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Aquatic Transitions

Wind induced impacts on hypolimnetic temperature and thermal structure of Candlewood Lake (Connecticut, U.S.A.) from 1985–2015

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Climate change has affected freshwater lakes in many ways, including shifts in thermal structure, stability, ice cover, annual mixing regimes and length of the growing season, all of which impact ecosystem structure and function. We examine the impacts climate variables, especially wind speed, had on water temperature and thermal stratification at three sites in Candlewood Lake (Connecticut, U.S.A.) between 1985 and 2015. Despite the lack of regional time-related trends in air temperature or precipitation over the 31 year period, there was a significant decline in wind speed during spring and summer months, with a mean decline of 31% over the study period. Even though a wide range in mean July epilimnetic temperature (22.8–28.2°C) was observed, there was no trend over time. In contrast, a significant cooling trend was recorded for the hypolimnion that was highly correlated with the declining wind speed. Decreasing wind speed was also correlated with an increase in the strength of the thermocline estimated from maximum RTRM values. Despite the lack of a warming trend in surface waters over the entire study period, the strength of summer thermal stability estimated using total RTRM scores was highly correlated with epilimnetic temperature. The potential consequences of declining wind speed, a cooling hypolimnion, and a stronger thermocline are discussed.

KEYWORDS

climate change, hypolimnetic cooling, relative thermal resistance to mixing, thermal structure, wind speed

1 | INTRODUCTION

Anthopogenic climate warming and associated shifts in precipitation patterns, coupled with the seasonality of these changes, have direct impacts on freshwater ecosystems (Huisman et al., 2004; Schneider & Hook, 2010; Winder & Sommer, 2012; Winslow, Read et al., 2017; Wrona et al., 2005). Regional (Torbick et al., 2016), continental (Gudmundsson et al., 2017; Rühland et al., 2015) and even potentially global-scale (O'Reilly et al., 2015) influences of anthropogenic climate change

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on freshwater ecosystems are now emerging. Climate changes can impact the length of the growing season, stability and thermal structure of the water column, duration and extent of ice cover, distribution of nutrients and dissolved gases, concentrations of dissolved organic carbon (DOC), and associated optical characteristics of freshwater lakes (Hobbie et al., 1999; Schindler & Smol, 2006; Vincent & Hobbie, 2000; Weyhenmeyer & Karlsson, 2009; Winslow, Hansen et al., 2017; Winslow, Read et al., 2017; Wrona et al., 2006). The physical and chemical changes will inevitably affect physiological responses and adaptive strategies of organisms, composition of the biota, survival and migration patterns of species, and shifts in trophic structure, all of which directly impact ecosystem structure and function. Since many responses are immediate, measureable, and leave evidence in the sediment record, lakes are excellent "sentinels" of climate change (Adrian et al., 2009; Williamson et al., 2009). However, given the complex nature of lake ecosystems, coupled with differences in basin morphology, annual mixing regimes, water turnover rates, chemistry, watershed characteristics, and other anthropogenic influences, caution needs to be exercised when evaluating impacts related to changes in any variable, including those related to anthropogenic climate warming (Adrian et al., 2009; Kraemer et al., 2015).

Under most scenarios, warming surface waters in lake ecosystems will increase primary productivity, especially under light saturation conditions, as well as heterotrophic consumption through increases in respiration (Winder & Sommer, 2012), which in turn will impact top-down versus bottom-up controls on overall plankton structure. Increasing surface water temperatures may also enhance development of blooms, especially of toxin-forming cyanobacteria (Paerl & Huisman, 2008; Steinberg & Hartmann, 1988), and coupled with enhanced stratification and reduced mixing, tends to favor smaller and more buoyant phytoplankton (Huisman et al., 2004; Rühland et al., 2015). This is especially true for cyanobacteria species that form aerotopes (gas vesicles) which increase bouyancy (Cronberg & Annadotter, 2006). In addition to potentially sinking at a slower rate, smaller phytoplankton taxa with larger surface area:volume ratios tend to take up nutrients more efficiently and reproduce at a faster rate, both qualities that yield additional competitive advantages. Smaller-sized cells would, however, be more prone to predation. Although the vast majority of studies on the impacts of anthropogenic-driven climate change on phytoplankton dynamics have focused on warming, little has been published on associated changes in wind speed. Since changes in wind speed can have profound impacts on thermal stratification and the degree of mixing, they can also result in significant shifts in phytoplankton structure.

Changes in climate-related variables can also significantly impact underwater light regimes, nutrient and gas concentrations, and ultimately the annual mixing regime. Higher levels of precipitation have been linked to enhanced transport of dissolved organic carbon (DOC) and ultimately changes in the light regime of receiving waterbodies (Brown et al., 2017; Weyhenmeyer & Karlsson, 2009). Stronger thermal stratification conditions will tend to increase loss of oxygen from hypolimnetic waters, potentially exacerbating internal nutrient loading (Hecky et al., 2010), and simultaneously influence transport of gases and nutrients across the metalimnion (Kortmann et al., 1994; Livingstone, 2003), both of which directly impact water quality. Over longer time periods, directional changes in the dynamics of winter ice resulting from climate warming could cause a shift in annual mixing patterns of mid-latitude lakes from a dimictic state to a monomictic state (Livingstone, 2008).

Candlewood Lake, the largest waterbody in the State of Connecticut, USA, is a reservoir built in the late 1920s. Significant water quality changes occurred between 1950 and the early 1980s resulting from increasing development of the surrounding watershed and invasion and spread of *Myriophyllum spicatum*. A monitoring program was established in 1985 and continues today to track further changes in water quality in relation to lake management efforts. A thorough statistical analysis of the long-term (1985–2012) database was recently completed with a focus on variables associated with trophic conditions and primary productivity of the lake (Kohli et al., 2017). Results from that study concluded that there has been a modest improvement in the trophic conditions based on Secchi disk transparency, chlorophyll-*a*, and total phosphorus concentration, despite a steady increase in dissolved salt concentration over time related to use of road deicing salts. Thermal profiling at each site in the lake has been included in the monitoring program since its inception, and form the data set used in this study.

Although wind is an important climate-related driver (Adrian et al., 2009; Ambrosetti & Barbanti, 1999) that is instrumental in determining the degree of mixing and ultimate characteristics of thermal stratification patterns in lakes (Wetzel, 2001), it is less often included in studies that evaluate impacts of anthropogenic climate change on freshwater ecosystems. Here, we evaluate the roles that wind speed, wind direction, atmospheric temperature and precipitation played on summer lake water temperature profiles, strength of thermal stratification, and depth of the thermocline in Candlewood Lake from 1985–2015. The potential consequences of a cooling trend in hypolimnetic temperature and an increase in the strength of the thermocline on the lake, with a focus on phytoplankton dynamics and nutrient conditions, are discussed.

