Final Report
Dr. David Richardson
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Title: Variability in water quality and the effect of climate change and teleconnections on lake thermal structure in the Sky Lakes of Shawangunk Ridge

Introduction

Freshwater lakes are fundamental to human well-being, especially low-nutrient, clear-water lakes, which provide essential ecosystem services such as drinking water, recreation, cooling, irrigation, and fishing (Green et al. 2015). However, such lakes are also endangered by climate change and anthropogenic activities, including watershed development, pollution, and food web alteration (Dodds et al. 2013). Some of these anthropogenic impacts can cause a low nutrient lake to transition to a eutrophic state with dramatically reduced ecosystem services due to turbid water; frequent, sometimes toxic, cyanobacterial blooms; and hypolimnetic anoxia that can cause fish kills (Smith and Schindler 2009). Here, we will examine how watershed and climate drivers affect ecosystem structure and function in the critical headwater Sky Lakes along the Shawangunk Ridge with a particular focus on lake trophic state (Carlson 1977).

As a result of climate change, the Hudson River Valley has experienced increases in air temperatures (Fig. 1) and some of the greatest increases in precipitation and extreme storm events in the country (Melillo et al. 2014). Global-scale teleconnections, such as the El Niño-Southern Oscillation (ENSO) or North Atlantic Oscillation (NAO) are cycles driving regional weather patterns and can exacerbate effects from climate change (Coats et al. 2006). For example, summer 2016 was an El Niño year resulting in record temperatures in this area in first half of 2016 (Mohonk Preserve pers. comm.). Lakes in this region may be changing faster than other regions of the world due to climate forcing and corresponding changes in air temperature and precipitation patterns (Karl et al. 2009). These changes can impact lake physical properties and heat distribution which will likely cause a variety of ecosystem-level consequences with concomitant impacts on ecosystem services. Lake warming results in lengthening of the stratification period with shorter ice cover periods (Benson et al. 2012). Across lakes of different trophic status, this may exacerbate extent and duration of hypolimnetic anoxic conditions leading to the loss of aquatic biota and changes in water chemistry (Palmer et al. 2014). In many lakes, anoxic conditions will free phosphorus bound in lake sediments, and, combined with changes in lake mixing regimes, will result in changes to nutrient dynamics and ultimately lake productivity (Verburg and Hecky, 2009). Increasingly warm surface temperatures could favor harmful cyanobacterial algal blooms and transition lakes towards a eutrophic state (Paerl and Paul 2012). Warming and increasingly anoxic deep water can both result in increases cyanobacterial recruitment in species that overwinter in and draw phosphorus from the sediments (e.g., Cottingham et al. 2015).

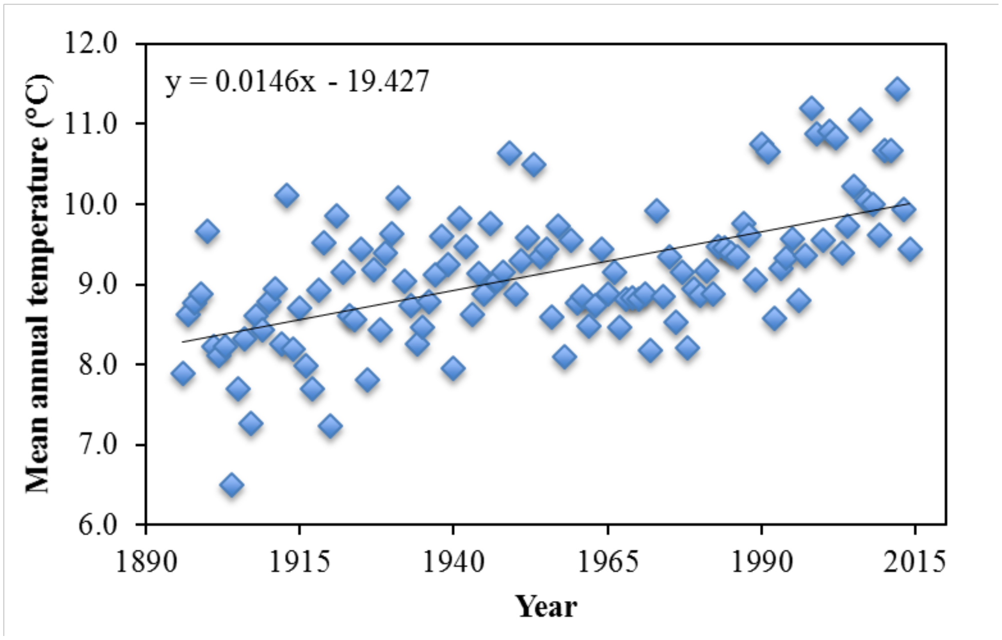

Figure 1. Annual air temperature for the Shawangunk Ridge over the last 119 years (1896 to 2014) with an increasing trend in annual air temperature ($p < 0.001$; R^2=0.34) with some the variance explained by the interannual increase. Unpubl. data from the Mohonk Preserve.

