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LETTER

Global lake response to the recent warming hiatus

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Abstract

Understanding temporal variability in lake warming rates over decadal scales is important for understanding observed change in aquatic systems. We analyzed a global dataset of lake surface water temperature observations (1985–2009) to examine how lake temperatures responded to a recent global air temperature warming hiatus (1998–2012). Prior to the hiatus (1985–1998), surface water temperatures significantly increased at an average rate of 0.532 °C decade^{-1} (±0.214). In contrast, water temperatures did not change significantly during the hiatus (average rate −0.087 °C decade^{-1} ±0.223). Overall, 83% of lakes in our dataset (129 of 155) had faster warming rates during the pre-hiatus period than during the hiatus period. These results demonstrate that lakes have exhibited decadal-scale variability in warming rates coherent with global air temperatures and represent an independent line of evidence for the recent warming hiatus. Our analyses provide evidence that lakes are sentinels of broader climatological processes and indicate that warming rates based on datasets where a large proportion of observations were collected during the hiatus period may underestimate longer-term trends.

Introduction

Global air temperatures have increased substantially over the last century (Hartmann *et al* 2013). However, during this time, there have been occasional decadal-scale periods of cooling or slower-than-average warming rates (Jones and Moberg 2003, Hartmann *et al* 2013, Dong and McPhaden 2017). The most recent warming anomaly (hereafter, 'hiatus') occurred from 1998–2012, when observed warming rates in air temperature fell below both the long-term average warming rate and warming rates predicted by global climate models (Medhaug *et al* 2017). While it is clear that human influence continues to dominate long-term warming, this hiatus was observed in both air temperature and sea surface temperature, with some debate as to the mechanism and extent of the phenomenon (Hausfather *et al* 2017, Medhaug *et al* 2017). Despite the sensitivity of lakes to climate change, it is unclear how and to what magnitude lakes responded to this hiatus.

It is critical to understand how lake temperatures are changing as temperature is the master-factor regulating many lake ecosystem characteristics and the services they provide. Warming may increase stratification and decrease ice duration on lakes (Magnuson *et al* 2000), exacerbating anoxia (North *et al* 2014), and change lake thermal regimes (Livingstone 2008). Warming also directly influences ecosystem metabolism (Yvon-Durocher *et al* 2010, 2012) and impacts organisms by increasing temperatures beyond thermal tolerances or preferred habitat characteristics (Comte and Grenouillet 2013, Burrows *et al* 2017, Hansen *et al* 2017).

The availability of a large set of globally distributed, long-term air temperature records provides the ability to better assess temporal variability in climate, such as warming anomalies, superimposed on long-term warming trends. However, our understanding of the response of lakes to such climate variability is unknown because globally-distributed, long-term (≥50 years) datasets of water temperature in freshwater ecosystems are comparatively rare. To go beyond lake-specific analyses to regional or global scales, aquatic researchers have often been constrained to examining trends of the two to three most recent decades (e.g. Schneider *et al* 2009, O'Reilly *et al* 2015, Winslow *et al* 2015). Critically, if the recent warming hiatus (1998–2012) reduced lake warming rates globally, then our empirical estimates of lake warming may be strongly influenced by this hiatus period and underestimate the long-term rate of warming in lakes.

Analyses of temperature trends in lakes have primarily focused on examining temperature changes as linear, secular changes with a single value representing the trend (e.g. O'Reilly *et al* 2015, Winslow *et al* 2015). Further, research addressing climate change impacts on lakes has often focused on how individual ecosystem characteristics, such as lake volume, depth, ice cover, or water clarity, introduce variability in thermal responses to climate change (O'Reilly *et al* 2015, Winslow *et al* 2015, Rose *et al* 2016). Recent work in lakes has also highlighted the among-season variability in warming trends (Winslow *et al* 2017, Woolway *et al* 2017). However, there have been few attempts to examine the effects of air temperature on long-term temporal variability in warming rates of lake water temperature.

