability demonstrate a clear response to climate change (Fig. 2). In terms of lake surface temperature, the average rate of change over all sites was 0.33 (95% CI: 0.16, 0.50; $p < 0.01$) °C $decade^{-1}$. The confidence interval in 74% of lakes did not include zero. The average rate of change in bottom water temperatures was -0.07 (95% CI: -0.11, -0.03; $p = 0.07$) °C $decade^{-1}$. 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 (Fig. 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 (95% CI: 0.34, 0.42; $p < 0.01$) °C $decade^{-1}$. The number of stratified days also increased, at an average rate of 4.13 (95% CI: 3.72, 4.54; $p < 0.01$) days $decade^{-1}$ (Fig. 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 Methods). Our results demonstrate that atmospheric stilling accelerated the response of lake surface temperature to climatic warming (Fig. 4). The average rate of change in lake surface temperature from the 'no-stilling' model run was 0.28 (95% CI: 0.26, 0.30; $p < 0.01$) °C $decade^{-1}$, 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 (95% CI: -0.01, 0.07; $p > 0.1$) °C $decade^{-1}$, 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 (95% CI: 0.24, 0.32; $p < 0.01$) °C $decade^{-1}$, ~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 (95% CI: 2.67, 3.49; $p < 0.01$) days $decade^{-1}$, 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 regards 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 as well as 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 regards 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 the predictor variables tested were statistically significant with regards 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 et al*., 2017b]. 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 [*Magee et al*., 2016; *Magee et al*., 2017; *Woolway et al*., 2017a; *Deng et al*., 2018]. However, the majority of these previous studies have focussed 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 has 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 et al*., 2018a]. 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.

Mean depth was also an important predictor of the sensitivity of the studied lakes to atmospheric stilling with regards 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 towards a tipping point between never stratifying (i.e. continuous polymictic) to experiencing prolonged periods of stratification (i.e. discontinuous polymictic) [*Woolway et al*., 2017a]. Although mixing regime shifts were not the focus of this study, and have been investigated elsewhere [*Woolway and Merchant*, 2019], we found a prolonging effect of atmospheric stilling on the duration of stratification across Northern 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 and 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 and Merchant*, 2018]. While these within-lake spatial variations were not captured in this investigation, and can be extremely important for some large lakes, the modelling 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 ms^{-1} $decade^{-1}$) [*McVicar et al*., 2012]. Therefore, at a global scale we anticipate the influence of atmospheric stilling on lake thermal dynamics to be even 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 continue. Some recent studies have suggested a break in the negative tendency of near-surface wind speeds, with a recovering/strengthening after the year ~2013 [*Azorin-Molina et al*., 2018b]. An increase in near-surface wind speed, which could be expected as a result of the projected increase in the frequency of extreme weather [*Woolway et al*., 2018b], could act to dampen lake thermal responses to climatic warming, even resulting in a decrease in lake surface temperature and thermal stability in lakes if large enough. It is as yet unclear if the physical environment of lakes will return to a 'pre-stilling' state given recent changes. Either way, this study demonstrates that the influence of long-term changes in near-surface wind speed needs to be taken into consideration when assessing climate change impacts on lake ecosystems.

References

Azorin-Molina, C., et al. (2018a), Wind speed variability over the Canary Islands, 1948-2014; focusing on trend differences at the land-ocean interface and below-above the trade-wind inversion layer, *Clim. Dynam*., 50 (11-12), 4061-4081

Azorin-Molina, C., et al. (2018b), State of the Climate in 2017, *Bulletin of the American Meteorological Society*, 99(8), S41-S43

Azorin-Molina, C., et al. (2014), Homogenization and assessment of observed near-surface wind speed trends over Spain and Portugal, 1961-2011, *J. Climate*, 27, 3692-3712

Balsamo, G., R. et al. (2012), On the contribution of lakes in predicting near-surface temperature in a global weather forecasting model, *Tellus Series A-Dynamic Meteorology and Oceanography* 64. doi:10.3402/tellusa.v64i0.15829

Borrel, G., et al. (2011), Production and consumption of methane in freshwater lake ecosystems, *Microbiol*., 162, 832-847