2 | STUDY SITE

Candlewood Lake, situated in western Connecticut and surrounded by five municipalities (Figure 1), is a dimictic waterbody with a surface area of 21.9 km^2 (Frink & Norvell, 1984). Approximately 3.5 km at its widest point, the lake is 18 km long and includes three north to south running arms which range in length from 4 to 8 km (Figure 1). The lake has a mean depth of 8.9 m, volume of 196×10^6 m^3, and retention time of approximately 3.3 years depending on the quantity of water used for hydroelectric generation (Kohli et al., 2017; Marsicano et al., 1995). The shoreline of approximately 105 km is convoluted, with many steep-sided areas, numerous bays and coves, and narrow passages (Jacobs & O'Donnell, 2002; Marsicano et al., 1995). The surrounding watershed is 105 km^2, with the majority situated in western Connecticut, and a small portion extending into New York State (Kohli et al., 2017). Based on the most recent study, the percentage of residential lands in the surrounding watershed remained at 28%, between 1990 and 2007, while the percentage of wooded lands increased 3% (Kohli et al., 2017). The outlet from the lake to the Housatonic River is through a penstock located at the dam on the northeast arm of the lake (Figure 1). Water that leaves through this outlet is used to generate electricity. The level of the lake is maintained more or less constant during spring, summer and fall. The lake typically starts to freeze in December, is frozen over by January, and becomes ice-free in March.

3 | MATERIALS AND METHODS

Thermal profiles taken as part of the long-term monitoring program for Candlewood Lake over the 31-year period from 1985 through 2015 were used in this investigation (Kohli et al., 2017). Three widely-spaced and fixed sites, Danbury Bay (DB), New Fairfield (NF) and Sherman (SH), each with a maximum depth between 11–12 m, were used in the study (Figure 1). The sites are 10–15 km away from the outlet. Thermal profiles were taken at each site once per month from May through October throughout the 31-year period ($n = 558$ thermal profiles). Temperature was taken at the very surface, 0.5, 1 m, and every additional meter interval to the bottom. The bulk of the analysis presented herein is based on profiles from spring (May–June; $n = 186$) during development of thermal stratification, and summer (July–August; $n = 186$) during the peak of thermal stratification. Temperature profiles were measured with a YSI Model 58 or Model 50B (Yellow Springs Instruments, Yellow Springs, OH, USA) between 1985 and 2003, and with a Eureka Manta I or Manta II (Eureka Water Probes, Austin, TX, USA) from 2004 onwards. Accuracy of the temperature sensors was ±0.1°C, and with a resolution of ±0.01°C. Instruments were cleaned and calibrated annually by the manufacturer.

We used the relative thermal resistance to mixing (RTRM) statistic as an estimate of the degree of stratification caused by differences in water density resulting from temperature changes (Vallentyne, 1957; Wetzel, 2001). RTRM is the ratio of the difference in density between the bottom and top of a specified water layer to the difference in density between water at 4 and 5°C:

$$\text{RTRM} = (\text{Density of bottom} - \text{Density of top})/(\text{Density @ } 4^\circ\text{C} - \text{Density @ } 5^\circ\text{C})$$

RTRM values account for the nonlinearity of the change in density with water temperature and add a quantitative measure of the difference in water density, and hence resistance to being mixed, between any two water layers. We calculated the RTRM value between each successive meter of water depth, e.g., the surface and 1, 1 and 2 m, etc. to the bottom. In practice, RTRM values above 30 are used to define the position of the metalimnion, the maximum RTRM valve depicts the depth of the thermocline (plane of maximum rate of change in density), and the total RTRM is the addition of valves over all depths and represents a measure of the total stratification stability (Kortmann et al., 1994).

Water temperature at depths of 1 m below the surface, and 1 m above the bottom were used as surrogates for epilimnetic and hypolimnetic temperature, respectively. Descriptive statistics, ANOVA, and regression analyses were performed using SigmaPlot version 12.5 or SPSS statistical software packages. Multiple regression analysis with forward selection was used to evaluate the importance and significance of climate factors on lake variables. A Shapiro-Wilk test was used to test for normality, a Spearman rank correlation between residuals and values of the dependent variable for constant variance testing, and a Durbin-Watson statistic to test for independence of residuals for all regression analyses. No transformations of variables were deemed necessary. We calculated results for July and August for all three sites, but since the trends were similar for both months we illustrate those for July. In addition to examining results for each site, we also pooled data from all sites for some analyses to reflect lake-wide conditions.

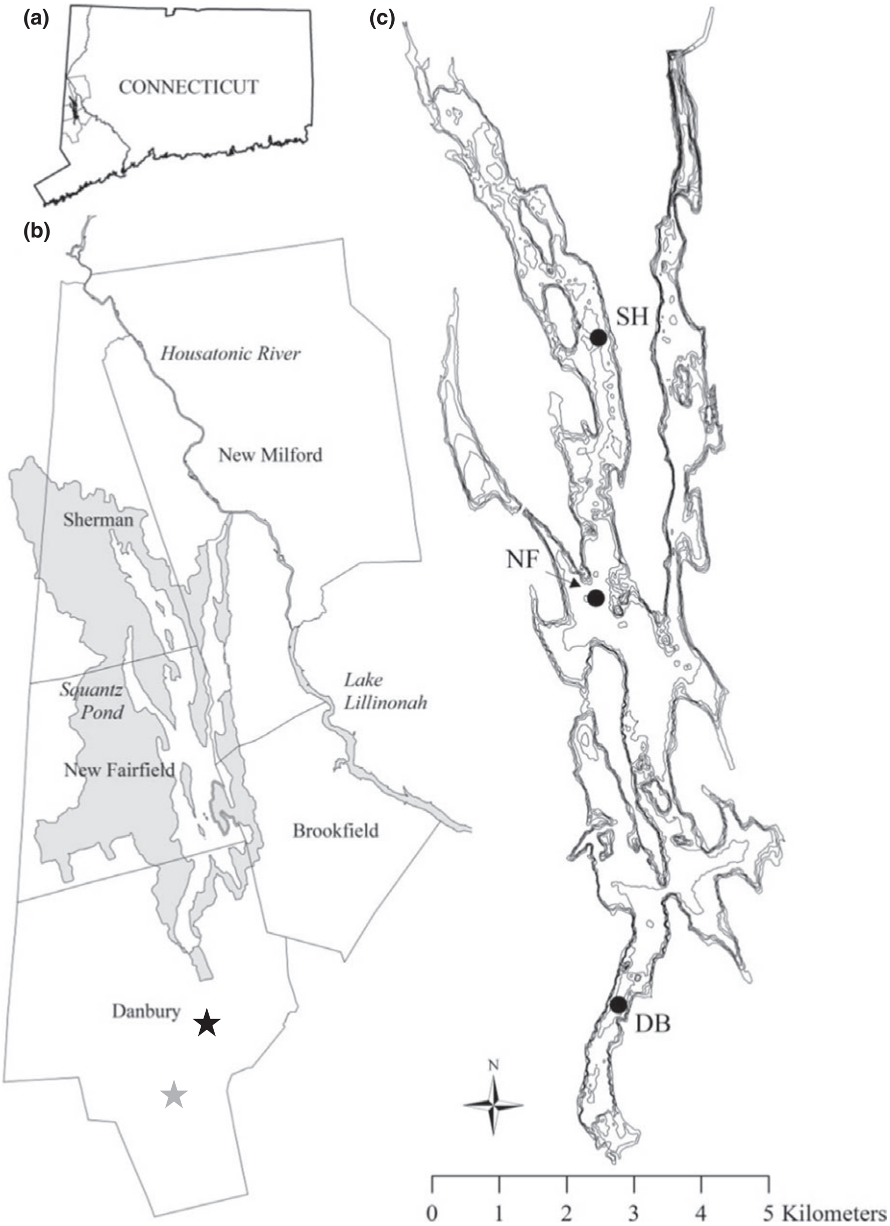

FIGURE 1 (a) Location of Candlewood Lake within the State of Connecticut. (b) Position of the lake with respect to the surrounding watershed (grey). Location of the WCSU weather station and the Danbury Airport are shown by the black and grey stars, respectively. (c) Details of the lake depicting locations of the three study sites, Danbury Bay (DB), New Fairfield (NF) and Sherman (SH).

