LIMNOLOGY and OCEANOGRAPHY

ASLO

*Limnol. Oceanogr.* 9999, 2020, 1–11

doi: 10.1002/lno.11654

# Atmospheric stilling and warming air temperatures drive long-term changes in lake stratification in a large oligotrophic lake

**Jonathan T. Stetler**,[1*] **Scott Girdner**,[2] **Jeremy Mack**,[2,a] **Luke A. Winslow**,[1] **Taylor H. Leach**,[1] **Kevin C. Rose**[1]

[1]Department of Biological Sciences, Rensselaer Polytechnic Institute, Troy, New York
[2]U.S. National Park Service, Crater Lake National Park, Crater Lake, Oregon

## Abstract

Lake surface temperatures are warming in many regions and have the potential to alter seasonal thermal stratification. However, the effects of climate change on thermal stratification can be difficult to characterize because trends in thermal stratification can be regulated by changes in multiple climate variables and other characteristics, such as water clarity. Here, we use long-term (1993–2017) data from near-pristine Crater Lake (Oregon) to understand long-term changes in the depth and strength of summer stratification, measured by the center of buoyancy and Schmidt Stability, respectively. The depth of stratification has shoaled significantly (2.4 m decade$^{-1}$), while stratification strength exhibited no long-term trend. Empirical observations and modeling scenarios demonstrate that atmospheric stilling at Crater Lake is associated with the 25-year shoaling trend as spring wind speeds declined over the observation period. While summer lake surface water and air temperatures warmed during the study period, spring air temperatures were variable and correlated with summer Schmidt Stability. Our results indicate that warmer spring air temperature resulted in earlier onset of stratification and stronger summer stratification. The observed shoaling of stratification depth at Crater Lake may have important ecological consequences, especially for non-motile primary producers who can become constrained within a thinner epilimnion and exposed to higher solar radiation and reduced upwelling of nutrients. Driven by climate changes, many large lakes may be experiencing similar trends in seasonal stratification.

Seasonal thermal stratification (hereafter, “stratification”) is a major regulator of physical, chemical, and biological processes in lakes and reservoirs. In freshwater lakes, stratification characteristics such as the depth and strength of stratification are determined primarily by vertical temperature gradients. In turn, stratification influences many lake features such as the depth of primary production (Leach et al. 2018), exposure of planktonic organisms to damaging ultraviolet light (Rose et al. 2009), movement and dispersal of plankton assemblages (Serra et al. 2007), the volume and quality of fisheries habitat (Hansen et al. 2017), deep-water oxygen levels and renewal (Jankowski et al. 2006; Piccolroaz and Toffolon 2018), and atmospheric gas exchange (Tranvik et al. 2009; Read et al. 2012).

Substantial evidence shows that lake surface temperatures are warming rapidly in response to climate change (O’Reilly et al. 2015; Winslow et al. 2018). However, the effects of climate change on lake stratification are less clear. Climate change can encompass changes in multiple characteristics such as air temperature, wind speed, and precipitation, which may influence the strength and depth of stratification in different ways. Some past research has hypothesized that increased temperatures would induce a shoaling of stratification and surface mixed layers (Hondzo and Stefan 1993; De Stasio Jr et al. 1996) by decreasing the depth of surface convective mixing (Fang and Stefan 1999; Jankowski et al. 2006). However, empirical evidence from long-term observations supporting this hypothesis is lacking. For example, Kraemer et al. (2015), found that the depth of stratification significantly deepened in 9 of 26 lakes, whereas none of their study lakes exhibited a significant shoaling in thermocline depth.

Warming surface waters may also increase the strength of stratification. Observations indicate that surface water temperatures are warming faster than deep-water temperatures in some regions, resulting in stronger water column stratification in some lakes (Kraemer et al. 2015; Winslow et al. 2015; Richardson et al. 2017). However, other research indicates that climate warming can induce earlier ice cover breakup, thereby resulting in a prolonged spring mixing period and warmer

*Correspondence: stetlj@rpi.edu

Additional Supporting Information may be found in the online version of this article.

[a]Current Address: Center for Innovation in Teaching and Learning, Lehigh University, Bethlehem, Pennsylvania, USA

deep-water temperatures, which in turn can reduce summer stratification strength (Couture et al. 2015).

In addition to warming air temperatures, changes in precipitation and wind speeds may occur as part of climate change and can regulate lake stratification. Precipitation is changing in many regions. For example, in the western United States, winter snowpacks have been declining in recent decades (Mote et al. 2005, 2018). Reduced snowpack decreases the volume of spring inflows to lakes, in turn altering summer water temperatures (Sadro et al. 2018). Further, long-term declines in wind speeds, also referred to as "atmospheric stilling" have been observed in many regions (Roderick et al. 2007; Pryor et al. 2009; McVicar et al. 2010; McVicar et al. 2012; Deng et al. 2018). Although stilling may not be directly driven by climate change (Vautard et al. 2010), wind plays an important role in determining the depth of stratification by regulating physical mixing, especially in larger lakes (Fee et al. 1996; Read et al. 2012). Indeed, wind speeds may be just as important as air temperature in driving changes in thermal stability, and may amplify or suppress air temperature warming effects, depending on the direction and magnitude of wind speed change (e.g., Magee and Wu 2017; Woolway et al. 2019). The relative and combined importance of changing wind speeds, precipitation, and inflows on stratification relative to warming or one another are largely unknown, especially when observed patterns in climate (e.g., warming temperatures and atmospheric stilling) are expected to have opposite effects on thermal characteristics.

Forecasting the future impacts of climate change on the depth and strength of stratification requires understanding the effects of changes in air temperature, wind speed, and precipitation in isolation and together in systems lacking other major types of environmental change that can impact stratification. However, because changes often occur simultaneously, it can be difficult to identify mechanisms producing stratification changes. In addition to long-term observations, one way to understand long-term physical changes in lakes is by the application of hydrodynamic modeling. Here, we use a long-term (25 years, 1993–2017) observational data set and calibrated hydrodynamic model to understand climate change impacts on the depth and strength of stratification in Crater Lake, Oregon as representative of potential climate change impacts in large lakes.

## *Materials and methods*

Our goal was to assess the degree to which climate changes (i.e., increases in air temperatures, changes in wind speeds and precipitation) induce changes in depth and strength of stratification. To do this we first analyzed long-term in situ observations from Crater Lake over a 25-year period (1993–2017) to characterize empirical trends in stratification strength and depth and identify potential drivers of long-term trends. Second, we calibrated and validated a one-dimensional lake hydrodynamic model (General Lake Model V 2.2 (GLM); Hipsey et al. 2019) to recreate observed long-term stratification trends. Finally, we ran a series of scenarios in GLM based on observed trends in Crater Lake. These scenarios manipulated components of climate change in isolation to assess their relative impact on long-term trends in depth and strength of stratification.

### Study site and observational data

Crater Lake is a deep (594 m) ultra-oligotrophic caldera lake with a surface area of 53.2 km$^2$ (Bacon et al. 2002). The lake has had no land use change over the observational period owing to its protected status in a U.S. National Park, enabling improved attribution of observed changes to climate. Summer water transparency is high, with Secchi disk depths usually around 30 m (Larson et al. 2007). Consistent summer vertical temperature profile observations have been collected since 1993 using a SeaBird profiling conductivity, temperature, and depth (CTD) sensor (model 19 and model 19plus) (Crawford and Collier 2007). Meteorological and surface water temperature data has been collected nearly continuously over the observation period of 1993–2017 by an on-lake weather buoy.

