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Title

Impact of the 2018 European heatwave on lake surface water temperature

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Abstract

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

Keywords

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

1. Introduction

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

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

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

In this contribution, we investigate the influence of the 2018 European heatwave on lake surface temperature across the continent. We hypothesised that the increase in air temperature at this time would have resulted in a continental-scale increase in lake surface temperature. We also hypothesised that lake surface temperatures during the 2018 European heatwave were higher than expected as a result of the decrease in near-surface wind speed and the increase in solar radiation, potentially leading to optimum atmospheric conditions for extraordinary lake surface warming in some regions. To place this event in the context of projected future changes, a numerical lake model driven by climate projections was used to compare lake surface temperatures during the 2018 heatwave to those predicted by the end of the 21st century.

2. Methods

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

2.2. Lake temperature model – To simulate the surface water temperature of each studied lake, we used the one-dimensional thermodynamic lake model FLake (Mironov 2008; Mironov et al. 2010). FLake has been tested extensively in previous studies, including detailed validations across a spectrum of lake contexts (Woolway and Merchant 2019). 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 in the current study were from ERA-Interim (Dee et al. 2011), available at a latitude-longitude resolution of 0.75º from 1979 to 2018. Time series data were extracted for the grid point situated closest to the centre of each lake, defined as the point on the lake most distant from land (Carrea et al. 2015).

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

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

2.4. Lake model experiments - To investigate the influence on lake surface water temperatures of air temperature, wind speed, and solar radiation, each of which experienced anomalous conditions during the 2018 European heatwave, we performed a lake model experiment, similar to that of Zhong et al. (2016). Firstly, we ran FLake with the meteorological data from ERA-Interim and calculated the 2018 May-Oct mean and maximum lake surface temperature in each studied lake. We then performed three additional model runs where, during each simulation, the seasonal cycle of the meteorological variable was maintained at its long-term mean (1981-2010) during 2018. For example, when investigating the sole influence of wind speed on lake surface water temperature in 2018, we compared the first model run with model outputs where the 2018 wind speed was replaced by its long-term mean. Then, by calculating the average difference between the May-Oct mean and maximum lake surface temperatures of these two model outputs, the sole influence of wind speed can be estimated. This was repeated for different meteorological variables (air temperature and solar radiation). The meteorological variable that was considered to have the greatest impact on surface water temperature in a given lake during the 2018 heatwave was selected according to the greatest lake surface temperature difference. We note that replacing a year of driver data with that of the long-term mean will influence the natural variability of the climatic drivers, which will also be different from one driver to another. In addition, momentum and mechanical energy fluxes across the lake-air interface scale as the wind speed squared and cubed, respectively. Thus, small changes in wind speed can have a relatively large influence on lake thermal dynamics (Woolway et al. 2019).

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

3. Results

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

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

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

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

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

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

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

4. Discussion

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

Solar radiation is one of the most important components of the lake surface energy budget, and thus one of the key drivers of lake surface temperature change. Previous studies have shown that solar radiation can contribute substantially to long-term surface water temperature change (Fink et al. 2014; Schmid and Köster 2016) and can contribute to average lake surface temperature being higher than over-lake air temperature (Woolway et al. 2017b). Near-surface wind speed is also an important driver of lake thermal dynamics. A decline in wind speed can influence lake surface temperature in many ways. 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 due to reduced wind mixing can lead to warmer surface waters. That is, lake surface temperatures increase more rapidly when the volume of water that participates directly in the air-water surface heat exchange is smaller, as is common in shallow lakes (Toffolon et al. 2014). A decline in wind speed over lakes can also result in less heat being mixed from the lake surface to greater depths, and subsequently lead to an increase in surface temperature and thermal stability (Magee et al. 2016; Woolway et al. 2017a; Mi et al. 2018; Woolway et al. 2019). In addition to the well-documented increase in air temperature during May-Oct in 2018, changes in solar radiation and wind speed resulted in optimum conditions for extraordinary lake warming, where the mean and maximum May-Oct temperatures were, on average, 1.5°C and 2.4°C warmer than the base-period. We demonstrated that by the end of the 21st century, May-Oct mean and maximum lake surface temperatures will increase considerably in Europe, and that the lake temperatures observed during May-Oct 2018 will become increasingly common.