We obtained temperature and precipitation data from the weather station at the Danbury, CT, Airport located 5.6 km from the southern end of Candlewood Lake (Figure 1). Mean monthly temperatures and total precipitation per month were used for our analyses. A complete set of wind speed and wind direction were not available from the Danbury Airport station. However, a complete wind data set covering the entire study period was available from the Western Connecticut State University Weather Center. The WCSU Weather Station is located on the Midtown Campus in Danbury, CT, 4.2 km northeast of the Danbury Airport and 2.4 km from the south end of the lake (Figure 1). Further, the position of the WCSU Weather Station, situated on a rooftop building approximately 10 m from ground level, has not changed over the study period, and this facility is the official weather station for a local television network. Daily means for all climate variables were averaged for the months of April through August, as well as for combinations of different months for the 31-year period. These months covered the period from ice-out through the development of summer thermal stratification. The mean temperature for the April through August period in 1991 was higher than usual. Data from two other weather stations (the Dutchess County Airport in Poughkeepsie, NY and Brainard Airport in Hartford, CT) corroborated the unusually warm period.

4 | RESULTS

4.1 | Climate variables

Daily air temperatures were averaged separately for the months of April through August for each of the 31 study years. The mean temperature for the period April 1 through July 31 (referred to herein as the mean temperature) was also calculated for each year. The mean temperature over the April through July period ranged from 15.3–19.1°C, with a mean of 16.6°C (Figure 2a). There was no significant time-related trend in air temperature for the April through July interval over the 31-year period. However, a significant decrease in air temperature was observed between 1993–2003 (r^2 = .62; p = .004), followed by a slight, but insignificant, increase since 2003. The total precipitation received on the lake between the April through July period ranged from 26–76 cm, with an average of 44 cm (Figure 2b). No significant trend in precipitation was found between 1985 and 2015.

Mean monthly wind speeds ranged from a low of 2.6 m/second in August, 2006, to a high of 6.1 m/second in June, 1993. The mean monthly wind speeds averaged over all years declined continuously from a high of 4.8 m/second in April to a low of 3.8 m/second for July and August (Table 1). Winds speeds were consistently lower during the summer months relative to the spring period for all 31 years. The wind speed significantly declined during each month from April through August over the study period (Table 1; Figure 2c). The largest declines occurred for the months of May (28%), June (28%) and August (35%), with a five-month decline of 31%. Wind speeds for the April–May period were significantly higher than

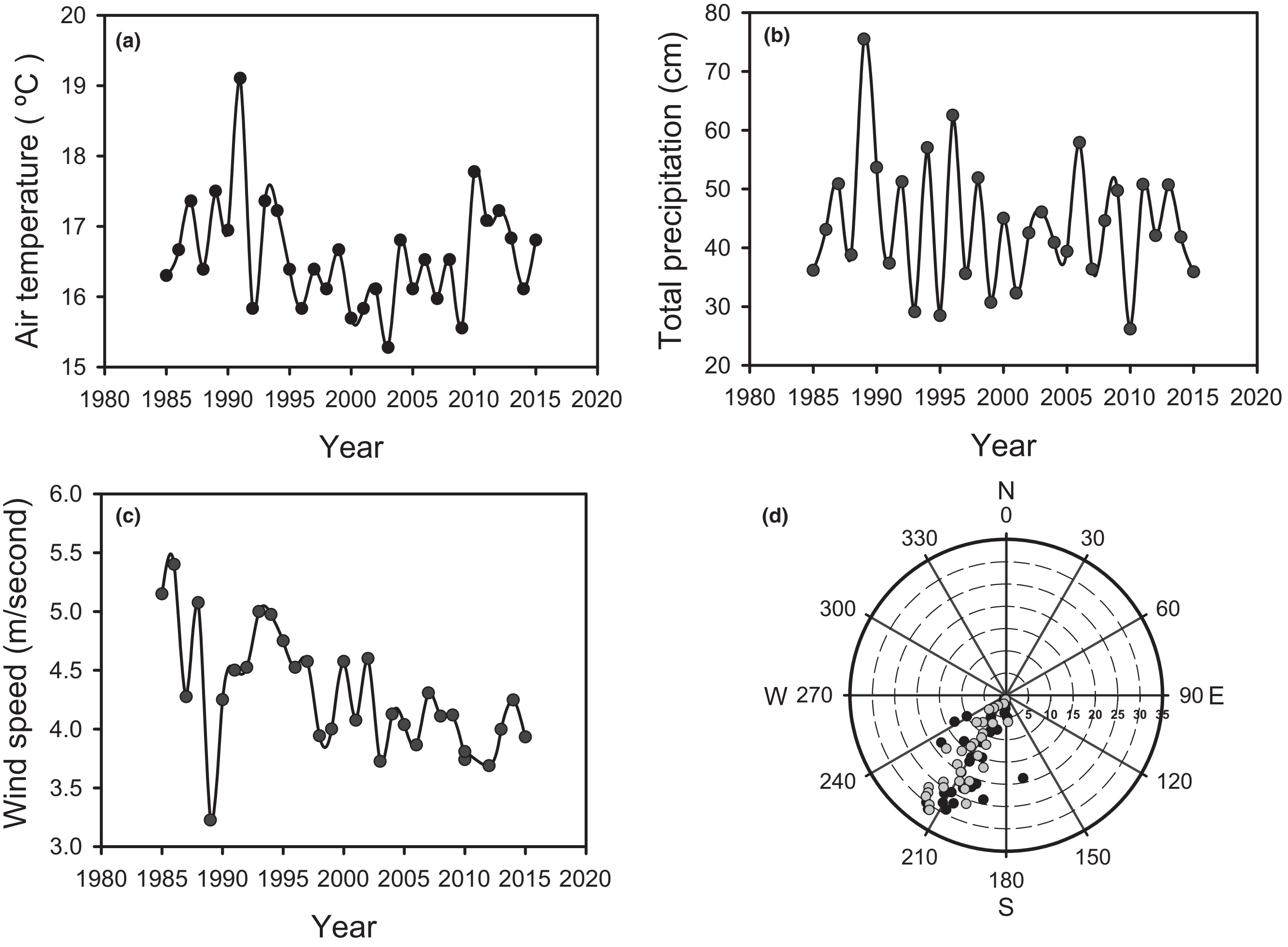

FIGURE 2 (a) Air temperature, (b) precipitation, (c) wind speed, and (d) wind direction for the period 1985–2015. Values for air temperature and wind speed represent means for the April 1 through July 31 period, and total precipitation is given for the same time period. Mean wind direction for April–May (black circles) and July–August (grey circles) is presented for all 31 years. Years from the start of the study are in distance along a radian line. There was a significant decline in wind speed over the study period.

