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Climate Change and Teleconnections Amplify Lake Stratification With Differential Local Controls of Surface Water Warming and Deep Water Cooling

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Key Points:

- Surface water warming was positively correlated with air temperature while deep water cooling was related to preceding spring conditions
- The stratified season length and strength has increased due to climate change and has been exacerbated by teleconnections
- Thermal stratification is expanding with the possibility of shifting mixing regimes from dimixis to monomixis in the future

Supporting Information:

- Supporting Information S1

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Abstract Temperate lakes are experiencing increases in warming and stratification duration while global-scale teleconnections potentially exacerbate effects of climate change. We examined interannual surface and deep water temperature change and stratification phenology in a long-term, weekly data set (1985–2017) from a dimictic lake in New York State, USA. We developed a metric, called mixing action, to capture multiple facets about the stratified period. We found warming in surface waters and cooling in deep water. Surface warming was positively correlated with air temperature. Deep water cooling was positively correlated with spring mixing period length and deep water spring temperature, indicating a lag effect. Mixing action was correlated with global temperature anomaly and spring North Atlantic Oscillation index. With increasing summer stratification strength and length, dimictic lakes like Mohonk may continue shifting toward monomictic mixing regimes with increasing summer hypolimnetic anoxia and changing lake biogeochemistry, productivity, and habitat for aquatic organisms.

Plain Language Summary Lakes are responding to global, regional, and local drivers of climate change, resulting in widespread lake warming and more stable layering of summer surface waters over cool deep waters. At the same time, global-scale ocean circulation patterns are driving regional weather patterns that can enhance the effects of climate change. Using weekly observations (1985–2017) from a lake in New York State, USA, that fully mixes twice a year, we found long-term trends of warming in surface waters and cooling in deep waters. Summer surface warming was directly controlled by rising air temperatures, but deep water cooling was associated with spring conditions, suggesting a delayed response. The overall trend of increasingly stable summer water conditions could be explained by increasing global temperatures and the spring circulation patterns in the North Atlantic Ocean, such that in years with unusually warm springs, the effects of climate change were intensified. Trends toward more extreme temperature differences between surface and deep water in relatively small lakes can be detrimental for oxygen levels and chemical cycling that ultimately support freshwater plants and animals.

1. Introduction

Lake summer surface water temperatures (SWT) are highly responsive to changes in global climate (O'Reilly et al., 2015) and often result in increasing stratification strength (Crossman et al., 2016; Kraemer et al., 2015). Anthropogenic global climate change (AGCC) affects lake thermal structure through the modification of local weather like air temperature, precipitation, wind, and cloud cover (Vincent, 2009). Concurrently, large-scale atmospheric and oceanic circulation patterns (teleconnections) can affect the same local weather variables possibly exacerbating changes in thermal structure in lakes. Consequently, models predict that the timing and length of the stratified period will expand in some dimictic lakes (Edlund et al., 2017; Hamilton et al., 2018; but see Hadley et al., 2014). As a result, mixing regimes may shift from dimixis to monomixis in some lake ecosystems with the potential for increasing hypolimnetic hypoxia and radiating effects on biogeochemical processes and lake food webs (Ficker et al., 2017; Maberly et al., 2020; Woolway & Merchant, 2019).

Teleconnections, recurring and cyclical large-scale climate circulation patterns, link climatic variability in noncontiguous geographic regions and operate on multiannual timescales. Teleconnections can alter effects of climate change by modulating regional and local drivers and may account for a portion of variance around directional trends of stratification and aquatic ecosystem function controlled by climate change (Wilkinson et al., 2020). For example, while lakes in the northern hemisphere have shifted toward earlier ice-free dates due to long-term climate change (Sharma et al., 2019), variance around ice phenological trends can be attributed to teleconnections (NAO; Schmidt et al., 2019). Teleconnections have explained coherence in thermal structure extremes across wide geographic regions (e.g., Dokulil et al., 2006). In European lakes, NAO effects are strongest in winters and early spring, with a delayed and persistent effect on physics and ecology in European lakes (Gerten & Adrian, 2002). In North America, research has demonstrated how the El Nino-Southern Oscillation (ENSO) modulates spring ice phenology (Bai et al., 2012) and affects plankton dynamics (Rusak et al., 2008; Xiao et al., 2019). Along with AGCC, lakes integrate teleconnection signals as sentinels of broader global patterns (Adrian et al., 2009).

AGCC and teleconnections affect SWT in lakes through regional weather patterns that modify heat exchange across the air-water interface and incoming radiation. Increasing air temperature warms surface waters through conductive and convective heat fluxes (Kalinowska et al., 2019). Climatic changes alter the timing, magnitude, and mode of precipitation, especially during the winter with more rain and less snow, which shorten ice-cover duration and, in turn, mixing regimes (Sharma et al., 2019). Furthermore, lake thermal stability is strengthened with decreases in wind that can minimize mixing and modify evaporation related heat losses ("atmospheric stilling," Woolway et al., 2019). Finally, decreases in cloud cover allow increasing solar radiation to reach lake surfaces (O'Reilly et al., 2015).