Carrea, L., O. Embury, and C. J. Merchant (2015), Datasets related to in-land water for limnology and remote sensing applications: Distance-to-land, distance-to-water, water-body identifier and lake-centre co-ordinates, *Geosci. Data J*., 2, 83–97

Dee, D. P., et al. (2011), The ERA-Interim reanalysis: configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc*., 137, 553-597

Del Giudice, D., Y. Zhao, E. Sinha, A. M. Michalak (2018), Long-term phosphorus loading and springtime temperatures explain interannual variability of hypoxia in a large temperate lake, Environ. Sci. Technol. Lett., 52(4), 2046-2054

Deng, J., et al. (2018), Climatically-modulated decline in wind speed may strongly affect eutrophication in shallow lakes, *Sci. Tot. Environ*., 645, 1361-1370

Dunn, R. J. H., et al. (2012), HadISD: a quality-controlled global synoptic report database for selected variables at long-term stations from 1973-2011, *Clim. Past,* 8, 1649-1679

Edinger, J. E., D. W. Duttweiler, and J. C. Geyer (1968), Response of water temperatures to meteorological conditions, *Water Resour. Res*., 41137–1143. doi:10.1029/ WR004i005p01137

Friedl, M., and D. Sulla-Menashe (2015), MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC

Kirillin, G. (2010), Modeling the impact of global warming on water temperature and seasonal mixing regimes in small temperate lakes, *Boreal Environ. Res*., 15, 279–293

Kraemer, B. M., et al. (2015), Morphometry and average temperature affect lake stratification responses to climate change, *Geophys. Res. Lett*., 42, 4981-4988

Le Moigne, P., et al. (2016), Impact of lake surface temperatures simulated by the FLake scheme in the CNRM-CM5 climate model, *Tellus A*, 68

Lu, J., G. A. Vecchi, and T. Reichler (2007), Expansion of the Hadley cell under global warming, *Geophys. Res. Lett*., 34, L06805

MacCallum, S. N., and C. J. Merchant (2012), Surface water temperature observations of large lakes by optimal estimation, *Can. J. Remote Sens.,* 38, 25–44, doi:10.5589/m12-010

Magee, M. R., and C. H. Wu (2017), Response of water temperature and stratification to changing climate in three lakes with different morphometry, *Hydrol. Earth Syst. Sci*., 21, 6253-6275

Magee, M. R., et al. (2016), Trends and abrupt changes in 104 years of ice cover and water temperature in a dimictic lake in response to air temperature, wind speed, and water clarity drivers, *Hydrol. Earth Syst. Sci.,* 20, 1681-1702, doi:10.5194/hess-20-1681-2016

Markfort, C. D., et al. (2010), Wind sheltering of a lake by a tree canopy or bluff topography, *Water Resour. Res*., 46, W03530

McVicar, T. R., et al. (2012), Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation, *J. Hydrol*., 416-417,182-205

Messager, M. L., et al. (2016), Estimating the volume and age of water stored in global lakes using a geo-statistical approach, *Nat. Commun.*, 7, 13603, doi:10.1038/ncomms13603

Mestre, O. et al. (2013), HOMER: a homogenization software—methods and applications, *Q. J. Hungarian Meteorol. Serv*., 117, 47−67

Mironov, D. (2008), Parameterization of lakes in numerical weather prediction: Part 1. Description of a lake model. COSMO Technical Report, No. 11, Deutscher Wetterdienst, Offenbach am Main, Germany, pp. 41

Mironov, D., et al. (2010), Implementation of the lake parameterisation scheme FLake into the numerical weather prediction model COSMO, *Boreal Environ. Res*., 15, 218–230

North, R. P., et al. (2014), Long-term changes in hypoxia and soluble reactive phosphorus in the hypolimnion of a large temperate lake: consequences of a climate regime shift, *Glob. Change Biol*., 20, 811-823, doi:10.1111/gcb.12371

O'Reilly, C. M., et al. (2003), Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa, *Nature*, 424, 766-768

O'Reilly, C. M., et al. (2015), Rapid and highly variable warming of lake surface waters around the globe, *Geophys. Res. Lett.,* 42, 10773-10781, doi:10.1002/2015GL066235

Paerl, H. W., and J. Huisman (2009), Climate change: a catalyst for global expansion of harmful cyanobacterial blooms, *Environ. Microbiol. Rep*., 1, 27-37

Pryor, S. C., et al. (2009), Wind speed trends over the contiguous United States, *J. Geophys. Res*., 114, D14105

R Core Team (2018), R: A language and environment for statistical computing, R Foundation for Statistical Computing. Vienna, Austria. (Available at http://www.R-project.org/.)