### Metrics of stratification

We examined summer vertical temperature profiles from the down cast of the CTD profile to characterize long-term trends in summer stratification depth and strength. In 1999, a new CTD instrument was introduced (SBE model 19plus). During that year, both CTDs were cast together, and temperatures were strongly correlated ($r^2 = 0.998$, $P < 0.001$). We applied a small correction factor to CTD profiles collected prior to 1999 using the linear regression obtained in 1999, and used these corrected data prior to 1999 for all analyses. Mean stratification measurements taken between July 15th and September 15th (hereafter referred to as "summer") were averaged together from vertical temperature profiles to create annual ($n$ = 25 years) averages. We chose to exclude profiles in the beginning of July and end of September because the lake exhibited strong day to day variability in stratification; indicating that stratification for the summer was not fully set up yet in early July, and by the end of September stratification was weakening and deepening (Fig. S1). On average, there were five temperature profiles collected each season (range: 3–8).

We used rLakeAnalyzer V1.11.4 (Read et al. 2011; Winslow et al. 2018*b*) in R (R Core Team 2016) to calculate mean annual summer metrics of stratification. We calculated Schmidt Stability (Idso 1973) and used it as a measure of stratification strength. Schmidt Stability is a measure of the amount of energy required to mix a lake to isothermal conditions without heat exchange. We used the center of buoyancy as a measure of stratification depth. Center of buoyancy is defined as the depth of the 50th percentile of the Brunt-Väisälä buoyancy frequency throughout the entire water column. The center of buoyancy is an integrative metric of stratification depth that is relatively stable over hours to days (e.g., compared with thermocline depth; Fig. S2) and therefore useful to characterize long-term trends from periodic profile data.

### Model description

We used GLM V 2.2 (Hipsey et al. 2019), an open source one-dimensional hydrodynamic model to simulate the annual progression of lake water temperatures and estimate seasonal stratification depth and strength from 1993 to 2017. The one-dimensional approach used by GLM is robust to diverse conditions and has previously been applied across a wide variety of lake-types (Bruce et al. 2018). GLM uses lake specific morphometry and physical characteristics, along with meteorological data at an hourly timestep and daily inflow volumes to predict lake water temperatures throughout the entire water column. GLM required hourly time-series meteorological data including air temperature, wind speed, relative humidity, downwelling shortwave and longwave radiation, and precipitation in the form of rain and snow, which were obtained primarily from the on-lake buoy. The quality checking and processing of these data are described in the Supporting Information.

We ran the model seasonally to focus exclusively on summer conditions. For each simulation year, the model was initialized with an isothermal temperature profile of 3.9 °C 1 week before the date of the empirically observed onset of stratification. We chose an initial isothermal profile because high frequency temperature data in the surface mixed layer was largely absent (the surface mixed layer was always on average less than 20 m deep, and the two shallowest temperature sensors were at 0 m and 20 m). Further, using observed initial values from a sensor string resulted in poorer model fit. We initialized the model across various isothermal profiles to determine which temperature resulted in the most accurate model. We concluded that initializing the model with an isothermal temperature profile of 3.9°C yielded the most accurate model results (Figs. S3, S7). Model fit, as measured by root mean squared error (RMSE), based on an initial isothermal temperature of 3.9°C was 0.48°C.

We determined the onset of stratification based on temperatures sensors deployed in the lake. Surface water temperature observations were collected under an on-lake buoy near the center of the lake. However, surface data were occasionally missing due to equipment failure. In this case, missing data were filled in from a thermistor located at a lake level gage at a nearshore site, Cleetwood Cove. Surface temperatures from the buoy and Cleetwood Cove were significantly correlated with a 1 : 1 relationship ($P < 0.001$, $r^2 = 0.99$, slope = 1.0). Onset of stratification was identified as the day of year when mean daily surface water temperature at the weather buoy reached and remained above 3.98°C, the temperature of maximum density (Austin and Colman 2007). We did not run the model through winter because the model would occasionally incorrectly form ice on the lake, which would alter spring water temperature characteristics and reduce model accuracy. We also removed snowfall from the precipitation data which resulted in minimal ice formation. However, in the beginning of the model run, GLM would occasionally still form small amounts of ice (always less than 0.09 m) for a few days (always 15 d or less). More details are provided in the Supporting Information. Running the model seasonally provided accurate representation of temperature and stratification characteristics from spring through fall (approximately February through September; model accuracy results provided in the Results section). Simulations were ended on September 30th of each year.

### Empirical trends

We first characterized changes in meteorological variables through the study period. To do this, we calculated the Sen's slope (Sen 1968; Hipel and McLeod 1994) of daily mean values for wind speed and air temperature. We then calculated the seven-day moving average for each variable, excluding leap year days (February 29th). Further, we examined long-term annual trends in summer and spring (April and May) annual inflow volume and shortwave radiation.

We characterized long-term trends in key meteorological driver variables at different times of year by examining Sen's slope for each ordinal day. We examined trends climate characteristics in the summer period corresponding to our examination of trends in stratification indices. We also examined spring trends in air temperature and wind speed, as these may have effects that carry over into the summer period. We detected long-term patterns in stratification characteristics using the non-parametric Sen's slope (Sen 1968; Hipel and McLeod 1994) and tested their relationship to meteorological drivers using linear regressions. We used a Pettitt's test (Pettitt 1979) to determine if a single break point existed when no long-term trend was detected.

### Model parameterization and performance

GLM parameters (Table S2) were largely left as default values described in Hipsey et al. (2019), except for the bulk aerodynamic coefficient parameter for transfer of momentum, which was reduced from 0.0013 to 0.0004. This parameter was adjusted to improve fit of summer stratification depth. Metrics of stratification depth and strength have previously been shown to be sensitive to the bulk aerodynamic coefficient parameter in a "stress test" of GLM (Bruce et al. 2018). The light extinction coefficient (0.06 $m^{-1}$) was estimated from profiles of photosynthetically active radiation (PAR) irradiance vs. depth. Bathymetry data were previously collected from Gardner et al. (2000). Because there are not well-defined and permanent inflows (i.e., no large and permanent streams or rivers draining into Crater Lake), we calibrated the inflow parameters for the half angle (100) and stream bed slope

(0.05) as parameter values that produced the best model fit, described by the RMSE of annual summer center of buoyancy.

To assess model performance, we calculated RMSE for modeled center of buoyancy, Schmidt Stability, and water temperature at various depths relative to summer CTD casts (see Model accuracy and scenarios in results section). We calculated these values for annual observations (1993–2017). Annual field observations were based off of mean summer values from vertical profile observations. We compared empirical observations to simulated values on the same date and then calculated mean summer values.

### Climate scenarios

Following empirical analyses, we conducted a series of modeling scenarios to assess how three individual climate components (temperature, wind speed, or precipitation/inflow volume) affect long-term trends in stratification depth and strength using the calibrated GLM model. To run scenarios, all model parameter coefficients were set as described above. However, we initialized the model for each year on the same day of year because we were simulating changes in climate conditions that can affect the onset of stratification. The model was initialized on February 24th, which corresponds to 1 week before the earliest stratification onset of all observational years 1993–2017. When all models started on February 24$^{th}$ ice cover was slightly more prevalent than when the model began 1 week before the onset of stratification each year but always less than 0.11 m and persisted for a maximum of 28 d. Therefore, we chose to perform the same scenarios again, but allowing the model start date to vary based on the observed onset of stratification (i.e., 1 week before the onset of stratification each year). Initial water temperatures at each depth were set as an isothermal profile at 3.9°C. Consistent with our previous simulations, the model was terminated on September 30th each year. For each scenario, we characterized the long-term trend relative to observed conditions (mean and variance in stratification characteristics).