Air temperature and solar radiation directly affect epilimnetic heat, but the hypolimnion is largely isolated from the epilimnion in stratified dimictic lakes where heat is not readily transferred deep into the lake. Around the world, deep water temperature (DWT) trends vary considerably with both cooling and warming hypolimnia (Richardson et al., 2017; Winslow et al., 2015). There is some evidence from empirical studies and modeling efforts that suggest preceding spring conditions are predictive of hypolimnetic trends (Hamilton et al., 2018; Magee & Wu, 2017). Water clarity is additionally important by allowing solar radiation to penetrate below the thermocline (Read & Rose, 2013; Rose et al., 2016). This could indicate differential controls on epilimnetic water temperature trends compared to hypolimnetic trends in dimictic lakes.

While once rare, long-term data sets of year-round vertical profiles are critical in understanding interannual trends in changing thermal structure as well as studying how the transition mixing periods affect summer stratification in dimictic lakes (e.g., Foley et al., 2012; Livingstone, 2003; Magee & Wu, 2017). Recent advances in sensor technology have helped disentangle mechanisms responsible for changes in lake mixing regimes, particularly those that operate at longer timescales or have lag effects (Hampton et al., 2019). For instance, many lakes are warming faster than air (O'Reilly et al., 2015; Richardson et al., 2017) with antecedent winter and spring conditions speculated to affect this discrepancy. Open-water records in dimictic lakes from ice-off to ice-on will enable us to connect often ignored transition periods (Shogren et al., 2020) and spring conditions to summer thermal structure. However, we need metrics that examine the phenology (timing) of stratification, and strength over the entire season to best assess ecological and biogeochemical changes due to global climate processes.

Here, we used a 35-year data set of weekly, year-round temperature profiles for Mohonk Lake, NY, to evaluate local, regional, and global drivers of trends in lake thermal structure. Our objectives were twofold. First, we explored hypothesized climatic drivers at different seasonal scales and identified the mechanisms responsible for temperature changes in surface and deep waters in a small, dimictic lake (Figure S1). Second, we aimed to explain drivers of interannual variability in lake thermal structure and stratification phenology. We developed a metric to capture all details about the stratified period—including timing of onset of stratification, stratification strength, length of stratification—called mixing action, defined as the total energy required to mix a lake over an entire stratified season. We compared mixing action directly to global metrics of climate change and teleconnections because both simultaneously affect the same local weather variables. We expected mixing action to increase with global atmospheric warming, but that some of the variability from that relationship would relate to teleconnections.

2. Methods

2.1. Site Description and Data Collection

Mohonk Lake (41.766°N,−74.158°W) is small (6.9 ha), deep (z_{max} = 18.5 m), oligo-mesotrophic lake on the northern Shawangunk Ridge, New York State, USA (Richardson et al., 2018, 2019). Temperature profiles were sampled at 1m intervals through a hatch in a wharf at the northern end of the lake where depth was 13m which captures ~94% of lake volume (Figure S2). In 1985, profiles of lake temperature using a YSI variable resistor thermistor that was replaced in the early 1990s (Yellow Springs, Ohio) and Secchi depth were taken daily, and weekly from 1985 to 2016, mostly in the afternoon. In 2017, high-frequency (15 min) temperature data were taken using a NexSens T-Node temperature logger downsampled to daily profiles. Weekly profiles were linearly interpolated to daily timescales and merged with daily temperatures from 1985 and 2017 (Figure S3). All data are available (Mohonk Preserve, 2020). Air temperature (°C) and precipitation (mm) were measured at the lake using a National Weather Service rain gauge (Network ID: GHCND:USC00305426). Local wind observations were not available for this station. Ice-out day (as 100% clearance) was recorded each year by either the Smiley family or the Mohonk Preserve each year. Daily NAO indices were downloaded from the National Weather Service Climate Prediction Center (National Weather Service, 2020) and averaged monthly and seasonally. We obtained monthly multivariate El Niño/Southern Oscillation (ENSO) indices from the National Oceanic and Atmospheric Administration Physical Sciences Laboratory (NOAA Physical Sciences Laboratory, 2020). Seasonally, spring was defined as 21 March to 20 June, summer was defined as 21 June to 20 September, and winter was defined as 01 October of the previous year through 31 March (as defined by Rusak et al., 2008). Global annual temperature anomalies averaged over land and ocean were obtained from the National Oceanic and Atmospheric Administration (NOAA, 2020).