TABLE 1 Mean wind speeds (m/second) for the months of April through August, and combinations of months, over the 31-year study period, 1985–2015

Month	Minimum	Maximum	Mean	r^2	*p*-value	% decrease
April	3.7	6.0	4.8	.19	.04	18
May	3.5	6.0	4.5	.51	<.001	28
June	3.0	6.1	4.1	.24	.005	28
July	2.5	5.0	3.8	.19	.013	20
August	2.6	5.1	3.8	.48	<.001	35
April & May	3.7	5.8	4.6	.31	.001	22
April–June	3.5	5.6	4.5	.39	<.001	24
July & August	2.7	4.8	3.8	.41	<.001	29
April–August	3.2	5.3	4.2	.40	<.001	31

The minimum and maximum mean values observed during the 31-year period, and the overall mean across all years are given. Results of regression analyses of mean wind speed versus year are also given. The wind speed has significantly declined for each month, and each combination of months. The percent decline in wind speed over the study period is presented.

those for July–August (Figure 3). Wind direction was remarkably similar over the 31 year period (Figure 2d). Although the five-month mean direction ranged from 188–230 degrees (from North), the range was between 200–230 degrees for 28 of the years. There were no significant differences in wind direction between any of the months, or between the April–May and July–August periods. As a result, the prevailing winds consistently originate from the southwest and flow across the lake.

4.2 | In-lake variables

The annual mean July temperature at 1 m (epilimnion) for all three sites ranged from 22.8–28.2°C, with a 31-year mean of 25.6°C (Figure 4a). Although the pattern in July temperature at 1 m was very similar between sites (Figure 5), there was no significant trend over time. Similar results were observed for the months of June and August (not shown). The annual mean temperature taken 1 m from the bottom (hypolimnion) during July for the study sites ranged from 12.1–16.5°C, with a 31-year average of 14.0°C (Figure 4b). In contrast to epilimnetic temperature, there was a significant negative trend in bottom temperature at each site over the 31-year period ($r^2 = .31$; $p = .001$), with mean hypolimnetic temperature declining by over 3°C between 1985 and 2015 (Figure 4b). The mean total RTRM for all sites during July ranged from 198–418, with an overall mean of 295 (Figure 4c). Results were similar between sites. There was no significant trend in total RTRM over time at any of the sites. The July mean maximum RTRM (i.e., the average of all three sites; Figure 4d), which reflects the largest RTRM value between any two adjacent water layers one meter apart and identifies the position of the thermocline, ranged from 65–170, with an overall mean of 97 ($n = 93$ profiles; 31 years × 3 sites). Prior to 2009, the mean maximum RTRM scores remained relatively constant. However, post 2009 (six year period) this parameter was significantly greater ($p < .001$; ANOVA) than any previous six year time period. The average value for the six year periods prior to 2009 ranged from 82–92, compared to 138 after 2009. Based on data from all three sites, the mean depth of maximum RTRM during July ranged from 5.3–8.3 m, with an overall mean of 7 m (Figure 6). There was no difference between sites, with mean depths of maximum RTRM ranging from 6.7 (SH) to 7.3 (DB), and no significant change over the study period.

4.3 | Relationships between in-lake and climate variables

July bottom temperature and maximum RTRM were highly correlated with wind speed (Figure 7). The mean July bottom temperature for all three sites significantly declined ($r^2 = .46$; $p < .001$) with decreasing wind speed (Figure 7a), a relationship observed independently for each site and also for bottom temperature during August. The relationship was strongest based on declining wind speeds during the spring period, e.g., the April–May and April–June time periods (Table 2). Declining summer bottom temperature was also significantly correlated with declining summer wind speeds (July–August). The relationships were strongest for the Sherman site (Table 2). In contrast, maximum RTRM values in mid-summer significantly increased ($r^2 = .24$; $p = .005$) with a decline in wind speed (Figure 7b). This pattern was also observed at all sites

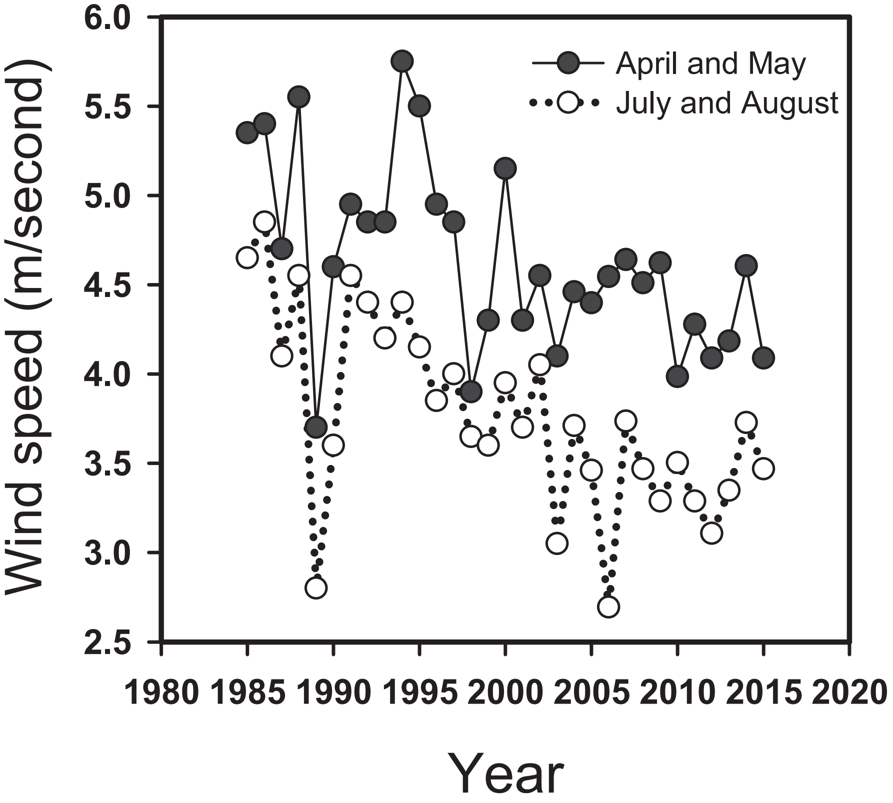

FIGURE 3 Mean wind speeds for April and May versus July and August between 1985 and 2015.

and for August. Summer bottom temperature and maximum RTRM were not correlated with air temperature, precipitation, wind direction, or any combination of climate variables. No significant relationships were found between other in-lake variables (e.g., epilimnetic temperature and total RTRM) and any of the climate variables. Even though there was no correlation with time over the 31-year period with epilimnetic temperature and total RTRM, these variables were highly correlated ($r^2 = .81$; $p < .001$; Figure 8a). Years with higher summer epilimnetic temperatures correspond with higher total RTRM. However, no relationship was found between July epilimnetic temperature and maximum RTRM (Figure 8b).

5 | DISCUSSION

Climate change is having a profound impact on freshwater lakes on local to global scales (Livingstone, 2003; O'Reilly et al., 2015; Torbick et al., 2016). Numerous studies have linked increases in water temperature, enhanced thermal stability, reduced ice cover, and other direct effects to climate warming using long-term (Adrian et al., 2009; Ambrosetti & Barbanti, 1999; Dokulil et al., 2006; Livingstone, 2003; Winder et al., 2008; Winslow, Read et al., 2017) and paleolimnological (Rühland et al., 2008, 2015) data. Impacts of changing precipitation patterns have also been identified in many of the investigations (Brown et al., 2017; Weyhenmeyer & Karlsson, 2009). However, few studies have incorporated wind speed and direction, along with air temperature and precipitation, possibly due to a lack of available data. If a region under study has experienced significant trends in both atmospheric warming and wind speed, but only records of the former variable are incorporated into the study, the contribution and importance of wind would not be realized.