We were interested in how stratification characteristics responded to perturbation in wind speeds and air temperatures. To do this, we created a minimum and maximum scenario for both meteorological variables. We performed scenarios where each year the model was simulated with values that represented either the minimum or maximum annual mean value throughout the simulation period over the 25 years. All other variables did not change during the scenarios.

For wind, we first calculated the annual mean wind speed for every year during the observation period. We then identified the minimum (2017, 2.27 m $s^{-1}$) and maximum (2011, 4.18 m $s^{-1}$) mean wind speed years. We then made each year of the simulation have the mean minimum and maximum annual values by multiplying each hourly wind speed value over the entire year by the annual percent difference between that year and the minimum or maximum value. This approach retained seasonal and day to day variability in wind speeds while altering the magnitude of wind speeds to match the long-term annual minimum or maximum. For comparison, mean wind speed over the entire observational period (1993–2017) was 3.50 m $s^{-1}$.

We next performed scenarios where air temperature was either the 25-year minimum or maximum annual value of the simulation period. Similar to our scenario for wind speed above, we first identified the long-term annual minimum (6.13°C, year 2011) and maximum (9.87°C, year 2015). We first converted temperatures to Kelvin (to avoid negative values) and then made each year of the simulation have the mean minimum and maximum annual temperature by multiplying each hourly air temperature value over the entire year by the annual percent difference between that year and the minimum or maximum value. This manipulation made the annual average equal to the long-term annual minimum or maximum, while still retaining seasonal and day to day variability. For comparison, the mean air temperature over the entire observational period (1993–2017) was 7.93°C.

We simulated variations in inflow volume and how this impacted stratification strength and depth. Because there were no long-term patterns or trends (see results), instead of using the annual minimum and maximum inflow volume values, we increased or decreased inflow volume by 3 $m^3$ $s^{-1}$ while keeping the timing of inflow discharge the same to assess the impacts of changing precipitation volume on stratification. A daily inflow rate of 3 $m^3$ $s^{-1}$ represents an annual inflow volume of approximately 0.09 $km^3$, which represents approximately 9%–17% of the total epilimnion as defined by the depth of center of buoyancy depending on the year. In the reduced inflow scenario, any inflow volume that was negative after reducing it by 3 $m^3$ $s^{-1}$ was set to zero. By comparison, the mean inflow rate over the entire observational period was 1.7 $m^3$ $s^{-1}$ (range: 0–5.34 $m^3$ $s^{-1}$).

## Results

### Empirical trends

Long-term observations demonstrate that depth of stratification in Crater Lake, measured by center of buoyancy, has been shoaling at a rate of 2.4 m $decade^{-1}$ over the period 1993–2017 (Fig. 1a, $P < 0.001$). This equates to a reduction of the epilimnion by approximately 55% over the 25-year study period. Conversely, we observed no consistent long-term trend in stratification strength, as described by Schmidt Stability (Fig. 1b; $P = 0.59$). Further, a Pettitt's test was used to test for a break point in the time series, but a significant break point was not found ($P = 0.85$). Instead, Schmidt Stability exhibited substantial year to year variability. Summer surface temperatures significantly warmed over the study period at a rate of 0.6°C $decade^{-1}$ (Fig. S4a, $P = 0.02$). Meanwhile, temperatures at 20 m became colder throughout the study period at a rate of – 1.23°C $decade^{-1}$ (Fig. S4b, $P = 0.01$).

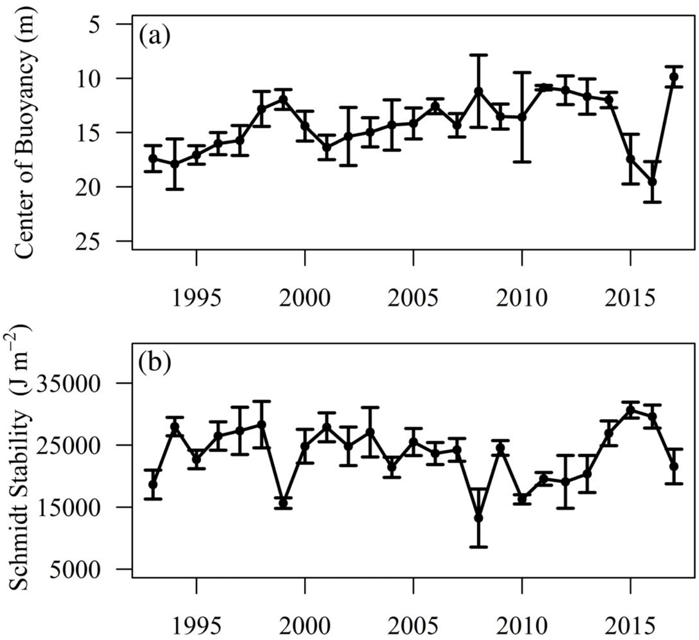


**Fig. 1.** Mean annual summer center of buoyancy (**a**) and Schmidt Stability (**b**). Error bars represent the standard error of mean profiles, defined as the period between July 15th and September 15th.

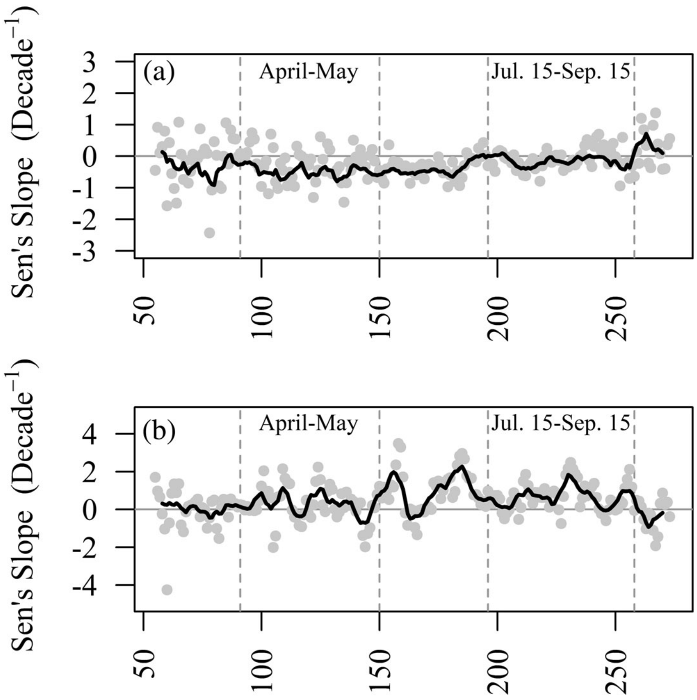


**Fig. 2.** (**a**) Seven-day moving average of the Sen's slope of daily mean wind speed values (**a**) and mean air temperature (**b**) from 1993–2017 (black line) and Sen's slope for each day (gray points). Horizontal gray line denotes a slope of 0 while vertical gray lines denote different times of the year.