2.2. Thermal Structure Metrics

We calculated four metrics of lake thermal structure for each profile: SWT as the mean temperature from 1 to 3m; DWT as the mean temperature from 10 to 12m (Figure S4); thermocline depth; and Schmidt stability. Thermocline depth was assigned to the average of the first two depths with a density rate of change over the profile exceeding 0.1 kg m^{-2} and represents the depth delineating thermal stratification layers (Read et al., 2011). Schmidt stability (J m^{-2}) was the measure of the quantity of work required to overcome thermal density stratification and completely mix the lake (Idso, 1973).

2.3. Stratification Phenology and Mixing Action

We calculated a breakpoint for Schmidt stability each spring using the "pettitt.test" function in the R "trend" package (Pohlert, 2020). We took the median from all annual spring breakpoints as a cutoff for thermal stratification (66 J m^{-2}) and identified the start and end of thermal stratification using this Schmidt stability cutoff (Engelhardt & Kirillin, 2014). Using those days of start and end of stratification, we identified the length of the stratified period, maximum Schmidt stability, and day of peak stratification (Figure S6). We broke each year into multiple time periods matching seasons and stratification phenology throughout the year: 7-day period following ice-off ("postice"), between ice-off and stratification onset ("spring mixed-period"), and between stratification onset and turnover ("summer stratified").

To summarize thermal stratification over the entire summer stratified period, we calculated mixing action as the sum of Schmidt stability under the entire stratified period. Mixing action summarizes the entire strength and duration of the stratified period and could be applied to any dimictic or monomictic lake reducing some of the inherent variability associated with selecting a single profile or summarizing from monthly sampling (e.g., O'Reilly et al., 2015; Richardson et al., 2017). Mixing action is the sum total of work that would be required to mix the lake over the entire stratified season. Similar to action in physics, mixing action (MA) has units of energy time (GJ day), and captures the variability in cooling or warming in the hypolimnion combined with stratification phenology (Figure S6). We calculated this discretely over the stratified period for each year using the generalized formula:

$$\text{Mixing action} = \text{SA} \sum_{t=\text{onset}}^{t=\text{turnover}} S \times \left(t_i - t_{i-1}\right) \quad (1)$$

where onset is the day of year (DOY) for stratification onset, turnover is the DOY for the end of stratification, SA is the surface area of the lake, S is the Schmidt stability, and t_i is the ith DOY and t_{i-1} is the previous DOY. Here, we used linearly interpolated Schmidt stability to daily values. Furthermore, mixing action could be calculated for the open water period (ice-on to ice-off) which results in similar values to the mixed-period (Figure S7).

2.4. Statistical Analyses

All data analyses were conducted in the R statistical environment (R Core Team, 2019). We assessed interannual temporal trends for a variety of lake and air temperature metrics: postice, spring, and summer air, surface water and deep water; stratification onset, turnover, and length, maximum stability, maximum stability day, and mixing action (Table S1). Using code derived from both "zyp" and "trend" R packages, we calculated Theil-Sen's estimator (Theil-Sen's slope) as the median slope from all finite pairwise slopes (Bronaugh & Consortium, 2019; Pohlert, 2020). For visualization, we calculated the intercept as the median intercept using the Theil-Sen's slope and all pairwise points. To test if a trend was significant, we used the Mann-Kendall rank based z-score and compared the p-value from that z-score to $\alpha = 0.05$.

We identified six local factors that could drive interannual variability in summer SWT and DWT. For SWT, we included summer mean daily air temperature, summer total daily precipitation, spring mixed-period SWT, stratification onset DOY, length of the mixed-period, and Secchi depth as a proxy for transparency. For deep water, we included summer SWT, ice off day of the year, spring mixed-period DWT, stratification onset DOY, length of the mixed-period, and transparency. For each set of factors, we carried out nonparametric Spearman correlations with either summer SWT or DWT, accounting for the multiple comparisons ($n = 6$ for each) with a Bonferroni correction ($\alpha = 0.05$). To reduce each of these sets of variables down to orthogonal variables, we ran principal component analyses using the prcomp function in R (see supplement for details).

After preliminary analyses indicated changes in MA over time, we tested how well global temperature anomalies and large-scale climatic oscillations could explain the observed patterns. We considered antecedent winter, spring, and summer NAO and ENSO indices (Table S1, Figure S8). We built time series models using the auto. arima () function in the R 'forecast' package for each individual predictor to address possible autocorrelation in the time series (Hyndman & Khandakar, 2008). Model selection was based on the Akaike information criterion (AICc); the top two models were combined into a final model.

3. Results

In Mohonk Lake, the thermocline generally began to set up in early spring and increased nonlinearly throughout the summer to a maximum of 8 m before turnover each autumn (Figure S9a). Schmidt stability followed a typical dimictic pattern with two mixing periods, inverse stratification in the winter, and strong thermal stratification in the summer (Figure S9b). Thermal stratification stability peaked in mid-to late summer before decreasing rapidly during turnover.