Temporal variability in long-term warming trends can be substantial in some aquatic ecosystems. In streams, near century-long stream gage observations compiled at some sites have shown that variability in warming rates depends on the time period examined. For example, Arismendi *et al* (2012) and Rice and Jastram (2015) found that statistically significant stream warming trends were most prevalent in the longest records, while fewer sites exhibited warming trends when time series started in the 1980s, suggesting decadal-scale variability. In contrast, a study of long-term temperature data from 20 lakes in Central Europe indicates a substantial increase in warming beginning in the late 1980s (Woolway *et al* 2017). These inconsistent patterns may be due to geographic variation in warming rates, differences in the major mechanisms driving water temperature among lotic and lentic systems, or the sensitivity of different aquatic ecosystems to air temperature warming.

The recent, well-studied air temperature warming hiatus between 1998 and 2012 (e.g. Meehl *et al* 2011, Medhaug *et al* 2017) represents a natural experiment and covers a period of time when abundant lake temperature data are available. To better understand how lakes respond to long-term variability in the air temperature warming rate, we examined long-term temperature records of *in situ* and satellite derived lake surface water temperature and contrasted how trends differed between the pre-hiatus (1985–1998) and hiatus-overlap (1998–2009) periods. Understanding this long-term lake warming variability is important to understanding observed change in aquatic systems and the limits of inferring future long-term trends from current data.

Materials and methods

Data

The primary lake water temperature data used here were collected and organized by the Global Lake Temperature Collaboration (GLTC) and released by (Sharma *et al* 2015). These temperature data are a combination of *in situ* and satellite-derived observations of lake surface temperature that were processed into summer averages (e.g. July, August, September in northern hemisphere temperate lakes). Collection, cleaning, organizing, and processing details are described completely in Sharma *et al* (2015), but are summarized in the supplement (supplemental text 1 available at stacks.iop.org/ERL/13/054005/mmedia). Briefly, near-surface lake water temperatures were collected from a variety of sources to create a global dataset of *in situ* and satellite observed summertime average temperatures from 1985–2009. *In situ* data were preferred when both were available. Satellite temperature was used only for lakes with 10×10 km of open-water. For *in situ* data, only lakes with area greater than 4 ha were included. Observations had a global distribution mimicking the global lake distribution, though *in situ* datasets were more common in North America and Europe (see figure 1 in Sharma *et al* 2015).

To expand our analysis of the hiatus-overlap period to the extent possible, we also analyzed the ATSR Reprocessing for Climate: Lake Surface Water Temperature dataset (ARC-Lake v3.0; MacCallum and Merchant 2012). We did not use ARC-lake for the core analysis as its time span is not sufficient to examine pre-hiatus warming rates (1995–2011; see supplemental text 3 for further discussion).

The warming hiatus is commonly reported as to have occurred over the 1998–2012 period (Hedemann *et al* 2017, Medhaug *et al* 2017). To define the time periods examined in this work, we used the intersection of available lake temperature data and the previously reported temporal extent of the recent warming hiatus. The lake water temperature data are available from 1985–2009, so for the purposes of this analysis the period of 1998–2009 was used to represent the 'hiatus-overlap period' and 1985–1998 represents the 'pre-hiatus' period.

For our primary analysis and visualization of air temperatures, we used the GISTEMP global temperature anomaly database (Hansen *et al* 2010, GISTEMP Team 2017) to calculate global air temperature trends for the pre-hiatus and hiatus-overlap periods. The GISTEMP anomaly data were processed to facilitate direct comparison with processed air and water temperature data included in Sharma *et al* (2015). The data were first subset by latitude to match the definition of summer temperatures used with the lake temperatures (see supplemental text 1). We then subset the data for both pre-hiatus and hiatus-overlap periods to match the lake water temperature time series and