The potential influence of wind on conditions such as stratification and phytoplankton structure should not be surprising given that an increase in warming is often coupled with a decline in wind speed (Barton, 2014; Feng et al., 2007), and since broad scale declines in wind speed have been well documented for regions impacted by anthropogenic warming (Pryor et al., 2009). Given that wind speed is, in part, a function of the difference in air temperature between regions, if anthropogenic warming results in a decrease in this temperature gradient then declining wind speeds would follow. Broad scale declines in wind speed have been well documented for the continental United States (Barton, 2014; Kulkarni & Huang, 2014; Pryor et al., 2009). Decreases of upwards to 15% over the last three decades have been observed over wide

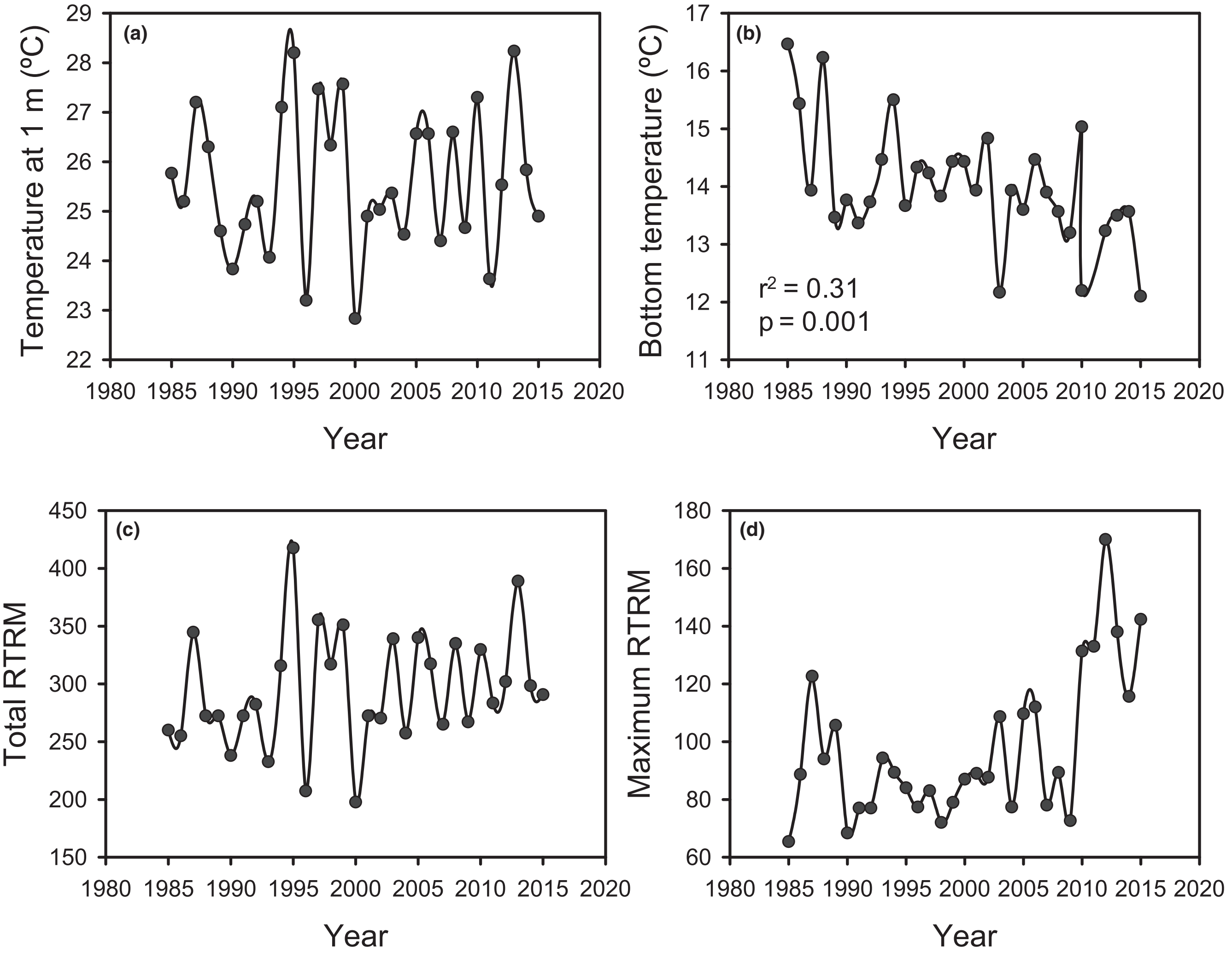

FIGURE 4 Trends in the July (a) epilimnetic water temperature, (b) hypolimnetic water temperature, (c) total RTRM, and (d) maximum RTRM in Candlewood Lake for the period 1985–2015. Values represent means for all three study sites. A significant decline in deep water temperature is noted.

geographic regions in North America and elsewhere in the world (McVicar et al., 2012). Further declines of at least 10% are forecast for sections of the United States during the summer period over the next century (Kulkarni & Huang, 2014). In addition, the direction of prevailing winds in North America, which directly influences atmospheric warming and precipitation patterns, has shifted significantly over the last 30,000 years (Feng et al., 2007). Thus, it is very possible that changes in wind speed have had equivalent, or even greater, impacts on lakes than has a change in atmospheric temperature, especially in mid and high latitudes that have experienced the most warming.

The importance of anthropogenic warming is undeniable, but as the primary agent responsible for supplying the energy for mixing water layers, the influence of wind can't be overlooked. Between 1985 and 2015, Candlewood Lake experienced a significant decline in wind speed during the spring between April and June, a time period representing post ice-out and development of summer stratification, as well as during the summer. The decline in wind speed was steady and consistent over the 31-year period, with an average decline of 9% per decade. Wind speeds were also consistently, and significantly, lower during the summer months of July and August than in spring. The decline in wind speed would reduce the amount of energy acting on the surface of the lake and available to mix warmer waters to deeper depths. The more wind energy acting on the lake surface during spring as surface waters warm from increasing solar radiation, the more heat will be transported to deeper sections of the lake (Hutchinson, 1957; Livingstone, 2003; Wetzel, 2001). Higher wind activity in spring would tend to extend the overturn period and result in higher temperatures throughout the water column as the stratification process commences (Hutchinson, 1957; Wetzel, 2001). Thus, other variables remaining constant, higher wind speeds during spring overturn and development of thermal stratification would yield a warmer hypolimnion. Alternatively,