Rates of change in air and water temperatures varied across different seasonal periods over the 35-year study (Table S1). Postice and summer air temperature increased by 0.17°C yr^{-1} ($p = 0.002$, Figure 1a) and by 0.04°C yr^{-1} in summer ($p = 0.019$, Figure 1c), respectively. However, spring air temperature did not change ($p = 0.40$, Figure 1b). SWT in post ice-off, spring, and summer all increased significantly by 0.06°C yr^{-1} ($p = 0.039$, 1">Figure 1d), 0.04°C yr^{-1} ($p = 0.025$, Figure 1e), and by 0.05°C yr^{-1} ($p < 0.001$, Figure 1f), respectively. Spring and summer DWT decreased by −0.03°C yr^{-1} ($p < 0.001$, Figure 1h) and −0.05°C yr^{-1} ($p < 0.001$, Figure 1i), respectively. However, postice DWT did not change ($p = 0.06$, Figure 1g).

Several facets of stratification changed over the 35-year study (Figure 2a). Stratification onset trended earlier each year (slope = −0.32 days yr^{-1}, $p = 0.009$), while timing of turnover did not change ($p = 0.34$, Figure 2b). Combined, the length of the stratified period increased at a rate of 0.5 days yr^{-1} ($p = 0.045$, Figure 2c). Maximum stratification increased (slope = 1.6 J m^{-2} yr^{-1}, $p = 0.015$, Figures 2a and Figure S5) but the day of maximum stratification remained stable ($p = 0.44$, Figure 2a). Ice-out date and length of ice cover were variable and did not exhibit directional trends (Table S1). Finally, mixing action, which compiles all the different stratification trends as the area under each curve in Figure 2a, has been significantly increasing (slope = 0.03 GJ d yr^{-1}, $p < 0.001$, Figure 2d).

Summer SWT was positively correlated with summer air temperature ($r = 0.8$, $p < 0.001$) and summer Secchi depth ($r = 0.52$, $p = 0.002$; Figure 3). Summer SWT was not correlated with DWT, summer total precipitation, spring mixed-period SWT, length of mixed-period, nor start of stratification (Figures 3c and Figure S10). Summer DWT was positively correlated with the length of the spring mixed-period ($r = 0.78$,