Read, J. S., et al. (2012), Lake-size dependency of wind shear and convection as controls on gas exchange, *Geophys. Res. Lett*., 39, L09405

Regier, H. A., J. A. Holmes, and D. Pauly (1990), Influence of temperature changes on aquatic ecosystems: an interpretation of empirical data, *Trans. Am. Fish Soc*., 119, 374–389

Rippey, B., and C. McSorley (2009), Oxygen depletion in lake hypolimnia, *Limnol. Oceanogr*., 54, 903-916

Roderick, M. L., et al. (2007), On the attribution of changing pan evaporation, *Geophys. Res. Lett*., 34, L17403

Rosenberry, D. O., et al. (2015), Groundwater – the disregarded component in lake water and nutrient budgets. Part 1: effects of groundwater on hydrology, *Hydrol. Process*., 29, 2895-2921

Sharma, S., et al. (2015), A global database of lake surface temperatures collected by in situ and satellite methods from 1985-2009, *Sci. Data*., 2, 150008, doi:10.1038/sdata.2015.8

Shatwell, T., R. Adrian, and G. Kirillin (2016), Planktonic events may cause polymictic-dimictic regime shifts in temperate lakes, *Sci. Rep*., 6, 24361

Simard, M., et al. (2011), Mapping forest canopy height globally with spaceborne lidar, *J. Geophys. Res. Biogeosci*., 116, G4

Tanentzap, A. J. et al (2008), Cooling lakes while the world warms: Effects of forest regrowth and increased dissolved organic matter on the thermal regime of a temperate, urban lake, *Limnol. Oceanogr*., 53, 404-410

Thiery, W., et al. (2014), Understanding the performance of the FLake model over two African Great Lakes, *Geosci. Model Dev.,* 7, 317-337

Thiery, W., et al. (2015), The impact of the African Great Lakes on the regional climate, *J. Climate*, 28, 4061-4085

Van Den Hoek, J., et al. (2015), Examining the utility of broad-scale satellite-based wind sheltering estimates for lake-level hydrodynamic modelling, *Remote Sens. Environ.*, 156, 551-560

Vautard, R., et al. (2010), Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness, *Nat. Geosci*., 3, 756-761

Verburg, P., R. E. Hecky, and H. Kling (2003), Ecological consequences of a century of warming in Lake Tanganyika, *Science*, 301, 505-507

Vinnå, L. R., et al. (2018), Tributaries affect the thermal response of lakes to climate change, *Hydrol. Earth Syst. Sci*., 22, 31-51

Winslow, L. A., T. H. Leach, and K. C. Rose (2018), Global lake responses to the recent warming hiatus, *Environ. Res. Lett.,* 13, 054005

Woolway, R. I., and C. J. Merchant (2017), Amplified surface temperature response of cold, deep lakes to inter-annual air temperature variability, *Sci. Rep*., 7, 4130, doi:10.1038/s41598-017-04058-0

Woolway, R. I., and C. J. Merchant (2018), Intralake heterogeneity of thermal responses to climate change: A study of large northern hemisphere lakes, *J. Geophys. Res. Atmos.,* 123, 3087-3098

Woolway, R. I., and C. J. Merchant (2019), Worldwide alteration of lake mixing regimes in response to climate change, *Nat. Geosci.,*

Woolway, R. I., et al. (2017a), Atmospheric stilling leads to prolonged thermal stratification in a large shallow polymictic lake, *Clim. Change*, 141, 759-773, doi:10.1007/s10584-017-1909-0

Woolway, R. I., et al. (2017b), Warming of Central European lakes and their response to the 1980s climate regime shift, *Clim. Change*, 142, 505-520, doi:10.1007/s10584-017-1966-4

Woolway, R. I., et al. (2017c), Latitude and lake size are important predictors of over-lake atmospheric stability, *Geophys. Res. Lett.,* 44, 8875-8883