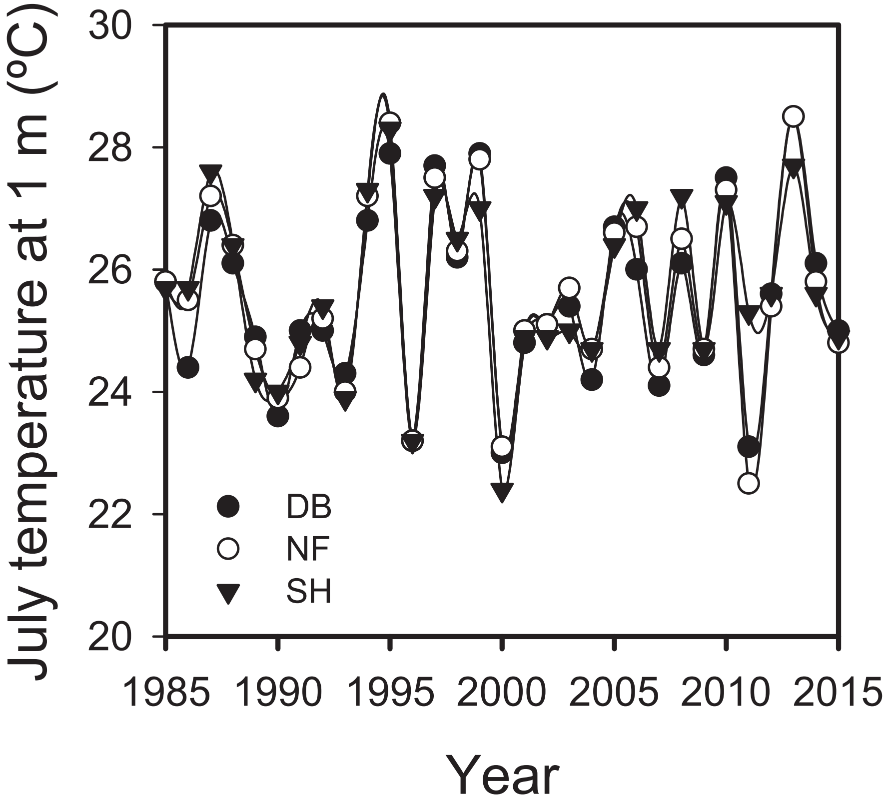

FIGURE 5 Trend in the July epilimnetic water temperature for each site, Danbury Bay (DB), New Fairfield (NF) and Sherman (SH), over the period 1985–2015.

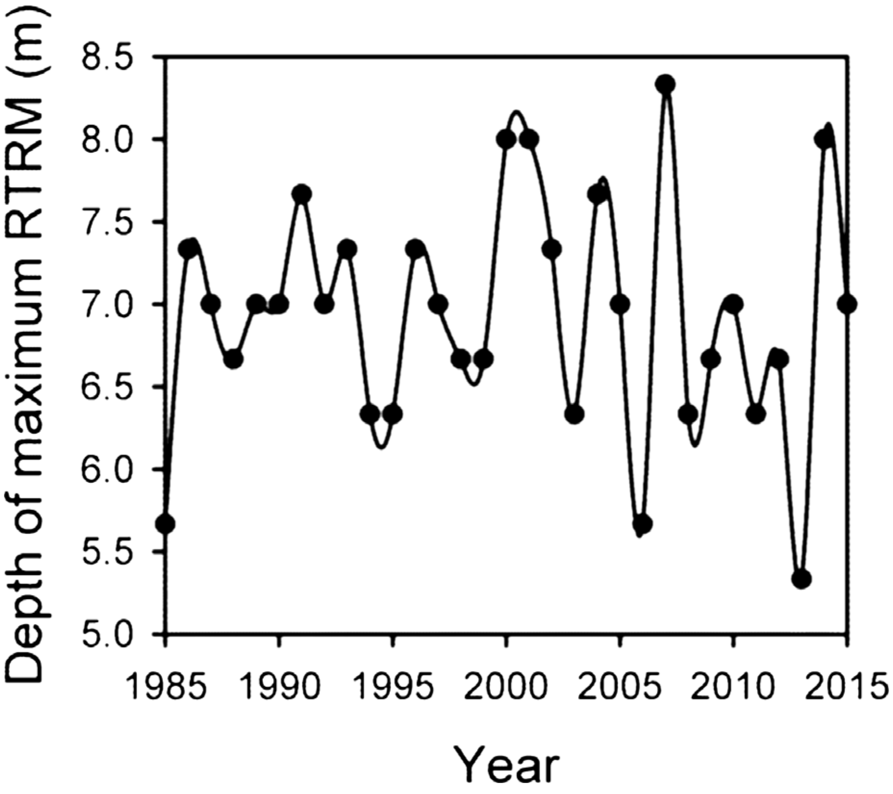

FIGURE 6 The mean depth of maximum RTRM in July for all three sites over the period 1985–2015.

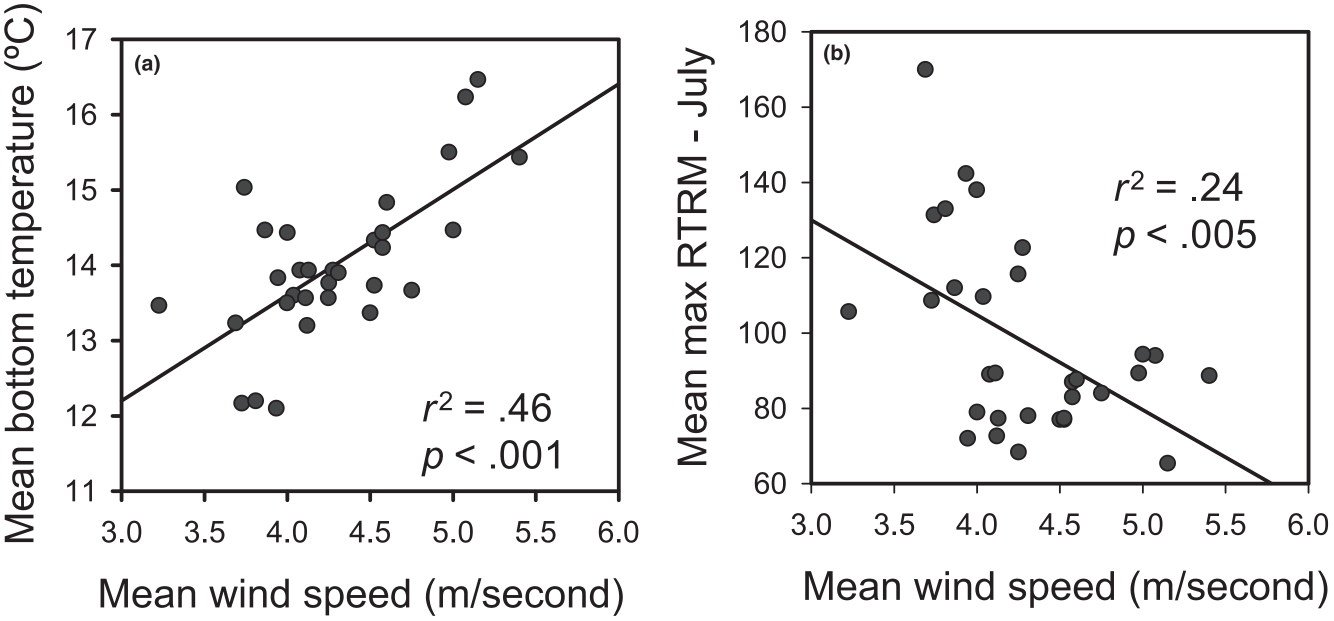

FIGURE 7 The relationships between mean wind speed during April–June versus (a) mean hypolimnetic temperature and (b) mean maximum RTRM during July.