Daily mean wind speeds exhibited long-term declines over most of the calendar year (Fig. 2a). The onset of stratification was most often in the months of April and May (n = 17; 68% of years). Similarly, while borderline significant ($P$ = 0.09), there is a general trend of declining wind speed in the April–May spring period. In contrast, there has been no long-term trend in daily mean wind speeds over the summer period (July 15th through September 15th; $P$ = 0.42), although there have been some shorter periods in mid-summer when wind speeds have declined (Fig. 2a). Meanwhile, mean air temperature has increased during the summer period (Fig. 2b; $P$ = 0.02 slope = 0.84°C decade$^{-1}$), but trends were much more variable in spring depending on the timeframe within the period of record ($P$ = 0.41). A Pettit's test revealed no significant break point in annual mean spring air temperatures ($P$ = 0.11). Spring shortwave solar radiation increased through the study period at a rate of 7.78 W m$^2$ decade$^{-1}$($P$ = 0.05). Summer shortwave radiation and spring and summer inflow did not exhibit any long-term trends throughout the study period (Fig. S5, all $P$s ≥ 0.15).

## Empirical meteorological conditions and summer stratification

Summer depth of stratification (measured by center of buoyancy depth) was significantly correlated with the frequency of spring low wind speeds (Fig. 3a; $P$ = 0.02, $r^2$ = 0.21) and mean summer wind speeds ($P$ = 0.02, $r^2$ = 0.22). However, the depth of stratification was not related to mean spring wind speed ($P$ = 0.68) or summer low wind speeds ($P$ = 0.20). Strength of summer stratification was significantly related to mean spring air temperature (Fig. 3b; $P < 0.001$, $r^2$ = 0.31), but not summer air temperature ($P$ = 0.12). Onset of stratification was also closely correlated with mean spring air temperatures ($P$ = 0.001, $r^2$ = 0.46,), with warmer air temperatures corresponding with earlier dates of stratification onset. Similar

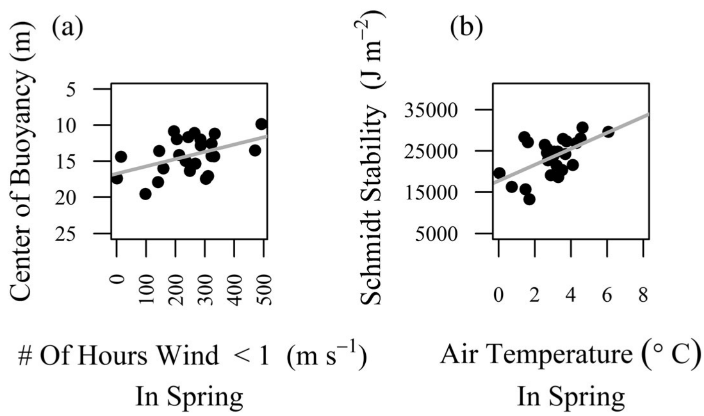


**Fig. 3.** Mean summer (July 15–September 15) center of buoyancy depth vs. low spring (April and May) wind spends (e.g., winds < 1 m s$^{-1}$; **a**). Mean summer Schmidt Stability vs. mean spring air temperature (**b**). Gray lines represent linear trends.

to spring air temperatures, there was no long-term trend in stratification onset ($P = 0.47$).

**Model accuracy and scenario results**

GLM accurately reproduced long-term trends of both depth and strength of stratification (Fig. S6). For the 25-year long-term trend, RMSE was 1.77 m for center of buoyancy and 4933.52 J m$^{-1}$ for Schmidt Stability. Summer water temperature RMSE was 0.48 °C and observed and simulated summer water temperatures were closely correlated throughout the entire water column (Fig. S7; $r^2 = 0.95$, $P < 0.001$).

Modeled perturbations to wind speeds strongly affected stratification depth. Simulations where wind speed was the long-term minimum (2.27 m s$^{-1}$) produced a 10% reduction in depth of stratification relative to the baseline simulation, while simulations at the long-term maximum annual wind speed (4.18 m s$^{-1}$) produced a 6% increase in depth of stratification (Table 1; Fig. 4). Slower winds also had a positive effect on water column stability, with the minimum wind speed scenario yielding an 11% increase in Schmidt Stability. Higher wind speeds had a small negative effect on Schmidt Stability with the maximum wind speed scenario yielding a 4% decrease in Schmidt Stability. However, the interannual variability often greatly exceeded the variability in Schmidt Stability due to differences in simulated wind speeds (Fig. 4). Slower wind speeds resulted in earlier onset of stratification by an average of 5 days, while faster wind speeds shifted onset of stratification later by an average of 2 days (Table 1).

Our warming scenario, had a small shoaling impact (2%) on the depth of stratification, and simulated colder air temperatures increased the depth of the center of buoyancy by 2% (Fig. 5; Table 1). In contrast to these small changes in the depth of stratification, air temperature changes had larger impacts on the strength of stratification. In the warming scenario, Schmidt Stability increased by 14%, while Schmidt Stability decreased by 11% when air temperature was set to the minimum annual value (Table 1; Fig. 5). However, similar to wind speeds, there was variability between the warming (or cooling) vs. the baseline simulation among years, with substantial differences in stratification strength in some years and essentially no difference in other years. Warmer temperatures resulted in earlier onset of stratification by an average of 5 days, and cooler air temperatures resulted in a later onset of stratification by 7 days (Table 1).

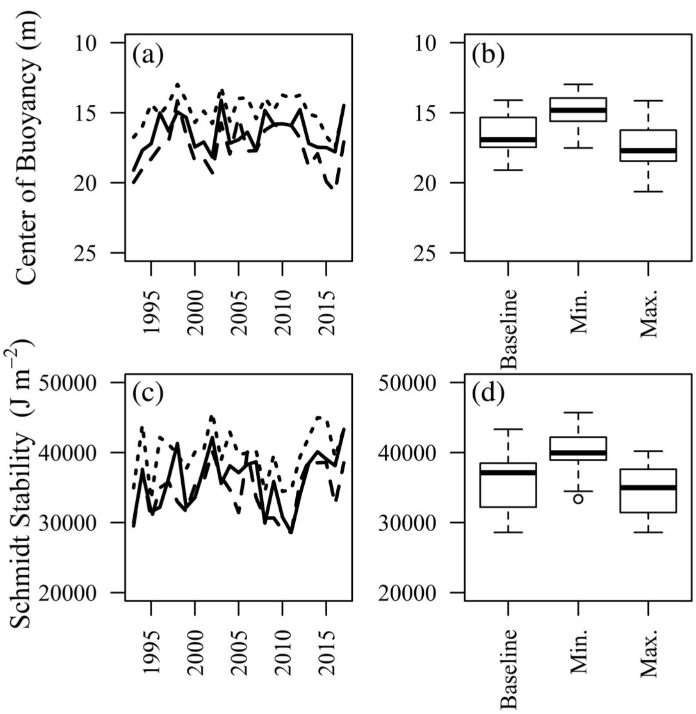


**Fig. 4.** Time series of wind speed scenarios of annual mean summer (July 15–September 15) center of buoyancy (**a**) and Schmidt Stability (**c**) from 1993 to 2017. Solid line denotes baseline scenario whereas dashed and dotted lines are scenarios where each year's wind speeds were altered so that each year's annual mean matched the mean of the highest and lowest mean year, respectively. Box and whisker plots in (**b**) and (**d**) represent distributions of annual summer center of buoyancy and Schmidt Stability, respectively from 1993 to 2017 for the different wind speed scenarios. Horizontal line denotes the median value.