Woolway, R. I., et al. (2018a), Geographic and temporal variations in turbulent heat loss from lakes: A global analysis across 45 lakes, *Limnol. Oceanogr*., 63, 2436-2449. doi:10.1002/lno.10950

Woolway, R. I., et al. (2018b), Physical and chemical impact of a major storm on a temperate lake: a taste of things to come?, *Clim Change*, doi:10.1007/s10584-018-2302-3

Woolway, R. I., et al. (2019), Substantial increase in minimum lake surface temperatures under climate change, *Clim. Change*. doi:10.1007/s10584-019-02465-y

Wüest A., and A. Lorke (2003), Small-scale hydrodynamics in lakes, *Annu. Rev. Fluid Mech.,* 35, 373-412

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Figures and legends

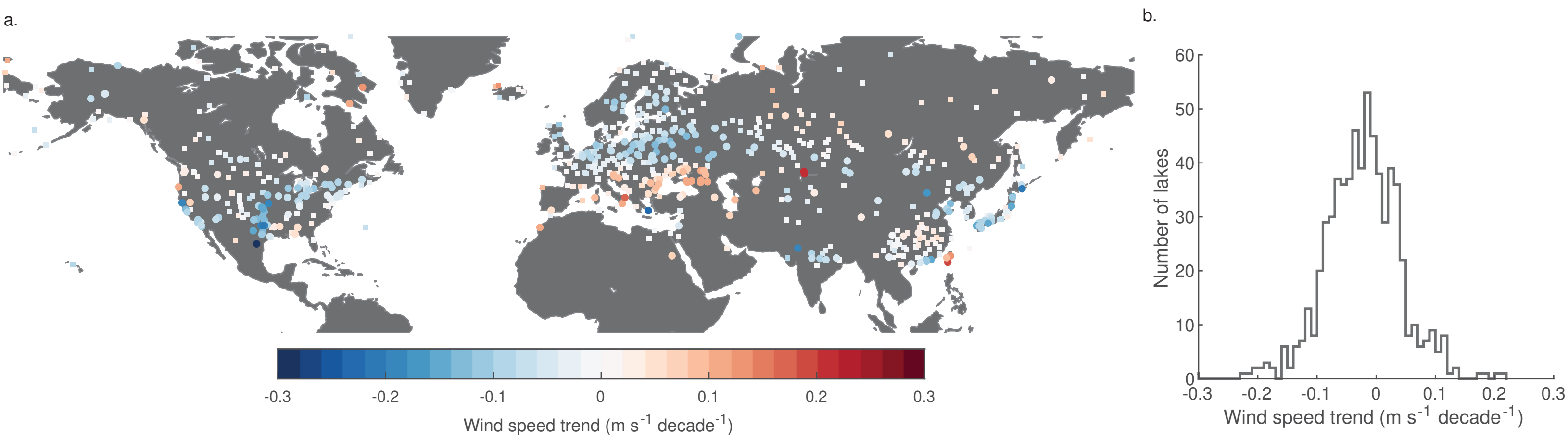
Figure 1. Observed mean wind speed changes across the Northern Hemisphere from 1980-2016. Shown are (a) the July-September averaged wind speed trends in locations of the lakes studied (n = 650), and (b) the frequency distribution of the calculated trends. Statistically significant ($p < 0.05$) trends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