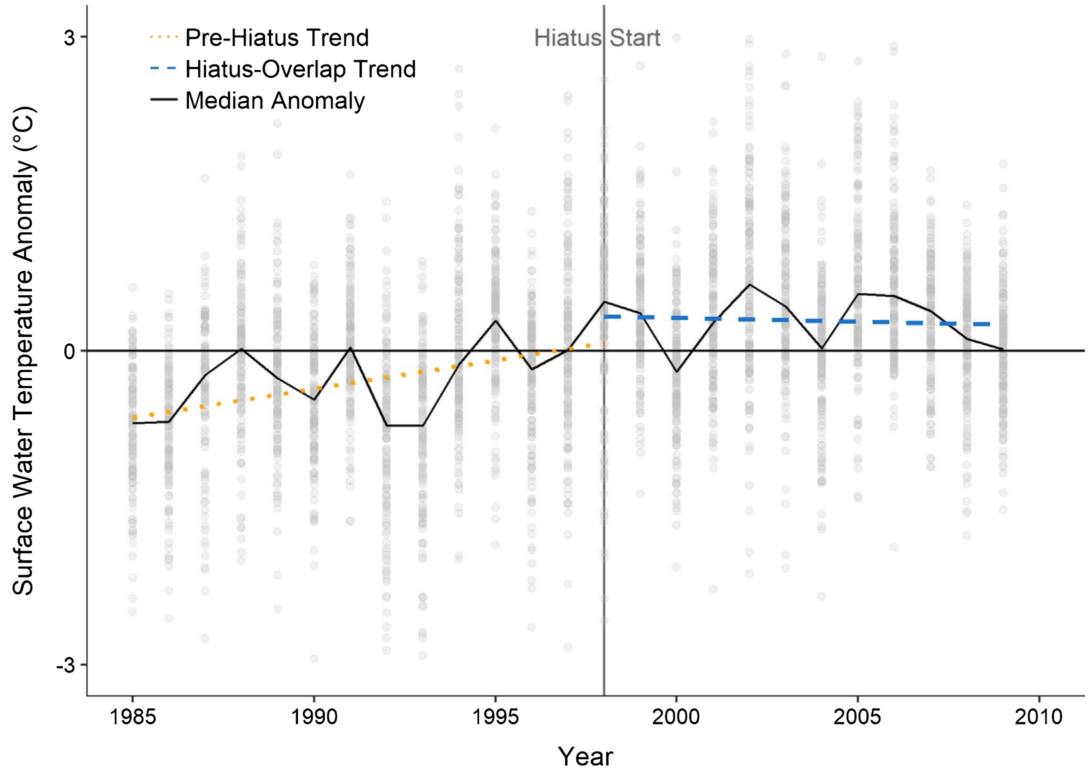

Figure 1. Median surface water temperature anomaly of all study lakes ($n = 155$; black line). Individual data points for each lake are shown in grey, where darker grey color indicates higher density of points. The two dotted lines indicate linear model fits to either the 1985–1998 (pre-hiatus) or 1998–2009 (hiatus-overlap) periods. The vertical line indicates the start year of the warming hiatus (1998). Pre-hiatus trend (orange) and hiatus-overlap trend (blue) had slopes of 0.523 ($\pm$0.214; $p = 0.03$) and −0.087 ($\pm$0.022; $p = 0.70$) °C decade^{-1} respectively.

averaged to calculate a mean annual summer air temperature anomaly. We calculated and compared trends in air temperature for both periods using a Sen's slope analysis (Sen 1968). When air temperature trends during the hiatus-overlap period were lower than during the pre-hiatus period, we defined that region as having exhibited a warming hiatus. In the examination of the potential drivers of difference in trend across the pre-hiatus and hiatus-overlap periods, we included additional temperature datasets that were processed and included as part of the released lake temperature database (Sharma *et al* 2015). These additional datasets were included to reduce potential bias emerging from any single source of global air temperature estimates. These include the Climate Research Unit (CRU, Harris *et al* 2014) and National Centers for Environmental Prediction (NCEP, Kanamitsu *et al* 2002) temperature datasets.