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

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

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

References

Adrian R, O'Reilly CM, Zagarese H, et al. 2009. Lakes as sentinels of climate change. Limnol Oceanogr. 54(6):2283–2297

Audet J, Neif ÉM, Cao Y, et al. 2017. Heat-wave effects on greenhouse gas emissions from shallow lake mesocosms. Freshwater Biol. 62:1130-1142

Balsamo G, Salgado R, Boussetta S, 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

Bartosiewicz M, Laurion I, Clayer F, Maranger R. 2016. Heat-wave effects on oxygen, nutrients, and phytoplankton can alter global warming potential of gases emitted from a small shallow lake. Environmental Science & Technology. 50:6267‑6275

Beniston M. 2004. The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. Geophys Res Lett. 31

Bruce L, Frassl M, Arhonditsis GB et al. 2018. A multi-lake comparative analysis of the General Lake Model (GLM): Stress-testing across a global observatory network. Environ Modell Softw. 102:274-291

Carrea L, Embury O, Merchant CJ. 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

Carrea L, Merchant CJ. 2019. GloboLakes: Lake Surface Water Temperature (LSWT) v4.0 (1995-2016). Centre for Environmental Data Analysis, 29 March 2019. doi:10.5285/76a29c5b55204b66a40308fc2ba9cdb3

Christidis N, Jones GS, Stott PA. 2015. Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. Nat Clim Change. 5:46–50

Comte L, Olden JD. 2017. Climatic vulnerability of the world's freshwater and marine fishes. Nat Clim Change. 7:718-722

Dee DP, Uppala SM, Simmons AJ, et al. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q J R Meteorol Soc. 137:553-597

Edinger JE, Duttweiler DW, Geyer JC. 1968. Response of water temperatures to meteorological conditions. Water Resour Res. 4:1137–1143

Fink G, Schmid M, Wahl B, et al. 2014. Heat flux modifications related to climate-induced warming of large European lakes. Water Resour Res. 50:2072-2085.

GISTEMP Team. 2016. GISS Surface Temperature Analysis (GISTEMP). NASA Goddard Institute for Space Studies. Dataset accessed 2019–04-16 at http://data.giss.nasa.gov/gistemp/

Hansen J, Ruedy R, Sato M, Lo K. 2010. Global surface temperature change. Rev Geophys. 48:RG4004

Hulme PE. 2016. Climate change and biological invasions: evidence, expectations, and response options. Biological Rev. 92:1297-1313

IPCC. 2014. Climate change 2014—Impacts, adaptation and vulnerability: Regional aspects. Cambridge and New York, NY: Cambridge University Press.

Jankowski T, Livingstone DM, Bührer H, et al. 2006. Consequence of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: implications for a warmer world. Limnol Oceanogr. 51:815–819

Jöhnk KD, Huisman J, Sharples J, et al. 2008. Summer heatwaves promote blooms of harmful cyanobacteria. Glob Chang Biol. 14:495–512

MacCallum SN, Merchant CJ. 2012. Surface water temperature observations of large lakes by optimal estimation. Can J Remote Sens. 38:25–44

Magee MR, Wu CH, Robertson DM, 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

Mantzouki E, Lürling M, Fastner J, et al. 2018. Temperature effects explain continental scale distribution of cyanobacterial toxins. Toxins 10(156)

Meehl GA, Tebaldi C. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science. 305:994–997

Messager ML, Lehner B, Grill G, Nedeva I, Schmitt O. 2016. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nat Commun. 7:13603