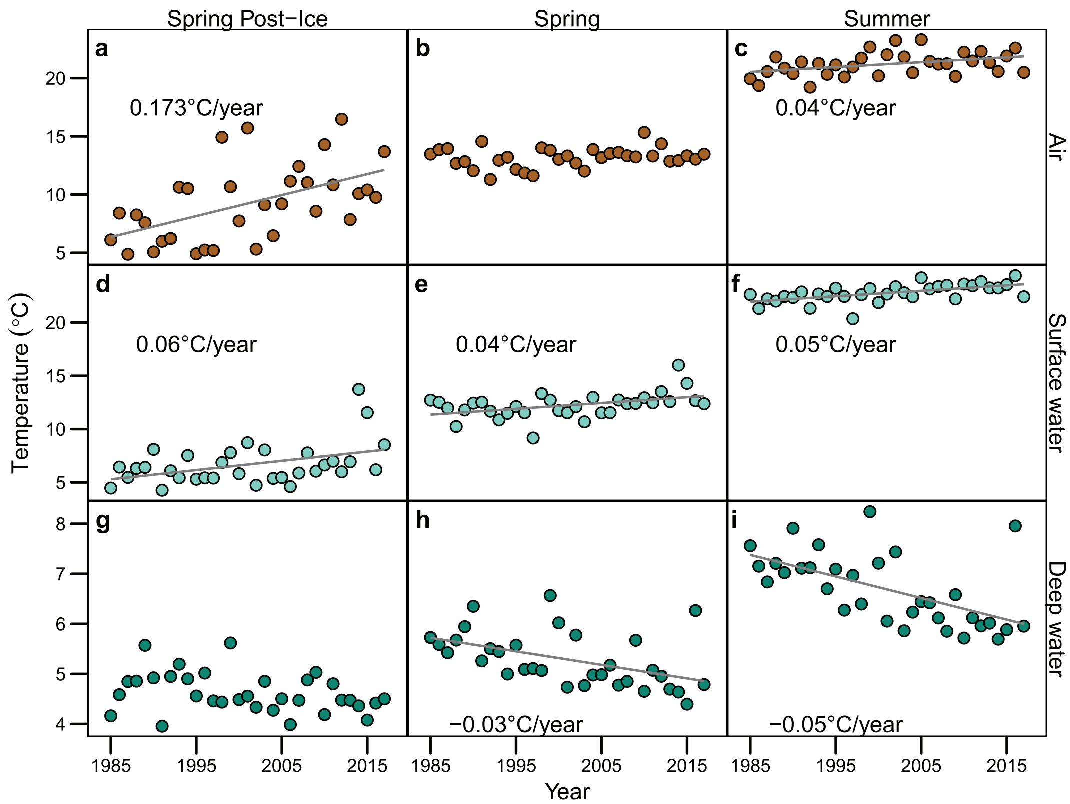

Figure 1. Spring 7-day postice off, spring (21 March–20 June), and summer (21 June–20 September) air, surface water (1–3m) and deep (10–12m) temperature trends. Significant ($p < 0.05$) trends are fitted with a gray line and Thiel-Sen's slopes are printed on each panel.

$p < 0.001$, Figure 3f) and spring mixed DWT ($r = 0.76$, $p < 0.001$, Figure 3e). Summer DWT was negatively correlated with ice-out day ($r = -0.50$, $p = 0.002$, Figure 3d). Summer DWT was not correlated with start of stratification nor transparency (Figure S10). Collectively, most of the variation in summer SWT increases could be explained by summer air temperature and transparency increases while summer DWT decreases could be explained by increasing mixed-period length, decreasing ice-out day, and increasing mixed-period DWT (Figure S11).

Increases in mixing action over the study period were best explained by increases in global temperature anomaly (ARIMA$_{(0,0,0)}$, $\sigma^2 = 0.070$), whereby higher anomalies were positively related to mixing action (Figure 4). Spring NAO explained the most variability in mixing action over time (ARIMA$_{(1,0,0)}$, $\sigma^2 = 0.080$; Table S2), where positive NAO indices were associated with lower mixing action. A model including both global temperature anomaly and spring NAO index generated the lowest overall AICc with no evidence of temporal autocorrelation (ARIMA$_{(0,0,0)}$, $\sigma^2 = 0.065$; Figure 4).

4. Discussion

As a result of changing climate, stratification length is getting longer and stronger in lakes around the world (Butcher et al., 2015; Kraemer et al., 2015). Mohonk Lake is no exception; over 35 years, thermal stratification has increased throughout the summer with deepening thermocline depth. Mohonk stratification period is increasing approximately three times faster than northern temperate European projections (4.8 days decade^{-1}; Figure 2c; Shatwell et al., 2019). The timing of stratification onset is occurring earlier, despite no trend of earlier-ice-out, and both strength and duration of thermal stratification has rapidly increased. Increasing mixing action, our new metric developed in this study, is related to the interplay between global climate change and teleconnections that combine through local weather drivers to affect lake thermal structure.