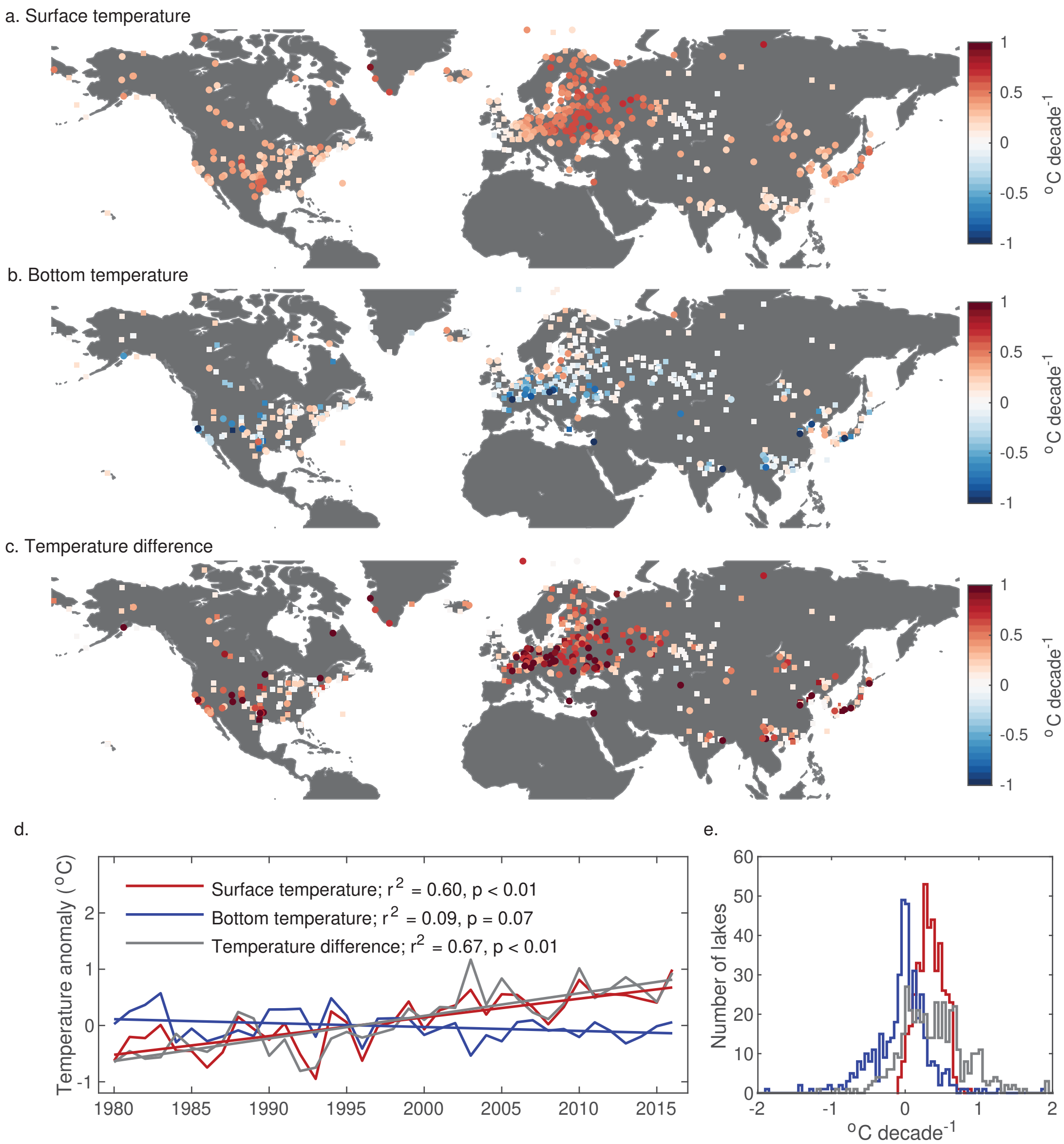
Figure 4. The influence of atmospheric stilling on the thermal response of lakes to climate change. Shown are the contributions (demonstrated via the rate of change) of atmospheric stilling to long-term changes in (a) lake surface temperature, (b) lake bottom temperature, (c) thermal stability, and (d)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