Mi C, Frassl MA, Boehrer B, Rinke K. 2018. Episodic wind events induce persistent shifts in the thermal stratification of a reservoir (Rappbode Reservoir, Germany). Int Rev Hydrobiol. 103:71-82

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

Mironov D, Heise E, Kourzeneva E, et al. 2010. Implementation of the lake parameterisation scheme FLake into the numerical weather prediction model COSMO. Boreal Environ Res. 15:218–230

Le Moigne P, Colin J, Decharme B. 2016. Impact of lake surface temperatures simulated by the FLake scheme in the CNRM-CM5 climate model. Tellus A. 68

Nakamura N, Huang CSY. 2018. Atmospheric blocking as a traffic jam in the jet stream. Science. 361(6397):42-47

Norris RD, Turner SK, Hull PM, Ridgwell A. 2013. Marine ecosystem responses to Cenozoic global change. Science. 341:492-498

O'Reilly C, Sharma S, Gray DK, et al. 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophys Res Lett. 42:10773-10781

Paerl HW, Huisman J. 2008. Climate - Blooms like it hot. Science. 320:57-58

Persson I, Jones ID. 2008. The effect of water colour on lake hydrodynamics: A modelling study. Freshwater Biol. 53:2345-2355

Piccolroaz S, Toffolon M, Majone B. 2013. A simple lumped model to convert air temperature into surface water temperature in lakes. Hydrol Earth Syst Sci. 17:3323-3338

Piccolroaz S, Toffolon M, Majone B. 2015. The role of stratification on lakes' thermal response: The case of Lake Superior. Water Resour Res. 51:7878- 7894

Piccolroaz S, Toffolon M, Robinson C, Siviglia A. 2018. Exploring and quantifying river thermal response to heatwaves. Water. 10:1098

Politi E, MacCallum S, Cutler MEJ, et al. 2016. Selection of a network of large lakes and reservoirs suitable for global environmental change analysis using Earth Observation. Int J Rem Sens 37(13):3042-3060

Rahmstorf S, Coumou D. 2011. Increase of extreme events in a warming world. Proc Natl Acad Sci USA. 108:17905–17909

Rasconi S, Winter K, Kainz MJ. 2017. Temperature increase and fluctuation induce phytoplankton biodiversity loss – Evidence from a multi-seasonal mesocosm experiment. Ecology and Evolution. 7:2936-2946

Reynolds CS. 2006. The ecology of phytoplankton. Cambridge University Press, Cambridge

Rinke K, Yeates P, Rothhaupt KO. 2010. A simulation study of the feedback of phytoplankton on thermal structure via light attenuation. Freshwater Biol. 55:1674-1693

Roe GH, Baker MB, Herla F. 2017. Centennial glacier retreat as categorical evidence of regional climate change. Nat Geosci. 10:95-99

Rose KC, Winslow LA, Read JS, Hansen GJA. 2016. Climate-induced warming of lakes can be either amplified or suppressed by trends in water clarity. Limnol Oceanogr Lett. 1:44-53

Russo S, Sillmann J, Fischer EM. 2015. Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ Res Lett. 10:124003

Schmid M, Köster O. 2016. Excess warming of a Central European lake by solar brightening. Water Resour Res. 52:8103-8116

Stefan HG, Fang X, Hondzo M. 1998. Simulating climate change effects on year-round water temperatures in temperate zone lakes. Clim Change. 40:547

Stott PA, Stone DA, Allen MR. 2004. Human contribution to the European heatwave of 2003. Nature. 432:610-613

Thackeray SJ, Henrys PA, Hemming D, et al. 2016. Phenological sensitivity to climate across taxa and trophic levels. Nature. 535:241-245

Toffolon M, Piccolroaz S, Majone B, et al. 2014. Prediction of surface temperature in lakes with different morphology using air temperature. Limnol Oceanogr. 59:2185-2202