Analysis

We selected lake temperature data from lakes that had at least twenty years of observations, including at least ten years of data in both the pre-hiatus period (1985–1998) and the hiatus-overlap period (1998–2009). This 20 year threshold (i.e. 10 years before and after 1998) was selected to be more conservative than the original, 13 year cutoff used by O'Reilly *et al* (2015) for the entire time period, 1985–2009. Some lakes had both *in situ* and satellite derived temperature. In these cases we used the same criteria as O'Reilly *et al* (2015) whereby preference was given to the *in situ* temperature data. In total, 155 lakes met the aforementioned criteria. We calculated a global average lake temperature trend following the technique used by the International Panel on Climate Change (Hartmann *et al* 2013). We calculated a temperature anomaly for each lake by subtracting its long-term (1985–2009) mean temperature from each observation. The global median anomaly was used in a linear regression for the whole observed period (1985–2009) and the pre-hiatus and hiatus-overlap segments (1985–1998 and 1998–2009, respectively). The p-value and standard error around the trend are reported to determine significance and convey uncertainty, respectively. To determine the significance of the broken-line regression (pre- and hiatus-overlap periods) vs. an overall regression with a single slope, we specified a linear mixed effects model with a broken-line regression (supplemental text 2).

We estimated individual lake trends in water temperature ($n = 155$) from pre-hiatus and hiatus-overlap time periods using a Sen's slope analysis. We then used a binomial distribution test statistic to determine whether each lake had the same slope before and during the hiatus. The test statistic assumed equal probability that each lake's temperature trend had the same slope during the two time periods. To examine the contributing drivers of the difference in lake water temperature trend, we compared the differences in individual lake temperature trends to differences in trends of all potential drivers included with the original dataset (Sharma *et al* 2015). The potential drivers included seasonal and annual mean of air temperature, total shortwave, and longwave radiation, cloud cover, and metrics of air temperature (min, max, mean, and diurnal temperature range). The trend differences for all drivers were calculated for each lake and then used in a multiple linear regression (MLR) model to predict the difference in water temperature trend between pre-hiatus and hiatus-overlap periods. Using the R package *leaps* (Lumley and Miller 2017), we tested all model permutations and selected the best model based on the lowest Akaike Information Criterion (AIC). Finally, we analyzed relative importance of all variables in the final model based on the relative contribution in predicting the difference in water temperature trend between the pre-hiatus and hiatus-overlap periods. We took into account the importance of the entry order in the regression by averaging over all possible orders using the R package *relaimpo* (Grömping 2006). We used a hierarchical partitioning of R^2 to avoid biases due to term order in incremental partitioning (Chevan and Sutherland 1991).

Lake geographic and morphological attributes can affect how they respond to warming. To test if lake attributes affected how lakes responded to the hiatus, for each lake we calculated the difference in trend magnitude between the hiatus-overlap and pre-hiatus periods. These differences were compared to lake-specific attributes with a Kendall non-parametric rank-correlation using a 95% confidence interval. Parameters examined included lake maximum depth, volume, area, latitude, longitude, and elevation. Lake area was $\log_{10}$ transformed before comparison as it had a highly non-normal distribution. We used the R statistical software environment for all analyses (R Development Core Team 2017).

Results

The global population of lakes showed no significant change in temperature during the recent warming hiatus (1998–2009; figure 1), with an overall temperature trend of $-0.087\,^{\circ}\mathrm{C\,decade}^{-1}$ (±0.022; $p = 0.70$). In contrast, in the pre-hiatus period before 1998, the lakes showed significant warming at an average rate of $0.523\,^{\circ}\mathrm{C\,decade}^{-1}$ (±0.214; $p = 0.03$). We also examined an independent, fully satellite-derived, global lake temperature dataset (ARC-lake) that covers more of the hiatus-overlap period (1998–2011), but starts in 1995 so was not sufficient to assess pre-hiatus warming (MacCallum and Merchant 2012). Within the ARC-lake dataset, the temperature trend in lakes during the hiatus-overlap period was also near zero ($-0.003\,^{\circ}\mathrm{C\,decade}^{-1}$; supplemental text 3) indicating that the years of the hiatus for which we do not have data likely did not alter our estimation of trends during that period.