TABLE 2 Results of regression analyses of the July bottom temperature versus wind speed

	DB		NF		SH	
Months	r^2	*p*-value	r^2	*p*-value	r^2	*p*-value
April–May	.30	.003	.20	.020	.51	<.001
April–June	.33	<.001	.25	.008	.60	<.001
July–August	.27	.003	.18	.016	.46	<.001
April–August	.31	<.001	.22	.008	.58	<.001

Results are given for all three sites, Danbury Bay (DB), New Fairfield (NF) and Sherman (SH), and for four combinations of months, two representing spring time (April–May and April–June), one summer time (July–August), and for the April–August period. In all cases, there was a significant decline in July bottom temperature with declining wind speeds.

a decrease in wind energy, especially during the spring period, should result in less warm water delivered to the lake bottom during development of thermal stratification and lower hypolimnetic temperatures, which represents the situation in Candlewood Lake.

For the majority of lakes situated in areas experiencing atmospheric warming, the temperatures of surface waters have increased (Kraemer et al., 2015; Livingstone, 2003; Rühland et al., 2015; Torbick et al., 2016; Winder & Sommer, 2012; Winslow, Read et al., 2017). Future warming, especially of surface waters, is predicted for a range of lake types and climatic settings over the continental United States (Butcher et al., 2015). A similar trend is not necessarily true for hypolimnetic waters where a high degree of variability can occur across lakes in a given region (Winslow, Read et al., 2017). Adrian et al. (2009) noted that despite rising atmospheric temperatures, impacts on hypolimnetic temperatures are more “complex” and may trend up or down depending on differences in lake morphometry, seasons and other variables. In a study of 26 lakes spread over multiple continents and situated in regions experiencing atmospheric warming, Kraemer et al. (2015) reported mean increases in surface and bottom temperatures of 0.84 and 0.05°C, respectively, between 1970 and 2010. However, significant increases in the bottom temperatures were recorded in only nine of the waterbodies, whereas the temperature actually declined slightly in five lakes and significantly so in another. Using data from a 30-year monitoring program to examine shifts in planktonic diatoms for two lakes in the Experimental Lakes Region in Ontario, Canada, Wiltse et al. (2016) reported that the mean hypolimnetic temperature increased in Lake 239, but significantly declined in nearby Lake 224. In another study of six Wisconsin lakes based on data from between 1981–2015, Winslow, Read et al. (2017) reported warming trends in hypolimnetic waters for five of the waterbodies, but a significant decline in temperature

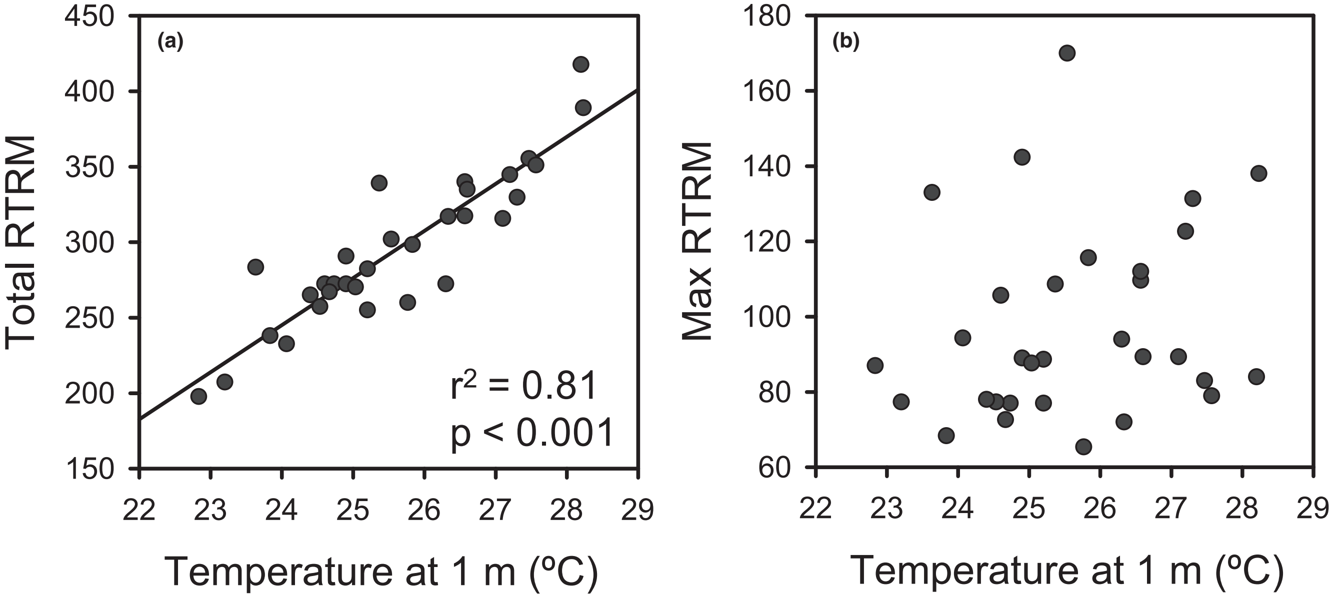

FIGURE 8 The relationships between July epilimnetic temperature versus (a) total RTRM and (b) maximum RTRM during July. The relationship with total RTRM is highly significant, but no relationship was observed with maximum RTRM.

for one lake. Causes of the cooling trends in these studies were not identified, although Winslow, Read et al. (2017) suggested a possible decline in water clarity. None of the studies suggested a link with wind speed. In the case of Candlewood Lake, the cooling trend recorded in the hypolimnion during summer stratification was significantly linked to declining spring and early summer wind speeds.

Intensified stratification caused by climate warming can potentially affect lake trophic status. According to Winder and Sommer (2012), enhanced stratification stretching over longer time periods could increase depletion of oxygen in bottom waters resulting in longer anoxic periods and increased rates of internal loading of nutrients (Wilhelm & Adrian, 2008). In contrast, intensified stratification would also tend to cause a decline in the transport of nutrients across the metalimnion (Kortmann et al., 1994). A decline in hypolimnetic temperature, as witnessed in Candlewood Lake, could act to reduce internal loading from sediments in several ways. First, at the onset of thermal stratification the cooler bottom waters would contain higher concentrations of oxygen, meaning that aerobic bacterial processes would likely extend further into the summer period before switching to use of alternative electron acceptors other than oxygen. Assuming the water was saturated when delivered to the hypolimnion at the onset of stratification, the decrease in bottom temperature observed in Candlewood Lake would result in an 8% increase in dissolved oxygen. Second, and perhaps more importantly, bacterial affinity for substrates declines as the temperature drops below optimal conditions (Nedwell, 1999). Thus, a longer period of aerobic conditions, coupled with a decrease in substrate affinity due to the lower temperatures, would tend to reduce the internal loading of nutrients from sediments. The fact that Kohli et al. (2017) documented a slight decline in hypolimnetic total phosphorus concentrations at all three sites over the last three decades, lends support to the hypothesis that in Candlewood Lake declining hypolimnetic temperatures could have resulted in a decrease in internal loading of nutrients.