**Table 1.** Mean summer (July 15th–September 15th) center of buoyancy, Schmidt Stability, and onset of stratification (day of year) responses to scenarios conducted. Percent change is relative to the baseline simulation conducted without any change in wind speed, air temperature, or inflow volume. Percentages and onset of stratification were rounded to the nearest whole number.

| | Center of buoyancy | | Schmidt Stability | | Onset of stratification |
|---|---|---|---|---|---|
| | Mean (m) | Percent change | Mean (J m$^{-2}$) | Percent change | Mean onset DOY |
| Baseline | 16.48 | NA | 36,027 | NA | 97 |
| Wind annual minimum (2.27 m s$^{-1}$) | 14.85 | −10 | 39,934 | +11 | 92 |
| Wind annual maximum (4.18 m s$^{-1}$) | 17.53 | +6 | 34,509 | −4 | 99 |
| Air temperature annual minimum (6.13°C) | 16.88 | +2 | 32,078 | −11 | 104 |
| Air temperature annual maximum (9.87°C) | 16.22 | −2 | 41,011 | +14 | 92 |
| Inflow − 3 m$^3$ s$^{-1}$ | 16.57 | +1 | 36,390 | +1 | 97 |
| Inflow + 3 m$^3$ s$^{-1}$ | 16.43 | 0 | 35,898 | 0 | 97 |

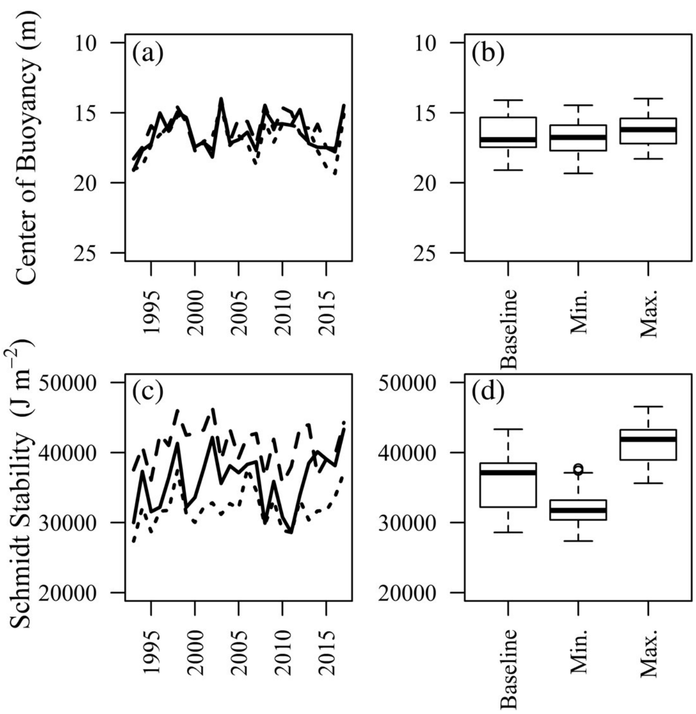


**Fig. 5.** Time series of air temperature scenarios of annual mean summer (July 15–September 15) center of buoyancy (**a**) and Schmidt Stability (**c**) from 1993 to 2017. Solid line denotes baseline scenario whereas dashed and dotted lines are scenarios where each year's air temperatures were altered so that each year's annual mean matched the mean of the highest and lowest mean year, respectively. Box and whisker plots in (**b**) and (**d**) represent distributions of annual summer center of buoyancy and Schmidt Stability, respectively from 1993 to 2017 for the different air temperature scenarios. Horizontal line denotes the median value.

We found very little effect of inflow volume on stratification depth, strength, or onset of stratification (Table 1). Reduced inflow volume slightly deepened the depth of stratification by 1% and increased the strength of stratification by 1%. Increased inflow volume had no effect on depth or strength of stratification.

Performing scenarios where the model was initialized 1 week before the onset of stratification every year resulted in similar findings. However, the effect of wind speed on stratification depth increased and the effect of wind speed on stratification strength decreased (Table S3).

## Discussion

We observed substantial changes in stratification characteristics at Crater Lake over a 25-year period. Our empirical observations, supported by modeling scenarios, indicate that both wind speed and air temperature are important drivers of the observed changes in stratification characteristics. Specifically, our results indicate that the depth of stratification has shoaled primarily due to a reduction in wind speed, and summer water column stability has exhibited periodic variation driven by variations in spring air temperature.

Early research predicted that warming temperatures would increase stratification strength (Butcher et al. 2015; Edlund et al. 2017) and consequently induce a shoaling of stratification depths (Boyd and Doney 2002; Behrenfeld et al. 2006). While our results demonstrate that depth of stratification is shoaling in Crater Lake, this observation is attributable primarily to decreasing wind speeds, and not warming air temperatures. Based on our modeling scenarios, the depth of stratification was shallower with calmer winds, while there was minimal impact of higher air temperatures on stratification depth. Empirically, wind speeds appeared to be declining in the spring (and parts of summer) and the depth of stratification was shallower when spring wind was calmer. Therefore, it appears that spring declines in wind speed were the largest contributor to the observed stratification shoaling trend at Crater Lake. Spring wind speed conditions are likely important as stratification is setting up, and differences from the long-term mean (e.g., low wind speed spring periods) are likely driving our observed trends in shoaling. In spring, stratification is weaker and higher winds can more easily stimulate deeper mixing. Declines in spring wind are thus important in regulating the depth of stratification during the summer. Relatedly, our results indicate that increasing air temperatures have had a negligible effect on the observed shoaling pattern, while declines in wind speed through time were much more important.

Declining wind speeds have been observed in many regions globally (McVicar et al. 2012) including the United States (Pryor et al. 2009). The causes of declining wind speeds at Crater Lake are unknown and warrant further investigation. Given widespread observations of declining wind speeds in many regions and the sensitivity of stratification depth to wind, shoaling may be occurring in other large lakes, with important biological and ecological consequences (e.g., Janatian et al. 2019). Additionally, wind speed decreases are also associated with prolonged seasonal duration of stratification (Woolway et al. 2017), reduced deep ventilation activity (Piccolroaz and Toffolon 2018), and in some cases, stronger stratification (Woolway et al. 2019; Christianson et al. 2020), indicating their importance in regulating various limnological characteristics.

Our empirical observations and modeling scenarios suggest that air temperatures are an important factor driving long-term variability in the strength of stratification. We observed variability the onset of stratification and summer stratification strength that corresponded with spring air temperature variability. Spring air temperatures may influence summer stratification strength by influencing the date of onset of stratification, which then controls the phenology of summer stratification. Spring air temperatures have been thought to play a key role in determining summer lake stratification characteristics (Schindler 1971; Fee et al. 1996; Mi et al. 2018) and our observations are consistent with previous work that has demonstrated that warmer air temperatures correspond with more strongly stratified lake water columns (Kraemer et al. 2015; Winslow et al. 2015; Richardson et al. 2017). However, stratification strength can also be sensitive to wind. For example, Mi et al. (2018) demonstrated with the use of GLM that strong perturbations to wind speeds (+10 m $s^{-1}$) over just a short period of time (48 h) in the spring and early summer (April–June) can result in substantial decreases in summer lake stability. The relative importance of changing wind speeds and air temperature on stratification strength is likely regulated by the magnitude of changes in these climate drivers as well as the lake morphometry, with larger lakes likely exhibiting greater wind sensitivity (Read et al. 2012).