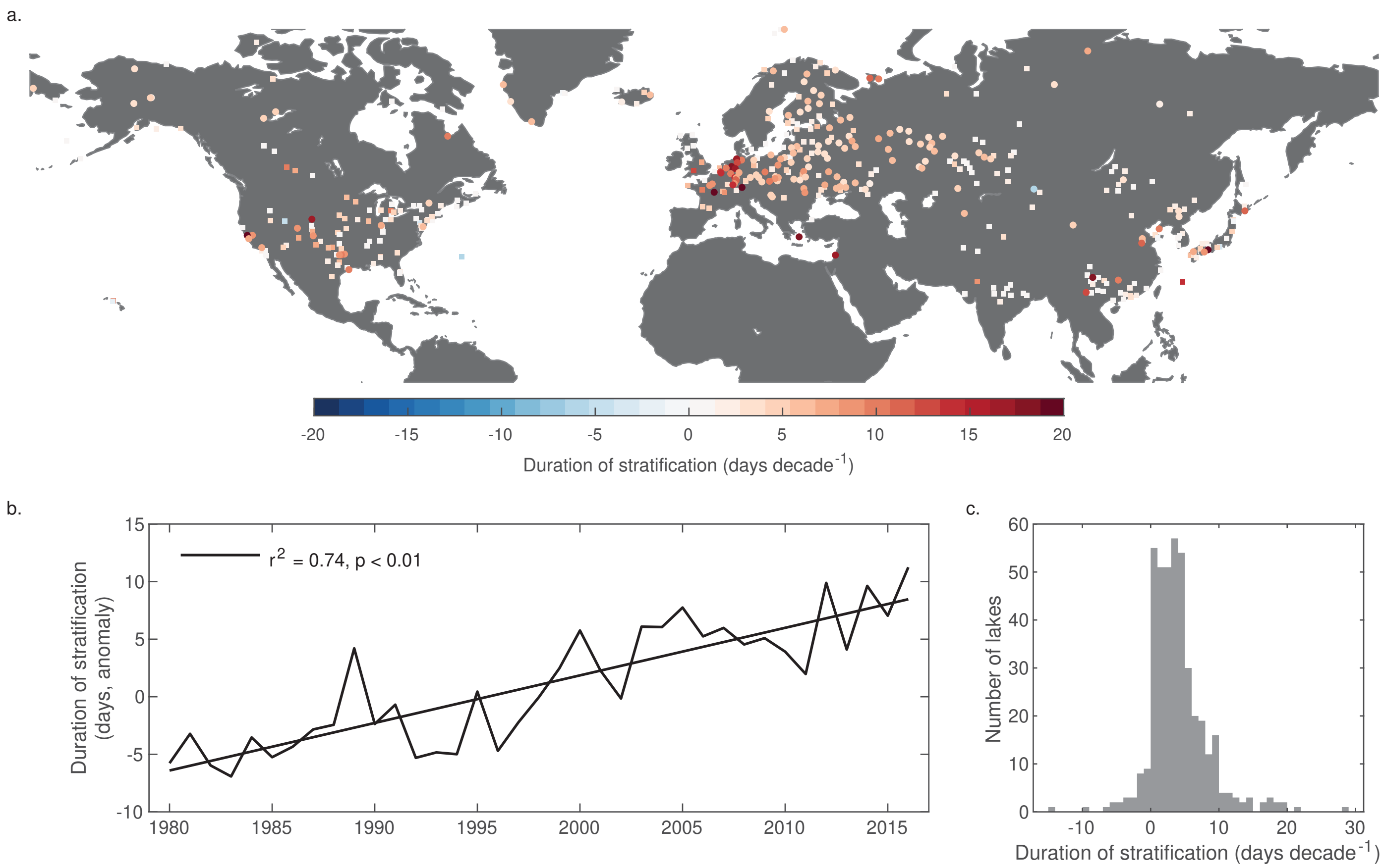
a.
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Wind speed trend (m s-1 decade-1)
b.
60
50
40
30
20
10
0
Number of lakes
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Wind speed trend (m s-1 decade-1)

Figure 2.