Toreti A, Belward A, Perez-Dominguez I, et al. 2019. The exceptional 2018 european water seesaw calls for action on adaptation. Earth's Future. 7(6):652-663

Verpoorter C, Kutser T, Seekell DA, Tranvik LJ. 2014. A global inventory of lakes based on high-resolution satellite imagery. Geophys Res Lett. 41:6396-6402

Vinnå LR, Wüest A, Zappa M, Fink G, Bouffard G. 2018. Tributaries affect the thermal response of lakes to climate change. Hydrol Earth Syst Sci. 22:31-51

Woodward G, Perkins DM, Brown LE. 2010. Climate change and freshwater ecosystems: impacts across multiple levels of organization. Philos Trans Royal Soc B. 365:2093-2106

Woolway RI, Jones ID, Hamilton DP, et al. 2015. Automated calculation of surface energy fluxes with high-frequency lake buoy data. Env Mod Soft. 70:191–198

Woolway RI, Meinson P, Nõges P, Jones ID, Laas A. 2017a. Atmospheric stilling leads to prolonged thermal stratification in a large shallow polymictic lake. Clim Change. 141:759-773

Woolway RI, Verburg P, Merchant CJ, et al. 2017b. Latitude and lake size are important predictors of over-lake atmospheric stability. Geophys Res Lett. 44:8875-8883

Woolway RI, Merchant CJ. 2017. Amplified surface temperature response of cold, deep lakes to inter-annual air temperature variability. Sci Rep. 7:4130

Woolway RI, Merchant CJ. 2018. Intra-lake heterogeneity of thermal responses to climate change: A study of large Northern Hemisphere lakes. J Geophys Res Atmos. 123:3087-3098

Woolway RI, Merchant CJ. 2019. Worldwide alteration of lake mixing regimes in response to climate change. Nat Geosci. 12:271-276

Woolway RI, Merchant CJ, Van Den Hoek J, et al. 2019. Northern Hemisphere atmospheric stilling accelerates lake thermal responses to a warming world. Geophys Res Lett. 46:11983-11992

Zhong Y, Notaro M, Vavrus SJ, Foster MJ. 2016. Recent accelerated warming of the Laurentian Great Lakes: Physical drivers. Limnol Oceanogr 61:1762-1786

Zhong Y, Notaro M, Vavrus S. 2019. Spatially variable warming of the laurentian great lakes: an interaction of bathymetry and climate. Clim Dyn. 52:5833-5848

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Competing interests

The authors declare that there are no competing interests.