Across the entire time series (1985–2009), lake temperature warmed at an average rate of $0.394\,^{\circ}\mathrm{C\,decade}^{-1}$ (±0.085). The mixed effects broken-line regression model split at 1998 was a significantly better fit than the single trend version ($\Delta\mathrm{AIC} = -76.1$). The difference in trends among the pre- and hiatus-overlap periods was not sensitive to the two-year difference in length of the observational time period (14 years pre-hiatus vs 12 years hiatus overlap). Trends for the pre-hiatus period were also still consistently larger than hiatus-overlap period trends when the pre-hiatus time period was shortened to 12 years (to be consistent with the hiatus-overlap period length). 1998 was the most obvious change point year in the water temperature time series, with the lowest model AIC for a broken-line regression (figure S1) and the second-largest difference in pre- and hiatus-overlap trends (figure S2).

A total of 83% of lakes (129 out of 155) had lower warming rates during the hiatus-overlap period compared with the pre-hiatus period (figure 2). However, among lakes, there was no significant relationship between the pre-hiatus temperature trend and hiatus-overlap temperature trend (figure 2(*a*); $p = 0.54$, $n = 155$). We found 126 lakes (63%) displayed a hiatus behavior coherent with regional air temperature (i.e. air and water temperature trends both were faster or slower during the hiatus-overlap period compared with the pre-hiatus period). Of these 126 lakes with coherent air-water temperature behavior, a large majority (105 lakes, or 83%) exhibited slower warming in both air temperature and water temperature during the hiatus-overlap period compared with the pre-hiatus period. Overall, 116 of the 155 lakes (74%) had water temperature hiatus behavior (pre-hiatus trend larger than hiatus-overlap trend) that had corresponding air temperature hiatus behavior (using the CRU air temp dataset). The NCEP and GISTEMP datasets each had fewer hiatus-corresponding lakes (both with 94 of 155, 60%).

Of the potential temporal drivers examined, difference in pre-hiatus and hiatus-overlap trend was significantly correlated with difference in trend for air temperature, cloud cover, and shortwave radiation. No other variables were included based on AIC model selection. Air temperature trend difference was the primary contributor to variance explained (67% of explained variability), with cloud cover and summer total radiation being small secondary and tertiary contributors (24% and 9% respectively; table 1).

For lake specific trends, latitude was the only lake parameter significantly correlated with the difference between hiatus-overlap and pre-hiatus trend magnitudes (figure S3). The difference in pre-hiatus and hiatus-overlap trends was positively correlated with