Watershed land use, often in the form of agricultural or developed land, increases lake nutrient concentrations and productivity (Knoll et al. 2003) and reduces water clarity. Across New York and northeastern USA, land-cover from 1973-2000 has dramatically shifted with increased abandonment of agricultural areas, increased areas of developed land, and reduced forested areas (Sleeter et al. 2013). Conversion of land to residential suburban and urban development increases impervious surfaces, storm runoff, and sources of nutrient concentrations (e.g., pet waste, fertilizer application, septic seepage) (Brabec et al. 2002). Ultimately, the amount of nutrients and rapid delivery of water result in increasing lake nutrient concentrations (Dodds et al. 2008).

Cyanobacteria could be the drivers of early shifts from clear water lakes to turbid, high production, even in low or increasing nutrient lakes. Many cyanobacterial taxa fix dissolved nitrogen gas alleviating the demand for high N concentrations when forming blooms (Wetzel 2001) and some acquire phosphorus from sediments and bottom waters through seasonal recruitment or buoyancy regulation on daily to weekly timescales (Cottingham et al. 2015). Once the N is fixed and the P acquired, cyanobacteria can act as biological pumps by releasing this ‘new’ N and P into the water column, where it can be accessed by other phytoplankton and microbes, thereby initiating positive feedback loops that further increase water column P, reduce the resilience of the low-nutrient state, and increase the probability of a switch to a eutrophic state (Cottingham et al. 2015).

We examined longitudinal differences in water quality along multiple lakes on top of the Northern Shawangunk Ridge for differences in lake physics, biology, and chemistry. We also used a focal lake with long-term temperature data to determine the effects of climate change on the Sky Lakes. This project connected various regional research partners and managers and provided training for an undergraduate research student. Finally, we created 2 short documentaries about the project that can be used for outreach by our various partners.

Site descriptions

The Shawangunk Ridge is part of the Appalachian Mountains and is located in the Hudson Valley, west of the Hudson River from the New York/New Jersey border to Rosendale. The Shawangunk Ridge spans Ulster, Sullivan, and Orange counties. The Northern Shawangunk Ridge contains 5 "Sky Lakes" that reside within protected and managed lands (i.e. state parks, state forests, or private preserves), are minimally influenced by humans and relatively isolated from the surrounding landscape, and are significant economic resources for the Hudson Valley region drawing in many tourists for outdoor recreation. However, the lakes have experienced external forcing including climate change. The lakes, because of their small size, high ratios of lake surface area to watershed area (Richardson et al. 2016), and underlying geology (Caine et al. 1991) are highly susceptible to climate change and even minor anthropogenic modifications of the landscape. The overarching research goal of this project was to determine how watershed and climate drivers affect ecosystem structure and function in the critical headwater Sky Lakes on the Shawangunk Ridge.

Methods

Sky Lakes sampling – During the summer, we sample all three study lakes along the Shawangunk Ridge on two separate time periods, once in June and once in July. We measured trophic state indices (chlorophyll *a*, Secchi depth, and total phosphorus concentrations), conductivity, dissolved organic carbon, and pH at the deepest location of each lake. We took temperature and dissolved oxygen profiles to look for thermal stratification and hypoxia and sampled the hypolimnion for total phosphorus concentration. As metrics for transparency, we compared Secchi depths from Minnewaska and Mohonk. Secchi depth measurements, used as a proxy for water clarity, were compiled for Minnewaska and Mohonk pelagic sites from three different sources: Mohonk Preserve, New York State Environmental Management Bureau (EMB), and sampling for this study. Mohonk Preserve collected weekly measurements between 1995 and 2016 at the pelagic site in Mohonk. EMB collected between 1 and 15 measurements per year between 1995 and 2016 at the pelagic site in Minnewaska. We collected Secchi depths every 1-2 weeks at the pelagic site in Minnewaska from 2013-2017. To make the comparisons across lakes and datasets consistent, we only analyzed data from June, July, and August when collection frequency was highest for both lakes. We partitioned Secchi depth data into three time periods based on the presence or absence of Golden shiners in Minnewaska as follows: 1) prior to the arrival (1995-2007: 'Pre'), 2) during the presence (2008-2013: 'During'), and 3) following the loss of Golden shiners (2014-2016: 'Post'). Mohonk Secchi depth data was similarly partitioned and used as a control for external drivers of water clarity. For each lake, we used Kruskal Wallis nonparametric ANOVAs for comparisons across the three time periods with post hoc means comparisons using Dunn test. On two separate dates in June 2017, we sampled all three Sky Lakes on the northern Shawangunk Ridge for phytoplankton communities. We determined phytoplankton community composition by counting and identifying 200 to 400 phytoplankton from each lake using the Ultermöhl method (Lund et al. 1958) and pooled the separate dates.