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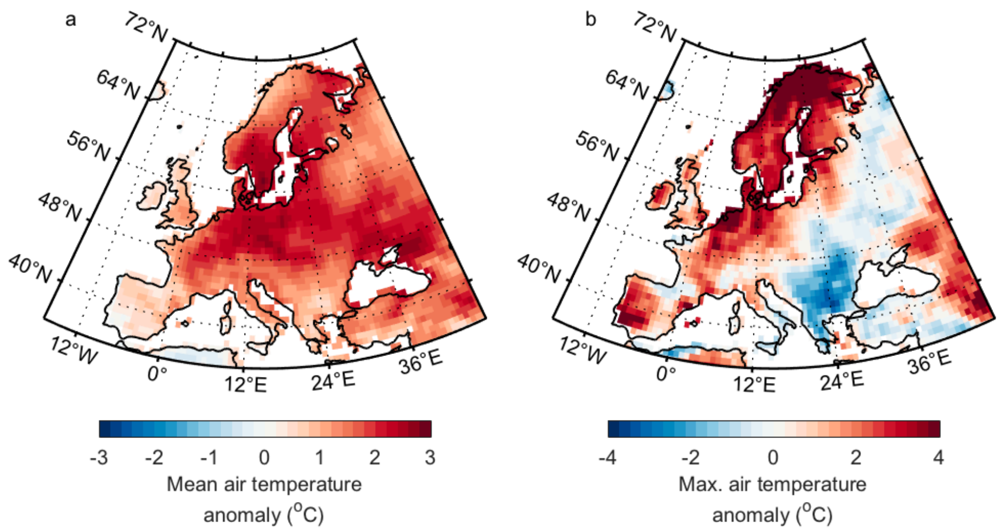
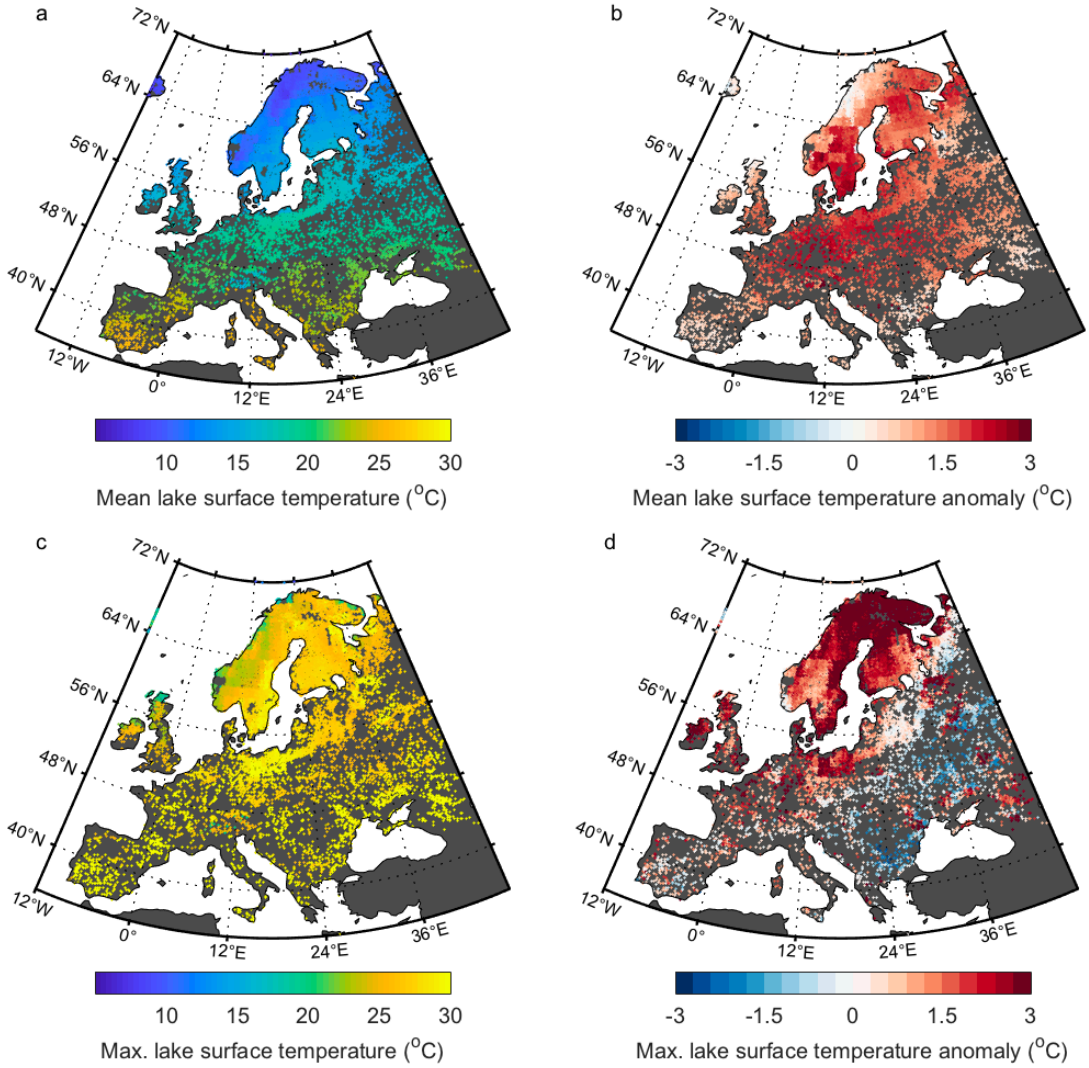


Figure 1. May-Oct 2018 surface air temperature anomalies (relative to the 1981-2010 average) in Europe, showing the (a) mean and (b) maximum temperatures. Air temperature data are from ERA-Interim (Dee et al. 2011).