The maximum RTRM value identifies the position and strength of the thermocline, the depth within the water column that presents the largest resistance to mixing. Maximum RTRM values greater than 80 represent especially significant changes in density. The mean maximum RTRM for July across all years and sites was 97, indicative of a strong and well-developed thermocline. However, there was a high degree of variability with values ranging from 65 to 170. The situation was similar for August, but with a slightly lower mean maximum RTRM of 91 and a range of 55–140. All else being constant, a decrease in wind speed during summer thermal stratification, and therefore a decline in wind energy acting on the waterbody, would result in a lesser percentage of the net heat absorbed in surface waters being mixed to deeper portions of the lake. This would increase both the temperature gradient and the maximum RTRM, resulting in a stronger thermocline. Such a pattern was documented for Candlewood Lake where an increase in maximum RTRM was significantly correlated with a decline in wind speed over time.

We originally anticipated that larger maximum RTRM values would be found at shallower depths given lower wind energy and a relatively constant wind direction. Although shifts in the depth of the thermocline (depth of maximum

RTRM) were observed over the 31-year period, a consistent pattern was not found. The range in depth of maximum RTRM during July was 5.3–8.3 m, with an overall mean of 6.9 m. Kraemer et al. (2015) found that the depth of maximum change in water density due to temperature differences (i.e., maximum RTRM) was difficult to predict due to the complex set of variables that impact this factor. In addition to shifts in wind energy, the depth of the thermocline during mid-summer is also related to the temperature of the epilimnion, heat exchange with the atmosphere, basin morphology, patterns of ice cover, timing and severity of storm events, and water clarity (Brown et al., 2017; Kraemer et al., 2015; Winslow, Hansen et al., 2017). In our study, spring and summer air temperatures were highly variable over the 31-year period, resulting in a high degree of variability in the summer epilimnetic temperature in the lake. This, in turn, contributes to variability in the depth of the thermocline (Kraemer et al., 2015). Interestingly, the summer epilimnetic temperature and depth of the thermocline were virtually identical between the three sites, indicating that the complex of variables influencing thermocline depth is similar across the lake.

Changes in the degree of turbulent mixing linked to shifting wind patterns can significantly alter the composition of the phytoplankton community in surface waters (Huisman et al., 2004; Rühland et al., 2015; Winder & Sommer, 2012). Changes in the mixing regime relative to the degree of thermal stratification can directly impact the position of an organism within the water column, the ability of the organism to remain in surface waters, and can shift competitive advantages for light and nutrient resources (Livingstone, 2003; Winder & Sommer, 2012). It has long been known that increased wind-induced mixing, as well as artificial mixing of smaller ponds, can favor heavier phytoplankton, such as diatoms and some green algae, by keeping them suspended in surface waters and enabling them to compete for light and nutrient resources (Bailey-Watts et al., 1987; Huisman et al., 2002; Kortmann et al., 1994; Reynolds et al., 1983). In contrast, reduced mixing and periods of calm weather favor smaller species and more buoyant organisms, especially cyanobacteria that produce aerotopes (gas vesicles). Under conditions of low turbulence, aerotope-aided cyanobacteria can often accumulate near or at the surface effectively absorbing a significant portion of the light energy, while the heavier species (e.g., diatoms) sink lower in, or even out of, the epilimnion (Findlay et al., 2001; Huisman et al., 1999, 2004; Walsby et al., 1997). Smaller species, especially ones with added form resistance, will also sink more slowly than large-celled taxa under low mixing regimes. Other factors, such as elevated water temperatures, low TN:TP ratios, and ability to fix nitrogen, can further favor growth of cyanobacteria (Cronberg & Annadotter, 2006), including toxin-producing forms (Paerl & Huisman, 2009). Less mixing during thermal stratification can further reduce the degree of eddy turbulence acting at the thermocline, which in turn, would reduce the movement of materials (e.g., gases and nutrients) between the hypolimnion and epilimnion (Hutchinson, 1957; Livingstone, 2003; North et al., 2014).

The potential impact of climate warming on the specific composition of planktonic diatoms has received significant attention and was recently reviewed by Rühland et al. (2015). Integrating results from modern, long-term, and paleolimnological data sets representing a wide range of latitudes and spanning most continents, Rühland et al. (2015) documented numerous examples where the relative abundances of small diatoms have increased at the expense of larger and heavier diatom species. In many of the examples, changes in lake thermal structure attributed to climate warming correlated with the switch towards smaller diatoms (e.g., Winder et al., 2008). A common observation in many of the lakes was a decrease in the relative concentrations of *Aulacoseira*, coupled with a concurrent increase in smaller cyclotelloid species (e.g., *Discostella stelligera*) or colonial forming pennate diatoms (e.g., *Asterionella*). In addition to enhanced thermal stratification, other climate-related variables such as changes in duration and timing of ice cover, length of overturn periods, wind patterns and precipitation were also found to impact diatom phytoplankton structure (Rühland et al., 2015). The potential impact of each of these variables is, in turn, influenced by basin morphology, fetch length, and landscape characters (Butcher et al., 2015; Fee et al., 1996; Gorham & Boyce, 1989; Kraemer et al., 2015). Other factors, such as nutrients, quality and quantity of light, pH, and zooplankton dynamics, also play important roles in structuring phytoplankton communities, including diatoms (Adrian et al., 2009; Rühland et al., 2015; Saros et al., 2012; Winder et al., 2008). For example, Saros et al. (2012) reported that nitrogen concentrations significantly impacted the response of *D. stelligera* to warming-induced changes in mixing depth, highlighting the complex interaction of factors controlling phytoplankton community structure. Given our findings, it is certainly possible that decreases (increases) in wind speed have also played a significant role in causing observed increases (decreases) in small-celled diatoms at the expense of larger and heavier species. Including wind speed in future studies may aid in explaining changing patterns in phytoplankton species composition.

Although the composition of the phytoplankton was not part of the long-term monitoring program at Candlewood Lake, cyanobacteria dominated the summer phytoplankton in the mid 1980s (Freeda & Siver, 1986), continue to dominate the summer plankton today, and there have been more cases of surface accumulations of buoyant cyanophytes noted by the Candlewood Lake Authority (CLA) over the last decade. Species of *Dolichospermum* (*Anabaena*) have (Freeda & Siver, 1986) and continue to dominate the summer phytoplankton community, and the surface accumulations, in Candlewood

Lake. The increased occurrence of surface accumulations of this and other buoyant cyanobacteria is especially interesting since Kohli et al. (2017) found no significant increase in either chlorophyll-*a* or total phosphorus concentrations in the epilimnion at any of the sites in Candlewood Lake over the last three decades. It is very likely that the uptick in surface accumulations of cyanobacteria is a response to reduced mixing caused by the declining wind speeds, especially during July and August.

In conclusion, despite the lack of trends in air temperature or precipitation over the 31-year study period, a decline in wind speed was significantly correlated with a decline in the temperature of the hypolimnion, and with an increase in thermocline strength in Candlewood Lake. A decline in wind speed during spring and early summer, as documented for Candlewood Lake, reduced mixing of warming surface waters to deeper depths during formation of thermal stratification, and shortened the period of spring overturn, both resulting in a cooler hypolimnion. It is highly probable that a decline in wind speed is a primary driver for cooling hypolimnia being reported in other lakes worldwide. Likewise, the decline in wind energy resulted in less warm surface water being driven to deeper sections of the water column, which yielded a greater difference in water density between the surface and bottom of the lake, and hence an increase in thermal stratification. Potential implications of a cooling hypolimnion and enhanced thermal stability of the water column on phytoplankton structure and composition, distribution of nutrients, and other processes are many.

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