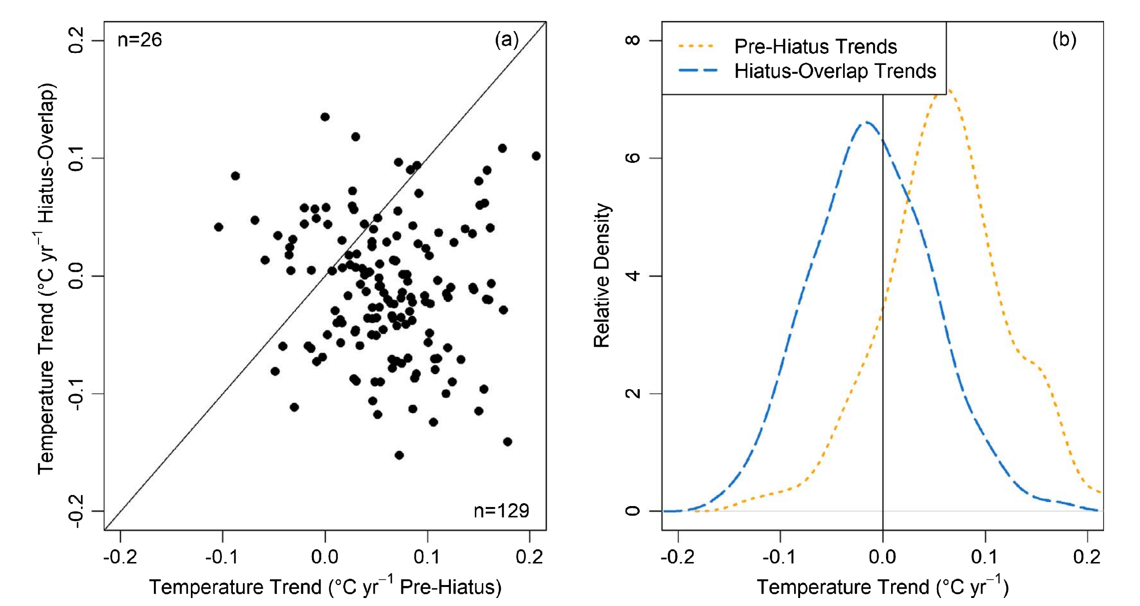

Figure 2. Lake-specific temperature trends for the hiatus-overlap and pre-hiatus periods. (*a*) Scatterplot comparing trends for each lake. The solid line indicates a 1:1 relationship between air temperature and water temperature warming rates. (*b*) A density plot of the population of lake-specific temperature trends in the pre-hiatus versus hiatus-overlap periods. A large majority of lakes (83%) had pre-hiatus temperature trends that were higher than during the hiatus.

Table 1. Relative contribution of each potential temporal driver of water temperature trend to the difference in pre-hiatus and hiatus-overlap water temperature trend. Relative importance is presented as variable-specific contribution to overall model R^2 (with normalized contribution in brackets).

Variable	Relative importance
Mean summer air temperature (CRU)	0.204 [67%]
Mean summer cloud cover	0.073 [24%]
Mean summer total radiation	0.028 [9%]

the absolute value of latitude ($p = 0.019$); on average, high latitude lakes showed a larger difference between the two period trends. There were no significant correlations between the other lake characteristics (i.e. surface area, mean depth, max depth, and elevation) and the difference in pre- and hiatus-overlap trends.

Several patterns emerged that characterized the geographic variations in lake responses to the climate warming hiatus (figure 3). Among continents, lakes on the southern third of South America and most of the US state of Alaska showed non-hiatus behavior (i.e. faster warming during the hiatus compared to the pre-hiatus period), corresponding to a region where the air temperatures also showed non-hiatus behavior. Southern Sweden and the European Alps region had variable responses to the hiatus, with some lakes having slower warming and others faster warming during the hiatus. In central Europe, air temperatures showed slower warming during the hiatus while in Sweden, air temperatures warmed faster during the hiatus. Southern Africa showed a region of consistent lake temperature hiatus with non-corresponding air temperature.

Discussion

This study is the first to examine the global response of lake temperature to decadal scale climate variability by examining lake temperature data during a broadly-observed period of muted air temperature warming. Our analysis revealed that lakes across the globe responded coherently to the recent hiatus in air temperature warming. The sensitivity of lakes to decadal-scale variability in air temperature trends reveals that water temperatures have likely exhibited similar decadal-scale variability as air temperature records. Such air temperature records, which often span a longer record than water temperature, play an important role in understanding the long-term warming rates of lakes (Piccolroaz *et al* 2017).

These results demonstrate that climate change effects on lake temperature are more nuanced than just facilitating a monotonic water temperature warming trend. Past work has already shown a diversity of warming trends across lakes (O'Reilly *et al* 2015), across water depths (Winslow *et al* 2015), and among seasons (Winslow *et al* 2017, Woolway *et al* 2017). Understanding the long-term variability of warming trends is critical to placing the change observed over recent decades in the broader context of change over decades to centuries. Long-term models of air temperature over the last half-century indicate decadal-scale stable or declining temperatures in future air temperatures are likely (Schurer *et al* 2015, Hedemann *et al* 2017). In response to such variability, our results suggest that lake temperature trends will also exhibit corresponding decadal-scale or shorter periods of stable or declining water temperatures.