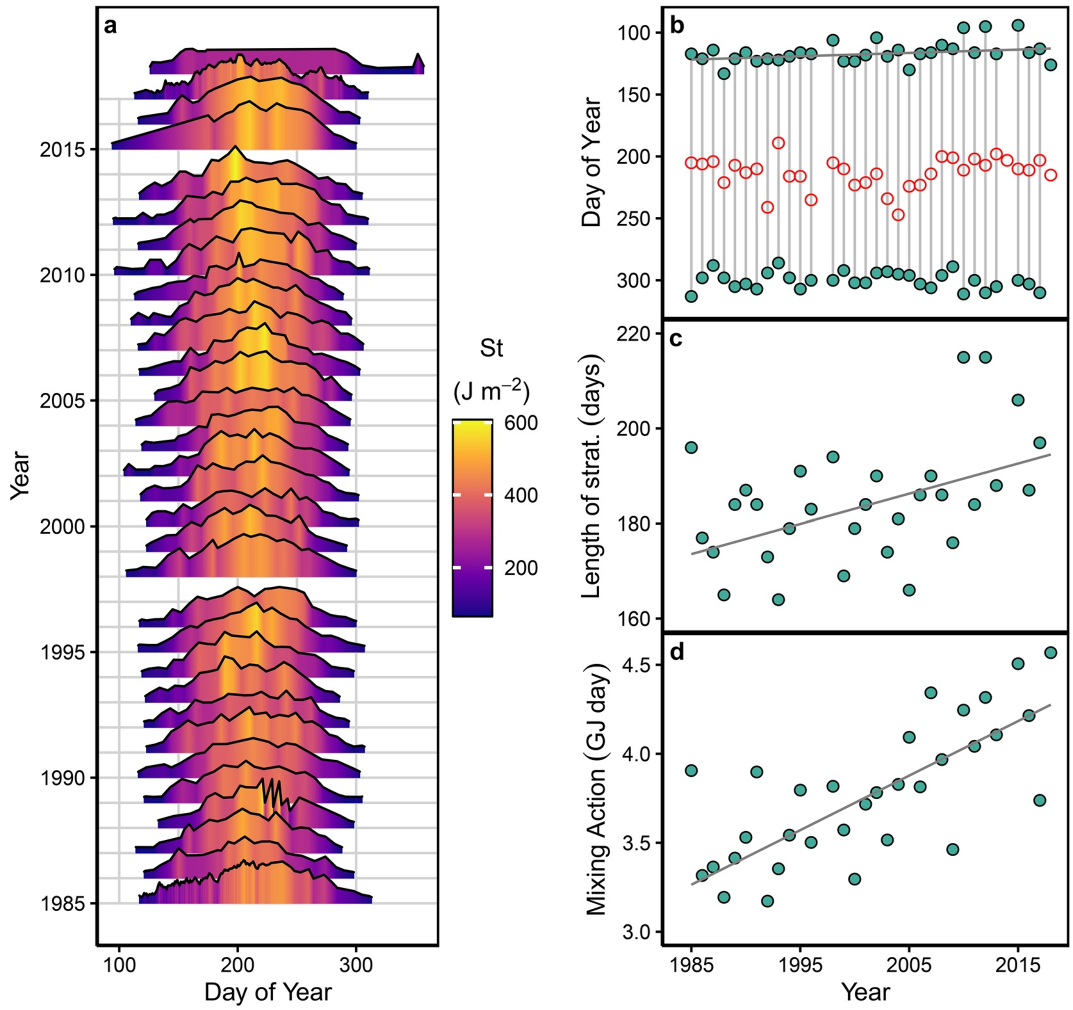

Figure 2. Phenology of thermal stratification in Mohonk Lake from 1985–2017. (a) Schmidt stability during stratified periods for each year (1997 and 2014 was missing parts of the year and removed from analysis; further explanation in online supplementary materials). (b) Day of year of onset of stratification (top filled points), maximum annual stratification stability (open circles), and end of stratification (bottom filled points) for each year. The vertical line connecting the points indicates the length of thermal stratification for each year. (c) Annual length of stratification (0.47 days yr^{-1}). (d) Annual mixing action (0.03 GJ day yr^{-1}). Gray trend lines indicate significant Theil-Sen's slope ($p < 0.05$).

In this study, mixing action was strongly related to the global temperature anomaly indicating the accumulation of global effects on a localized lake and realizing the potential of lakes to act as sentinels of climate change (Figure 4). Climate change can affect a variety of regional variables that then drive lake temperature and stratification. For example, climate change is increasing air temperature but also modifying precipitation patterns, solar radiation, and wind (Easterling et al., 2017). Simultaneously, teleconnections affect local weather variables that subsequently affect lake thermal structure (Durkee, 2008). We chose to examine the effects of climate change and teleconnections indices on mixing action because this allows us to tease apart the synchronous effects of both on local weather.

NAO has varying effects on spring conditions, such as precipitation extremes or rain-on-snow events, in northeastern North America. During springs with a positive index, NAO manifests as cooler surface temperatures and higher precipitation in the northeastern United States, resulting in higher streamflow (Coleman & Budikova, 2013). In contrast, during springs with a NAO negative index, large precipitation events are kept out of the northeastern United States and seasonal temperatures are typically above normal (Coleman & Budikova, 2013). In Mohonk, mixing action was highest during negative spring NAO and