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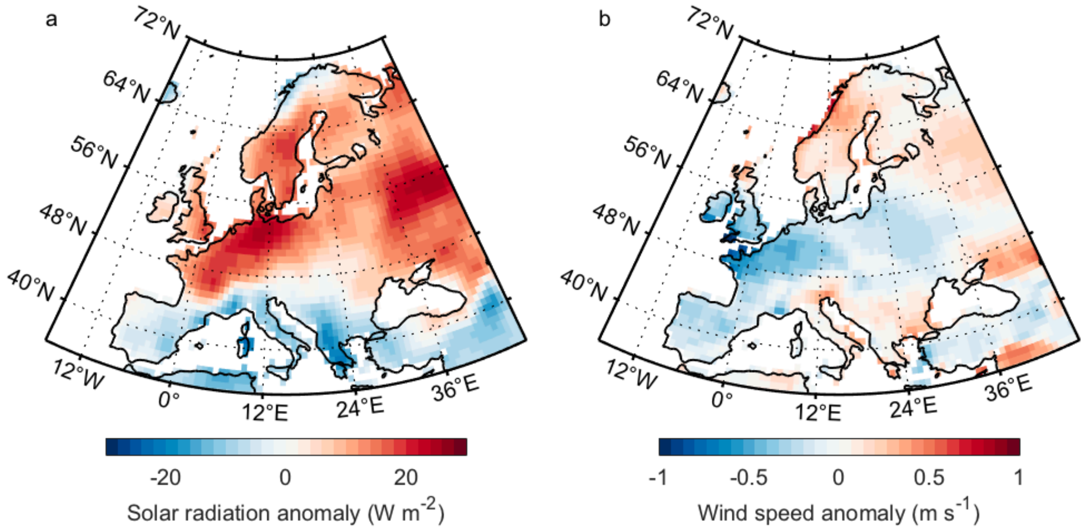

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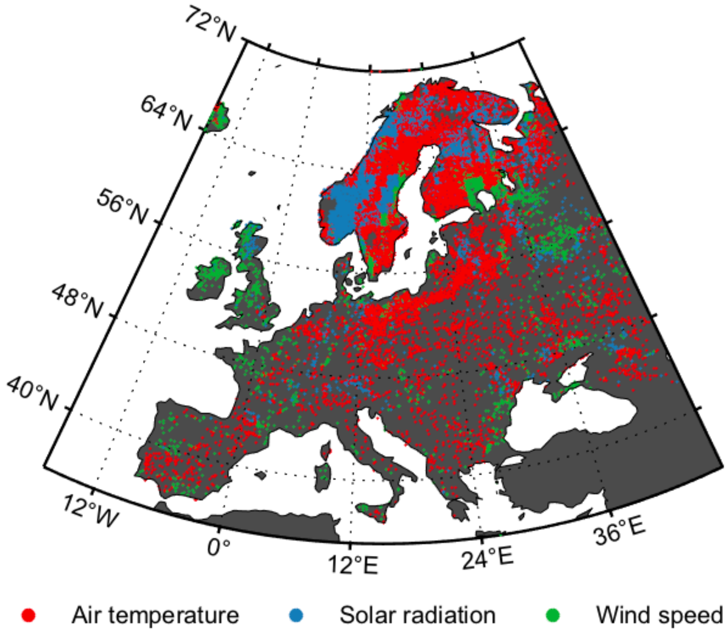