Commonly, sensitivity analyses will manipulate meteorological data by either changing the value by a constant value (e.g., Bueche and Vetter 2014) or as a percent change (e.g., Magee and Wu 2017; Bruce et al. 2018; Mi et al. 2018). The magnitude of change in a driver variable can have strong effects on the magnitude of change in a response variable. Thus, while performing scenarios in this way is useful, it is possible that the conclusions of these scenario analyses could be incorrect if the magnitude of change is unrealistic. For example, an increase of air temperature of 5°C or an increase of wind speed of 10 m $s^{-1}$ would surely alter the depth and strength of stratification in Crater Lake, but the magnitude of change in these driver variables is beyond the range of the observation period or reasonable extrapolation from this period. We chose to manipulate meteorological data so that scenarios were conducted at the maximum and minimum of the historically observed range. This is likely a conservative approach to estimating the impacts of future climate changes, as future changes could introduce novel meteorological conditions, including the possibility of even lower wind speeds and warmer air temperatures, which could facilitate continued trends in stratification strength and depth. Because we found no trends in inflow volume at Crater Lake, we performed synthetic simulations where we manipulated values by a large amount (3 $m^3$ $s^{-1}$) to test for any effect of inflow volume on stratification characteristics at Crater Lake. We found inflow volume to have negligible effects on stratification depth, strength, or onset even when it was changed substantially.

Our hydrodynamic model was predictive of long-term trends and supported empirically based patterns and relationships. However, the model did not always reproduce thermal characteristics well. Because the model occasionally formed ice cover on Crater Lake which is exceedingly rare, we ran the model seasonally and removed precipitation in the form of snow from the meteorological data. While small periods of ice persisted upon model initiation for a few days, we found our model was able to reproduce changes and variability in summer time stratification characteristics. It is likely that GLM was not able to accurately characterize very shallow thermal gradients and corresponding deep mixing that prevent ice from forming on Crater Lake most winters. Further, CTD profilers were switched in 1999, and though we corrected these early profiles with a linear regression, modeled Center of Buoyancy was much more accurate with the new sensor from 1999 to 2017 (RMSE 1.58 m) compared to the old CTD that was used from 1993 to 1998 (RMSE 2.27 m). However, the opposite was true for Schmidt Stability (RMSE from 1999 to 2017 was 2374.55 J $m^{-1}$ while from 1993 to 1998 RMSE was 2374.65 J $m^{-1}$. Overall, these uncertainty estimates indicate that a change in sensors, rather than model process error, may have been the root cause of some uncertainty. Despite these weaknesses, the model reproduced long-term patterns in seasonal (February through September) water temperature and stratification depth and strength. Our annual model accuracy also compares favorably with a previous study of 32 lakes using GLM. Bruce et al. (2018) found base model median RMSE for thermocline depth to be 11.3 m and full water temperature RMSE was 1.33°C. Our uncertainty compares at 1.77 m (center of buoyancy) and 0.48°C (water column temperature), respectively, but it should be noted that the Bruce et al. 2018 uncertainty measurements are based on base simulations, whereas ours are based on a calibrated model; see table B1 in Bruce et al. 2018 for more details).

Our thermal characteristic most often modeled with the highest uncertainty was stratification depth, which may have relatively high uncertainty due to factors including initial conditions, input data accuracy, model structure and parameter values, and uncertain validation data (Gal et al. 2014). We found that model uncertainty (RMSEs for center of buoyancy and Schmidt Stability) were sometimes larger than the magnitude of the impact of air and wind speed changes in our scenarios. This indicates that model predictive capacity is limited and thus its' ability to predict future changes is further limited. However, in our case, we used GLM to support insights gained from observed long-term trends and patterns. Together, the model and observational data provide complementary results which strengthen overall conclusions.

Our results indicated that overall inflow volume was relatively unimportant in regulating stratification characteristics of Crater Lake. One area not explored in our simulations is the effect of changes in inflow timing (e.g., the timing of peak discharge). In small lakes with short residence times, timing and volume of peak discharge can strongly influence summer temperatures and thus may regulate interannual variability in stratification (e.g., Sadro et al. 2018). In other regions such as the northeastern United States, increases in precipitation have been shown to increase dissolved organic matter loads and reduce lake water transparency, which can lead to a shoaling of stratification depth and strengthening of summer stratification (e.g., Pilla et al. 2018). While declines in water clarity can contribute to stratification shoaling, water transparency at Crater Lake increased throughout the study period, ruling this out as a potential driver of shoaling at Crater Lake. While Crater Lake is large and deep compared with most lakes, its protected status within a United States National Park has provided the opportunity to attribute observed trends in stratification to climate conditions alone because there have been essentially no watershed land use changes.

The implications of changes in the depth and strength of stratification are numerous, especially for lake food webs and biogeochemistry. Unless there are corresponding reductions in water clarity or incident solar radiation, a reduction in the depth of stratification will increase exposure of nonmotile organisms in the surface mixed layer to both photosynthetically active radiation (PAR) and ultraviolet radiation (UVR). Given the high water clarity of Crater Lake, this could result in substantially more UVR exposure and consequent damage to organisms. Additionally, shallower stratification without corresponding reductions in light penetration may increase the likelihood of deep chlorophyll maxima (DCM) formation in the stable water below the surface mixed layer. Crater Lake has historically had a DCM well below its depth of stratification due to its high clarity, as do many other lakes (Leach et al. 2018). However, shoaling thermoclines in lower clarity systems may allow enough light to penetrate such that a DCM can now form below the epilimnion. Stronger and shallower stratification may also inhibit nutrient upwelling and increase sinking velocities, thereby reducing productivity in surface waters (Winder et al. 2008; Winder and Hunter 2008). Additionally, stronger stratification may reduce gas exchange between lakes and the atmosphere because stratification alters turbulent energy in the water column (Cole et al. 2010). Finally, organisms like cyanobacteria that can self-regulate their buoyancy may become more dominant with a shoaling depth of stratification, especially in more productive lakes (Huber et al. 2012). Cumulatively, changes in stratification strength and depth may substantially alter community composition, trophic interactions, and services these ecosystems provide (Winder and Schindler 2004; Trolle et al. 2011).

Overall, our results suggest that climate change, including both atmospheric stilling and warming, has substantially altered the depth of stratification in Crater Lake, which could have important ecological and biological implications, especially for free-floating organisms such as phytoplankton and zooplankton. Our results also highlight the important role that spring meteorological conditions have on controlling summer stratification characteristics, including fluctuations in the timing of stratification onset. It is likely that similar processes are occurring in other large lakes undergoing similar climatic changes as Crater Lake. Whether these patterns are occurring in lakes more broadly may largely be a function of the magnitude of changes in meteorological conditions, lake sensitivity to meteorological changes, and other environmental changes such as water clarity (Rose et al. 2016).

## REFERENCES


Austin, J. A., and S. M. Colman. 2007. Lake superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. Geophys. Res. Lett. **34**: 6. doi:10.1029/2006GL029021

Bacon, C. R., J. V. Gardner, L. A. Mayer, M. W. Buktenica, P. Dartnell, D. W. Ramsey, and J. E. Robinson. 2002. Morphology, volcanism, and mass wasting in Crater Lake, Oregon. Geol. Soc. Am. Bull. **114**: 675–692.