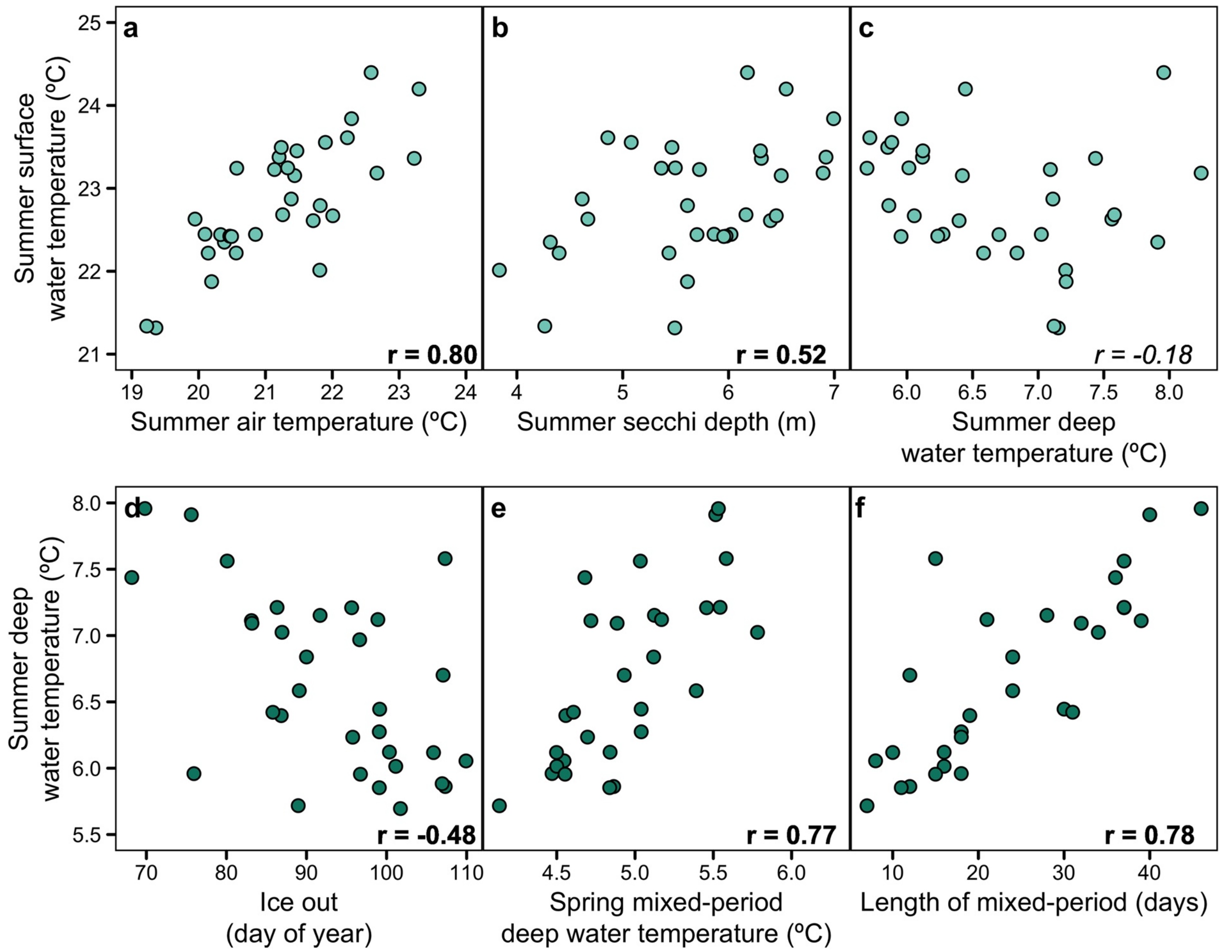

Figure 3. Correlations between summer surface water temperature and (a) summer air temperature, (b) summer secchi depth, (c) summer deep water temperature. Correlations between summer deep water temperature and (d) ice-out day of year, spring mixed-period deep water temperature, and length of mix-period. Pearson *r* values in **bold** are significant at $p < 0.001$.

lowest at high spring NAO further indicating the importance of a seasonal lag on summer thermal stratification. In years with high positive spring NAO, large precipitation events, wind events, decreased solar radiation, and cooler temperatures may delay the onset of stratification. During the stratified period, the hypolimnion might be largely isolated from atmospheric drivers. Therefore, the teleconnection signal would have the largest effect on the hypolimnion prior to stratification onset (Dokulil et al., 2006). For example, one of the largest tropical storms on record in the northeastern United States did not completely disrupt stratification in similar regional lakes during the peak of stratification in late summer (Tropical storm Irene, 2011; Klug et al., 2012). While the directional shift toward more stable and longer stratification is driven by higher global temperatures, some of that interannual variability can be explained by spring NAO.

Mohonk had summer warming rates comparable to other northeastern North American lakes which are warming faster than many other lakes from around the world (O'Reilly et al., 2015; Richardson et al., 2017). Similar to other lakes, Mohonk's surface warming was directly correlated with increases in air temperature and responded immediately to seasonal weather (Figure 3; Schmid & Köster, 2016). Simultaneously, transparency (as Secchi depth) during the stratified period increased 0.3 m decade^{-1}, indicating increases in water clarity. In this high-residence time, low-color lake, deeper thermoclines may shift the distribution of phytoplankton deeper in the mixed layer where nutrients are more plentiful, consequently resulting in an apparent increase in transparency (Cantin et al., 2011). While transparency was positively correlated with SWT, increases in water clarity likely caused slower rates of SWT warming than would be predicted