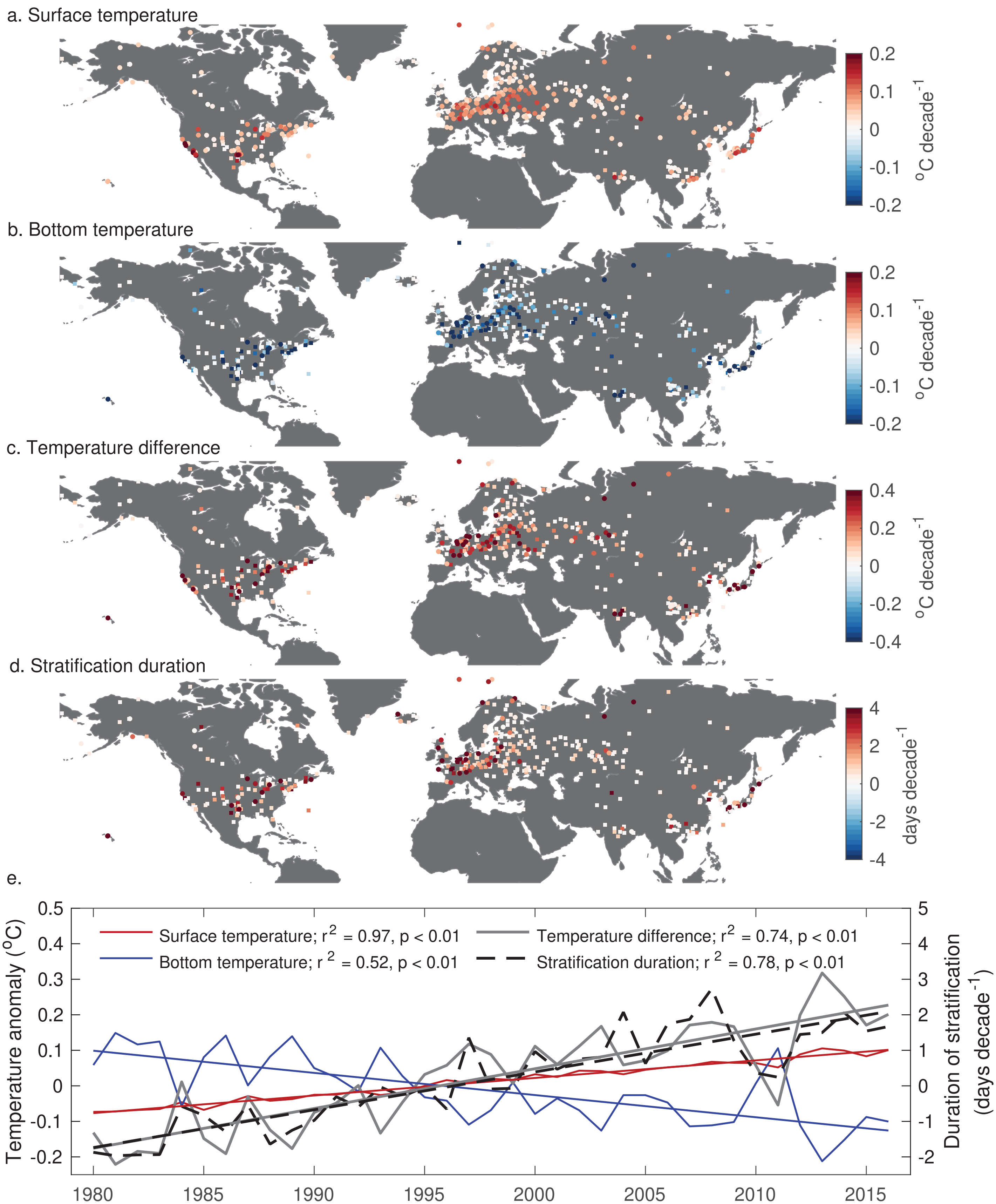
a. Surface temperature
b. Bottom temperature
c. Temperature difference
1
0.5
0
-0.5
-1
°C decade⁻¹
d.
e.
Temperature anomaly (°C)
Surface temperature; r² = 0.60, p < 0.01
Bottom temperature; r² = 0.09, p = 0.07
Temperature difference; r² = 0.67, p < 0.01
1980
1985
1990
1995
2000
2005
2010
2015
Number of lakes
°C decade⁻¹

Figure 3.



a.
-20
-15
-10
-5
0
5
10
15
20
Duration of stratification (days decade^{-1})
b.
r^2 = 0.74, p < 0.01
Duration of stratification (days, anomaly)
15
10
5
0
-5
-10
1980
1985
1990
1995
2000
2005
2010
2015
c.
Number of lakes
60
50
40
30
20
10
0
-10
0
10
20
30
Duration of stratification (days decade^{-1})

Figure 4.



a. Surface temperature
b. Bottom temperature
c. Temperature difference
d. Stratification duration
e.
0.2
0.1
0
-0.1
-0.2
°C decade⁻¹
0.4
0.2
0
-0.2
-0.4
4
2
0
-2
-4
days decade⁻¹
Temperature anomaly (°C)
Duration of stratification (days decade⁻¹)
Surface temperature; r² = 0.97, p < 0.01
Bottom temperature; r² = 0.52, p < 0.01
Temperature difference; r² = 0.74, p < 0.01
Stratification duration; r² = 0.78, p < 0.01
1980
1985
1990
1995
2000
2005
2010
2015