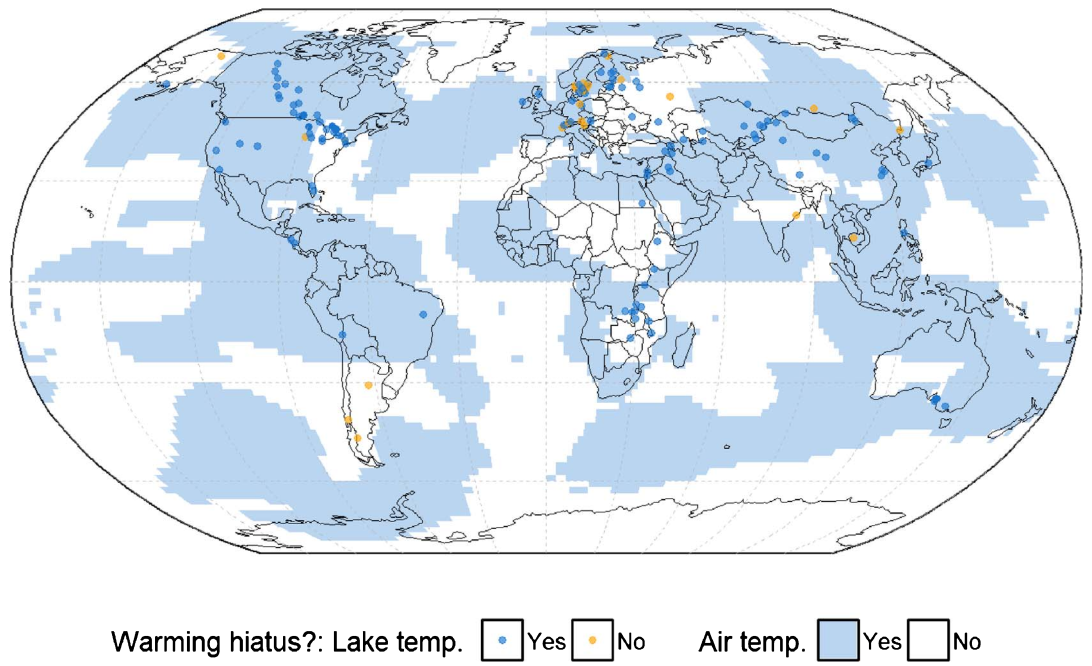

Figure 3. Global distribution of lakes ($n = 155$) colored by hiatus behavior. Blue points ($n = 129$) are lakes that showed a hiatus in warming with lower observed warming rates during the hiatus-overlap period (1998–2009) compared to the pre-hiatus period (1985–1998). Orange points ($n = 26$) are lakes that did not show a warming hiatus. The map background indicates regions that did (blue) and did not (white) show a hiatus in air temperatures warming over these same periods.

Current estimates of lake surface water temperature warming may underestimate the global, long-term warming rate. Many studies on lake surface temperature warming are based on datasets that span the 1998–2012 warming hiatus period. Furthermore, most long-term aquatic temperature datasets do not extend earlier than the 1970's or 1980's, meaning that most analyses today are at most c. 30 years in length, with the recent 14 year hiatus representing 25% or more of the data record. For example, Winslow *et al* (2015) analyzed lake water temperature in Wisconsin, USA collected between 1990–2012, a period during which the warming hiatus represents 63% of the total observation window. Other large-scale lake temperature trend study periods include 1985–2009 (45% overlap; O'Reilly *et al* 2015) and 1970–2010 (30% overlap; Kraemer *et al* 2015). In addition to these studies, the digitization of records is often biased through time, with a preference for digitizing contemporary records. Given that a large majority of lakes exhibited slower warming during the hiatus and the large percentage of temporal coverage the hiatus period represents in many lake temperature data sets, long-term rates of warming of lake surface water temperature may be revised upward in future studies.

While air temperature was the most important predictor of hiatus behavior, solar radiation and cloud cover also contributed to predicting variability in the difference in water temperature trend between the pre-hiatus and hiatus overlap periods. This is similar to the key drivers of water temperature trends identified in an analysis of the full long-term trend (O'Reilly *et al* 2015) as compared to our analysis, which looked at the difference in trend. This further supports that globally, changes in air temperature are the key driver of surface water temperature trends with solar radiation changes being a secondary contributor. Lake-specific characteristics did not play a substantial role in moderating the hiatus behavior. Latitude was the only lake characteristic that emerged as a signification predictor of the differences in water temperature trend between the pre-hiatus and hiatus overlap periods. The significant positive correlation with latitude is likely largely driven by polar amplification of warming (Polyakov *et al* 2002). The large differences in pre- and hiatus-overlap warming trends at high latitude may suggest that despite amplified polar warming, during the hiatus there was also a larger reduction in warming at high latitudes than at lower latitudes. The significant relationship with latitude disappeared when the variability in surface water temperature trend difference as predicted by air temperature trend difference was first removed (data not shown), further supporting the latitudinal correlation seen was primarily driven by polar amplification of warming.