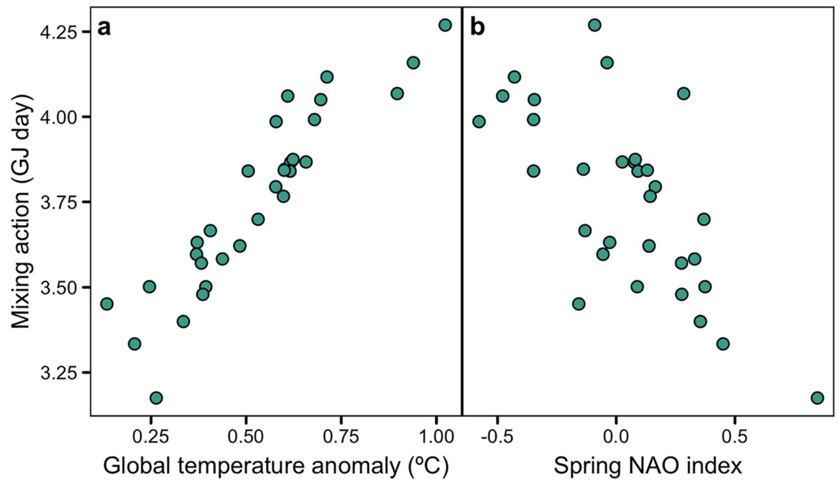

Figure 4. Predicted mixing action (GJ day) as a function of (a) global temperature anomaly and (b) spring North Atlantic Oscillation (NAO) index.

in the absence of changes in water clarity; furthermore, this may have, in part, caused greater absorption of solar radiation deeper in the water column warming the entire epilimnion (Rose et al., 2016). Overall, Mohonk's SWT were directly and immediately responsive to summer conditions, as is expected for smaller lakes.

Despite the majority of lakes warming on the surface, deep water trends are far more variable across the world with only some lakes with deep water cooling (Arvola et al., 2009; Magee & Wu, 2017; Richardson et al., 2017; Winslow et al., 2015). Though ice-out is not occurring earlier (Table S1), we have observed more frequent freeze-thaw cycles and decreasing ice thickness in the last decade, factors that are not represented in ice phenology data. Changing ice dynamics, combined with rapidly warming air temperatures in the week following ice-off increase SWT (Figures 1a and 1d) and earlier onset of stratification (Figure 2b) prevent early season turbulent mixing that would otherwise distribute heat deep in a dimictic lake. These spring conditions preceding stratification control DWT especially in lakes with cooling deep water trends (Magee & Wu, 2017; Read et al., 2012). Similarly, in Mohonk's case, spring DWT and spring mixed-period length were linked to summer hypolimnetic temperatures more than any factors concurrent in summer including SWT (Figure 3, Figure S7). Summer conditions, including air temperature and transparency, have a lack of direct control on hypolimnetic trends supporting differential controls on surface compared to deep water temperatures. As a small, deep lake, Mohonk is wind sheltered by a steep watershed on the east side, likely resulting in a lack of turbulent mixing to transfer heat down outside of the early spring mixed-period.

Factors such as wind and lake morphometry can further modulate individual lake responses to increasing thermal stratification. The onset of stratification is trending earlier in Mohonk, likely from warmer air temperatures in spring, particularly in the week following ice-off, resulting in increased thermocline stability and peak stability later in the summer (Figures 1d and 1e; Butcher et al., 2015). Harp Lake, at similar latitude but further inland, had no trends in stratification phenology despite having increasing thermal stability because summer maximum air temperature increases were driving thermal stability as opposed to ice off phenology or early spring trends (Hadley et al., 2014). Our results are consistent with Harp Lake as Mohonk had increasing summer temperatures that facilitated increasing summer thermal stability and increasing early spring air temperature following ice off that forced earlier thermal stratification. Due to their geomorphometry, smaller lakes are also more sensitive to processes affected by lake heating, like ice-off and stratification onset, compared to larger lakes (Crossman et al., 2016). Mohonk, deep but small in surface area, had an earlier onset and longer stratified period but did not experience changes in autumn turnover date (Figure 2b).

5. Conclusion

In the past, lake thermal structure and mixing regimes were predictable based on latitude and elevation with dimictic lakes occurring between 40°N and 60°N at lower elevations (Lewis, 1983). In temperate lakes, the stratification period is projected to continue increasing in length due to earlier onset of stratification over the next century (Maberly et al., 2020; Shatwell et al., 2019); thus, the traditional view of dimictic lakes in temperate regions is going to shift under climate change. At the current rate, stratification length would increase to 240 days by 2120; if thermal stratification expands and strengthens concurrently with a loss of ice, dimictic lakes may shift toward warm monomictic lakes (Ficker et al., 2017; Maberly et al., 2020; Sharma et al., 2019). Given the currently unabated trajectory of climate warming (Hoegh-Guldberg et al., 2018), lake thermal structure will continue to rapidly change and be pushed to the extremes in some years by teleconnection cycles, that are also nonstationary, with important implications for ecosystem function (Easterling et al., 2017). Understanding the mechanisms underpinning changes in lake thermal structure and mixing regimes in lakes of different shapes, sizes, and landscape settings is critical in predicting how lakes will function under continued climate change.

Data Availability Statement

Data are available in the Environmental Data Initiative repository (Mohonk Preserve et al., 2020). Daily air temperature and precipitation data from the Mohonk Preserve Weather station are available from the US Weather Bureau/National Weather Service rain gauge (Network ID GHCND:USC00305426).

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