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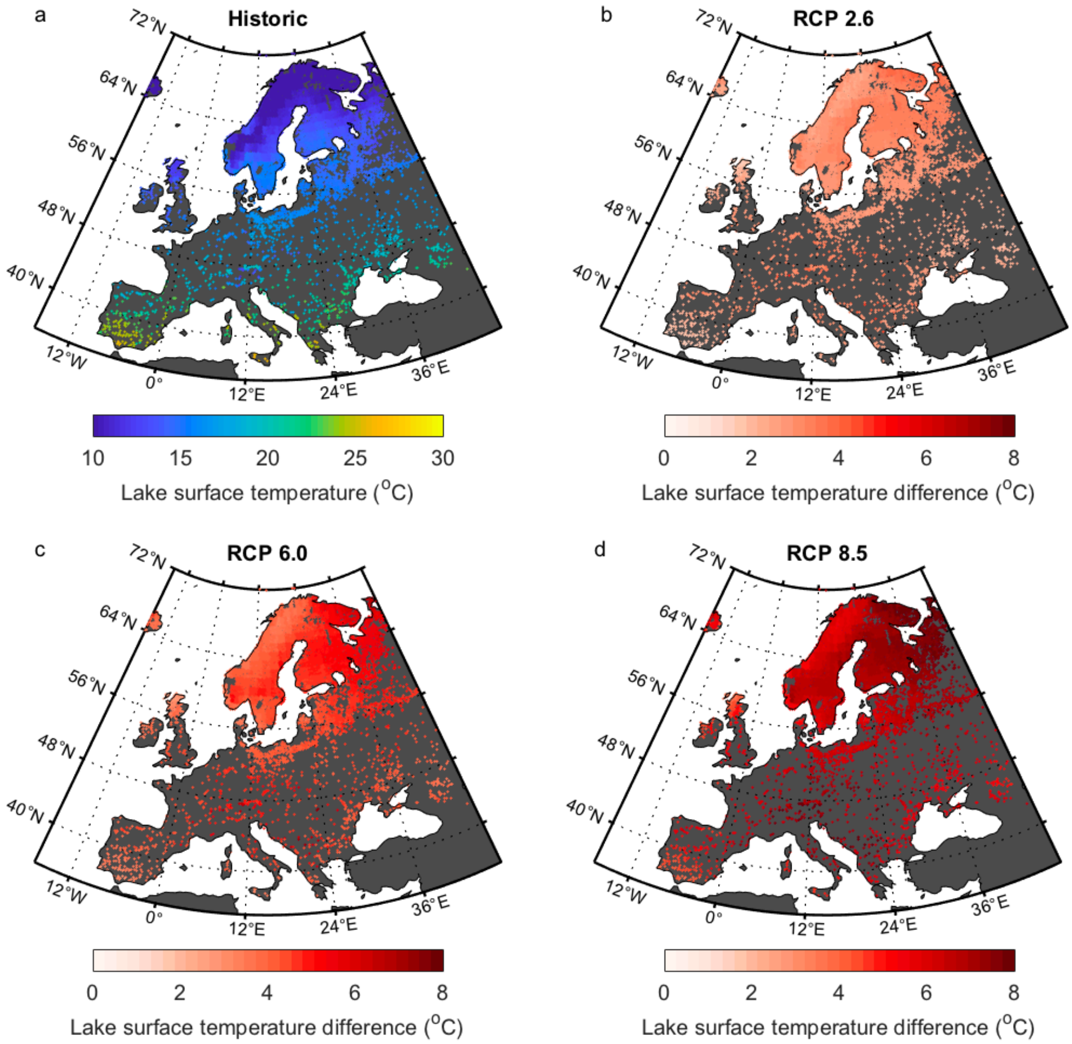