Behrenfeld, M. J., et al. 2006. Climate-driven trends in contemporary ocean productivity. Nature **444**: 752–755. doi:10.1038/nature05317

Boyd, P. W., and S. C. Doney. 2002. Modelling regional responses by marine pelagic ecosystems to global climate change. Geophys. Res. Lett. **29**: 53–51. doi:10.1029/2001GL014130

Bruce, L. C., and others. 2018. A multi-lake comparative analysis of the General Lake Model (GLM): Stress-testing across a global observatory network. Enviorn. Modell. Softw. **102**: 274–291. doi:10.1016/j.envsoft.2017.11.016

Bueche, T., and M. Vetter. 2014. Simulating water temperatures and stratification of a pre-alpine lake with a hydrodynamic model: Calibration and sensitivity analysis of climatic input parameters. Hydrol. Process. **28**: 1450–1464. doi:10.1002/hyp.9687

Butcher, J. B., D. Nover, T. E. Johnson, and C. M. Clark. 2015. Sensitivity of lake thermal and mixing dynamics to climate change. Clim. Change **129**: 295–305. doi:10.1007/s10584-015-1326-1

Christianson, K. R., B. M. Johnson, and M. B. Hooten. 2020. Compound effects of water clarity, inflow, wind and climate warming on mountain lake thermal regimes. Aquat. Sci. **82**: 6. doi:10.1007/s00027-019-0676-6

Cole, J. J., D. L. Bade, D. Bastviken, M. L. Pace, and M. Van de Bogert. 2010. Multiple approaches to estimating air-water gas exchange in small lakes. Limnol. Oceanagr. Methods **8**: 285–293. doi:10.4319/lom.2010.8.285

Couture, R. M., H. A. de Wit, K. Tominaga, P. Kiuru, and I. Markelo. 2015. Oxygen dynamics in a boreal lake responds to long-term changes in climate, ice phenology, and DOC inputs. Eur. J. Vasc. Endovasc. Surg. **120**: 2441–2456. doi:10.1002/2015JG003065

Crawford, G. B., and R. W. Collier. 2007. Long-term observations of deepwater renewal in Crater Lake, Oregon. Hydrobiologia **574**: 47–68. doi:10.1007/s10750-006-0345-3

De Stasio Jr, B. T., D. K. Hill, J. M. Kleinhans, N. P. Nibbelink, and J. J. Magnuson. 1996. Potential effects of global climate change on small north-temperate lakes: Physics, fish, and plankton. Limnol. Oceanogr. **41**: 1136–1149. doi:10.4319/lo.1996.41.5.1136

Deng, J., H. W. Paerl, B. Qin, Y. Zhang, G. Zhu, E. Jeppesen, Y. Cai, and H. Xu. 2018. Climatically-modulated decline in wind speed may strongly affect eutrophication in shallow lakes. Sci. Total Environ. **645**: 1361–1370. doi:10.1016/j.scitotenv.2018.07.208

Edlund, M. B., J. E. Almendinger, X. Fang, J. M. R. Hobbs, D. D. VanderMeulen, R. L. Key, and D. R. Engstrom. 2017. Effects of climate change on lake thermal structure and biotic response in northern wilderness lakes. Water **9**: 678. doi:10.3390/w9090678

Fang, X., and H. G. Stefan. 1999. Projections of climate change effects on water temperature characteristics of small lakes in the contiguous US. Clim. Change **42**: 377–412. doi:10.1023/A:1005431523281

Fee, E. J., R. E. Hecky, S. E. M. Kasian, and D. R. Cruikshank. 1996. Effects of lake size, water clarity, and climatic variability on mixing depths in Canadian Shield lakes. Limnol. Oceanogr. **5**: 912–920. doi:10.4319/lo.1996.41.5.0912

Gal, G., V. Makler-Pick, and N. Shachar. 2014. Dealing with uncertainty in ecosystem model scenarios: Application of the single-model ensemble approach. Environ. Model. Software **61**: 360–370. doi:10.1016/j.envsoft.2014.05.015

Gardner, J. V., L. A. Mayer, and M. Buktenica. 2000. Cruise report R/V surf surveyor cruise S1-00-CL mapping the bathymetry of Crater Lake, Oregon. USGS Open-File Report 00–405.

Hansen, G. J., J. S. Read, J. F. Hansen, and L. A. Winslow. 2017. Projected shifts in fish species dominance in Wisconsin lakes under climate change. Glob. Chang. Biol. **23**: 1463–1476. doi:10.1111/gcb.13462

Hipel, K. W., and A. I. McLeod. 1994. Time series modelling of water resources and environmental systems. Elsevier Science.

Hipsey, M. R., and others. 2019. A General Lake Model (GLM 3.0) for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). Geosci. Model Dev. **12**: 473–523. doi:10.5194/gmd-12-473-2019

Hondzo, M., and H. G. Stefan. 1993. Regional water temperature characteristics of lakes subjected to climate change. Clim. Change **24**: 187–211. doi:10.1007/BF01091829

Huber, V., C. Wagner, D. Gerten, and R. Adrian. 2012. To bloom or not to bloom: Contrasting responses of cyanobacteria to recent heat waves explained by critical thresholds of abiotic drivers. Ocealagia **169**: 245–256. doi:10.1007/s0042-011-2186-7

Idso, S. B. 1973. On the concept of lake stability. Limnol. Oceanogr. **18**: 681–683. doi:10.4319/lo.1973.18.4.0681

Janatian, N., K. Olli, F. Cremona, A. Laas, and P. Nõges. 2019. Atmospheric stilling offsets the benefits from reduced nutrient loading in a large shallow lake. Limnol. Oceanogr. **65**: 717–731. doi:10.1002/lno.11342

Jankowski, T., D. M. Livingstone, H. Bührer, R. Forster, and P. Niederhauser. 2006. Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: Implications for a warmer world. Limnol. Oceanogr. **51**: 815–819. doi:10.4319/lo.2006.51.2.0815

Kraemer, B. M., and others. 2015. Morphometry and average temperature affect lake stratification responses to climate change. Geophys. Res. Lett. **42**: 4981–4988. doi:10.1002/2015GL064097

Larson, G. L., R. L. Hoffman, D. C. McIntire, M. W. Buktenica, and S. F. Girdner. 2007. Thermal, chemical, and optical properties of Crater Lake, Oregon. In Long-term Limnological Research and Monitoring at Crater Lake, Oregon. Hydrobiologia **574**: 69–84.