There are many challenges with lake water temperature datasets that suggest caution in over interpreting our results. Unfortunately, there exists no updated version of the GLTC dataset that extends through the end of the hiatus (2012) and into more recent years, though an updated version is planned for the future (C. O'Reilly, personal communication, June 29, 2017). Despite the GLTC dataset's incomplete hiatus overlap, our analysis of an independent, satellite-observed lake water temperature dataset that extends through 2011 suggests relative robustness of the insignificant hiatus-overlap lake temperature trend (supplemental text 3). With expanded and updated datasets, future work can examine how lake temperature responded to the record warm years of 2015 and 2016. Further, the GLTC dataset includes time series with missing years, variable observation frequencies, and differing observation error. Thus, expanding, maintaining and, to the degree possible, improving global lake temperature dataset collection is critical to monitoring and understanding ongoing ecological responses to climate change.

Although a large majority of our study lakes exhibited a warming hiatus, there was some variation among regions. Similarly, the air temperature warming hiatus also showed regional variability in the degree to which air temperatures exhibited a warming hiatus (figure 3). The coherence between air and water temperatures, and the fact that air temperatures did not consistently exhibit a hiatus in all regions (based on our definition here), help explain why about 10% of studied lakes did not exhibit a warming hiatus. Southern South America is an example where faster air temperature warming during the hiatus period was reflected in a similar phenomenon of lake water temperature warming (i.e. no warming hiatus in either air or lake temperature). Central Europe and southern Sweden had neighboring lakes with different hiatus responses. Some lakes in Southern Sweden may have exhibited stronger warming hiatuses than others due to reductions in lake water clarity driven by long-term increasing trends in dissolved organic carbon concentrations (Monteith *et al* 2007). Water clarity losses have been shown to slow warming in lake surface waters (Rose *et al* 2016). Additionally, the hiatus behavior of Central European lakes may be influenced by the high topographic variability and long-term trends in solar radiation in this region (Rangwala and Miller 2012, Fink *et al* 2014, Schmid and Koester 2016).

There is mounting evidence that air temperature warming was slow during the 1998–2012 period, and our results support that water temperature warming slowed concurrently. While there are ongoing revisions to past temperature records that have revised our view on the 'global warming hiatus', these revisions have not altered the relatively slow terrestrial warming observed during 1998–2012. Recent work has shown systematic bias in observations of sea surface temperature (Hausfather *et al* 2017), although these revisions did not impact estimates of terrestrial warming, which is a more relevant metric for lake warming (as lakes are embedded in the terrestrial environment). Further, while global satellite-based air temperature trends have been revised to be 140% larger than previously reported (Mears *et al* 2017), their revised global temperature dataset still shows near-zero warming rates for the 1998–2012 period specifically (figure S4).

Conclusion

We analyzed observed surface water temperatures from 155 globally-distributed lakes to examine how lake temperature responded to the global warming hiatus during the overlapping 1998–2009 period as compared to the pre-hiatus (1985–1998) period. Estimates of average and lake-specific trends indicate that globally, lake warming rates slowed during the hiatus period coherent with slower air temperature warming. There was some regional variability in lakes showing hiatus behavior driven, in part, by regional differences in air temperature and solar radiation trends. This response of lakes to the hiatus-overlap period suggests that current estimates of long-term lake warming have underestimated trends due to the high degree of temporal overlap between lake temperature records and the hiatus. In the future, the sensitivity of lakes to long-term climate variability suggests lakes will show decadal-scale variability concurrent with variability in global air temperature trends. The observed response of lakes to the 1998–2012 hiatus both supports the evidence of a large-scale warming hiatus and indicates global lake warming rates may have been underestimated and may be revised upward in the future.

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