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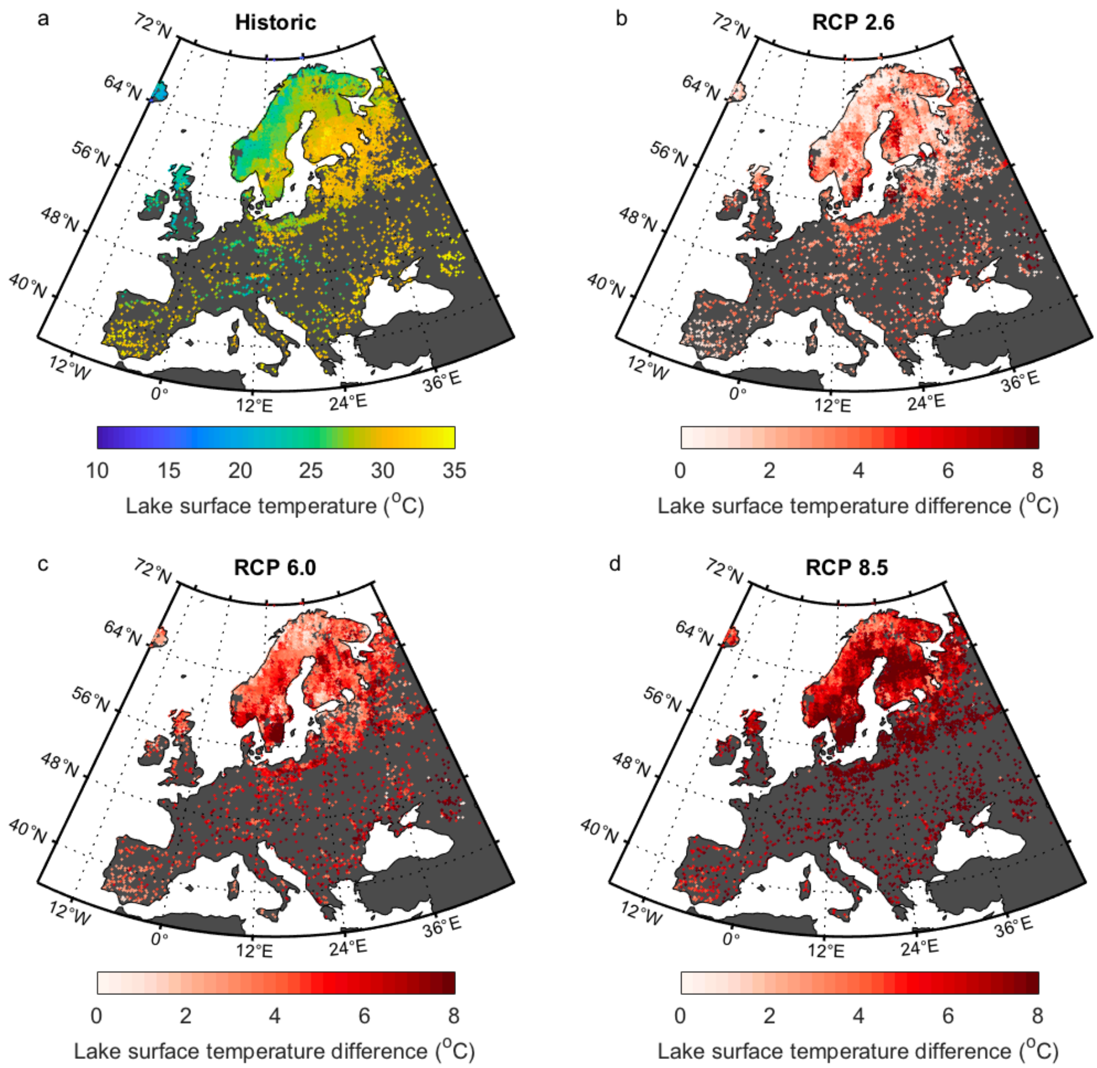

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