Leach, T. H., and others. 2018. Patterns and drivers of deep chlorophyll maxima structure in 100 lakes: The relative importance of light and thermal stratification. Limnol. Oceanogr. **63**: 628–646. doi:10.1002/lno.10656

Magee, M. R., and C. H. Wu. 2017. Responses of water temperature and stratification to changing climate in three lakes with different morphometry. Hydrol. Earth Syst. Sci. **21**: 6253–6274. doi:10.5194/hess-21-6253-2017

McVicar, T. R., T. G. Van Niel, M. L. Roderick, L. T. Li, X. G. Mo, N. E. Zimmermann, and D. R. Schmaltz. 2010. Observational evidence from two mountainous regions that near-surface wind speeds are declining more rapidly at higher elevations than lower elevations: 1960–2006. Geophys. Res. Lett. **37**: 6. doi:10.1029/2009GL042255

McVicar, T. R., and others. 2012. Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. J. Hydrol. **416**: 182–205. doi:10.1016/j.jhydrol.2011.10.024

Mi, C., M. A. Frassl, B. Boehrer, and K. Rinke. 2018. Episodic wind events induce persistent shifts in the thermal stratification of a reservoir (Rappbode Reservoir, Germany). Int. Rev. Hydrobiol. **103**: 71–82. doi:10.1002/iroh.201701916

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining mountain snowpack in western North America. Bull. Am. Meteorol. Soc. **86**: 39–50. doi:10.1175/BAMS-86-1-39

Mote, P. W., S. Li, D. P. Lettenmaier, M. Xiao, and R. Engel. 2018. Dramatic declines in snowpack in the western US. Npj Clim. Atmos. Sci **1**: 2. doi:10.1038/s41612-018-0012-1

O'Reilly, C. M., and others. 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophys. Res. Lett. **42**: 10–773. doi:10.1002/2015GL066235

Pettitt, A. N. 1979. A non-parametric approach to the change-point problem. J. R. Stat. Soc. C-Appl. **28**: 126–135. doi:10.2307/2346729

Piccolroaz, S., and M. Toffolon. 2018. The fate of Lake Baikal: How climate change may alter deep ventilation in the largest lake on Earth. Clim. Change **1-14**: 181–194. doi:10.1007/s10584-018-2275-2

Pilla, R. M., and others. 2018. Browning-related decreases in water transparency Lead to long-term increases in surface water temperature and thermal stratification in two Small Lakes. Geophys. Res. Biogeosci. **123**: 1651–1665. doi:10.1029/2017JG004321

Pryor, S. C., and others. 2009. Wind speed trends over the contiguous United States. J. Geophys. Res. **114**: 14. doi:10.1029/2008JD011416

R Core Team. 2016. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing, Retrieved from www.r-project.org/

Read, J. S., and others. 2012. Lake-size dependency of wind shear and convection as controls on gas exchange. Geophys. Res. Lett. **39**: 9. doi:10.1029/2012GL051886

Read, J. S., D. P. Hamilton, I. D. Jones, K. Muraoka, L. A. Winslow, R. Kroiss, and E. Gaiser. 2011. Derivation of lake mixing and stratification indices from high-resolution lake buoy data. Environ. Model. Software **26**: 1325–1336. doi:10.1016/j.envsoft.2011.05.006

Richardson, D. C., and others. 2017. Transparency, geomorphology and mixing regime explain variability in trends in lake temperature and stratification across Northeastern North America (1975–2014). Water **9**: 442. doi:10.3390/w9060442

Roderick, M. L., L. D. Rotstayn, G. D. Farquhar, and M. T. Hobbins. 2007. On the attribution of changing pan evaporation. Geophys. Res. Lett. **34**: 17. doi:10.1029/2007GL031166

Rose, K. C., C. E. Williamson, J. E. Saros, R. Sommaruga, and J. M. Fischer. 2009. Differences in UV transparency and thermal structure between alpine and subalpine lakes: Implications for organisms. Photochem. Photobiol. Sci. **8**: 1244–1256. doi:10.1039/b905616e

Rose, K. C., L. A. Winslow, J. S. Read, and G. J. Hansen. 2016. Climate-induced warming of lakes can be either amplified or suppressed by trends in water clarity. Limnol. Oceanogr. **1**: 44–53. doi:10.1002/lol2.10027

Sadro, S., J. O. Sickman, J. M. Melack, and K. Skeen. 2018. Effects of climate variability on snowmelt and implications for organic matter in a high elevation lake. Water Resour. Res. **54**: 4563–4578. doi:10.1029/2017WR022163

Schindler, D. W. 1971. Light, temperature, and oxygen regimes of selected lakes in the experimental lakes area, northwestern Ontario. J. Fish. Res. Board Can. **28**: 157–169. doi:10.1139/f71-029

Sen, P. K. 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. **63**: p1379–p1389.

Serra, T., J. Vidal, X. Casamitjana, M. Soler, and J. Colomer. 2007. The role of surface vertical mixing in phytoplankton distribution in a stratified reservoir. Limnol. Oceanogr. **52**: 620–634. doi:10.4319/lo.2007.52.2.0620

Tranvik, L. J., and others. 2009. Lakes and reservoirs as regulators of carbon cycling and climate. Limnol. Oceanogr. **54**: 2298–2314. doi:10.4319/lo.2009.54.6_part_2.2298

Trolle, D., D. P. Hamilton, C. A. Pilditch, I. C. Duggan, and E. Jeppesen. 2011. Predicting the effects of climate change on trophic status of three morphologically varying lakes: Implications for lake restoration and management. Enviorn. Modell. Softw. **26**: 354–370. doi:10.1016/j.envsoft.2010.08.009

Vautard, R., J. Cattiaux, P. Yiou, J. N. Thépaut, and P. Ciais. 2010. Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. Nat. Geosci. **3**: 756–761. doi:10.1038/ngeo979

Winder, M., and D. E. Schindler. 2004. Climate change uncouples trophic interactions in an aquatic ecosystem. Ecology **85**: 2100–2106. doi:10.1890/04-0151

Winder, M., and D. A. Hunter. 2008. Temporal organization of phytoplankton communities linked to physical forcing. Ocealagia **156**: 179–192. doi:10.1007/s00442-008-0964-7

Winder, M., J. E. Reuter, and S. G. Schladow. 2008. Lake warming favours small-sized planktonic diatom species. Proc. R. Soc. B **276**: 427–435. doi:10.1098/rspb.2008.1200

Winslow, L. A., J. S. Read, G. J. Hansen, and P. C. Hanson. 2015. Small lakes show muted climate change signal in deepwater temperatures. Geophys. Res. Lett. **42**: 355–361. doi:10.1002/2014GL062325

Winslow, L. A., T. H. Leach, and K. C. Rose. 2018. Global lake response to the recent warming hiatus. Environ. Res. Lett. **13**: 054005. doi:10.1088/1748-9326/aab9d7

Winslow, L.A. and others. 2018. Package rLakeAnalyzer: Lake Physics Tools. R package version 1.11.4. CRAN.R-project.org/package=rLakeAnalyzer.

Woolway, R. I., P. Meinson, P. Nõges, I. D. Jones, and A. Laas. 2017. Atmospheric stilling leads to prolonged thermal stratification in a large shallow polymictic lake. Clim. Change **141**: 759–773. doi:10.1007/s10584-017-1909-0

Woolway, R. I., and others. 2019. Northern Hemisphere atmospheric stilling accelerates lake thermal responses to a warming world. Geophys. Res. Lett. **46**: 11983–11992. doi:10.1029/2019GL082752

## Acknowledgments

We acknowledge support from US National Science Foundation grants BIO DEB-1754265, BIO EF-1638704, and NSF CISE 1761805 to KCR. We appreciate input from Dr. David Hamilton, Dr. Matt Hipsey, and Casper Boon on hydrodynamic modeling. The Crater Lake Long-term Limnological Monitoring Program is supported by the National Park Service. We acknowledge the program leadership of Dr. Gary Larson and Mark Buktenica. Special thanks to Dr. Robert Collier and Dr. Jack Dymond from the Oceanography Department at Oregon State University for initiating climate change studies that made this work possible. Data used in this publication are publicly available through the National Park Service Data Management System and Mesowest (https://mesowest.utah.edu/cgi-bin/droman/station_total.cgi; Station ID CL001 and CL002).

## Conflict of Interest

None declared.

*Submitted 15 August 2019*
*Revised 28 February 2020*
*Accepted 01 November 2020*

*Associate editor: Edward Stets*