Climate change and thermal stratification in Mohonk Lake **-** We have worked with the Mohonk Preserve to quality analyze and check historic Mohonk Lake limnology data dating from 1983 to

2016. We have calculated annual and stratified season (hereafter summer) surface and deep water temperature. We also calculated the Schmidt stability of stratification which is the measure of work required to overcome density stratification and completely mix a lake (Klug et al. 2012) and is an indicator of how stable stratification is in a lake. This was calculated using Mohonk Lake bathymetry for each day with a temperature profiles. We also integrated the area under the stability curve for each year, giving a total for how stable the stratification was in days J m^{-2} (see Fig. 2 for example annual curve of stability, the blue area is the integrated stratified period).

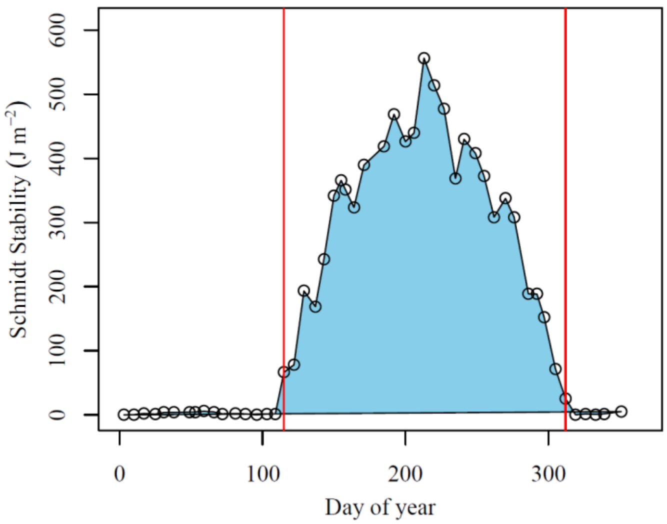

Figure 2. Example annual curve of Schmidt stability of stratification over 2007. The red lines indicate the onset of stratification in early May and turnover in late October.

Results and Discussion

Variability in trophic state across the Sky Lakes – We found three different levels of trophic status across the Sky Lakes that are close in proximity (< 20 km) across them all. Awosting is oligotrophic with low chlorophyll *a* (< 2.5 µg/L), low total phosphorus and total nitrogen concentrations (<4 µg/L and 77 µg/L), and high water clarity. Throughout the summer, Awosting's hypolimnion stayed oxic (Fig. 3). Mohonk is mesotrophic with higher chlorophyll *a* (2.5 to 5 µg/L), moderate total phosphorus and total nitrogen concentrations (13 µg/L and 440 µg/L), and high water clarity. Mohonk's hypolimnion went anoxic earlier in the summer and stayed anoxic throughout (Fig. 3). Minnewaska is oligotrophic/mesotrophic with low to moderate chlorophyll *a* (3 µg/L), low total phosphorus and total nitrogen concentrations (4 µg/L and 186 µg/L), and high water clarity. Minnewaska's hypolimnion approaches anoxia as the summer advances but still has moderate oxygen concentrations in the middle of the summer (Fig. 3).

Interestingly, despite the close proximity, the three lakes differ in chemistry and their food webs. The Sky Lakes have experience acid rain over the last 70+ years with only more recent recovery in the acid precipitation (Richardson et al. 2018). Awosting is still acidic (pH< 5.5) but follows the recovery of acid rain. Mohonk has always been neutral as a bedrock shale inlier neutralizes the acidic precipitation. Minnewaska has seen a recovery over the past 30 years that has elevated the pH above biologically relevant boundaries; Minnewaska used to be very acidic in the 1980s (pH < 5) but more recently has increased closer to neutral (pH ~ 6.5). This has results in major differences in their food webs. For example, Mohonk has always had fish stocked in the lake (e.g., brook trout, lake trout) and natural communities of minnows, sunfish, and basses with records dating back to the 1800s. Awosting has no fish and simple zooplankton/phytoplankton food webs as a result of the acidity. However, Minnewaska, likely with human assistance, has seen recent introductions of fish to result in rapidly increasing fish populations (Charifson et al. 2015) that have results in trophic cascades and increasing phytoplankton biomass (Richardson et al. 2016).

As a result of the trophic cascade, Minnewaska water clarity varied significantly over the three time periods ($\chi^2 = 41$, df = 2, $p < 0.001$), with a decrease during the golden shiners presence in the lake and then returned to previous transparent conditions following their loss. Secchi depth decreased by 57% after Golden shiners were introduced to Minnewaska ($p < 0.001$) and, following their loss, returned to pre-golden shiner depths ($p < 0.001$, Fig. 4). Mohonk Secchi depth remained constant during the same time frame ($\chi^2 = 3.6$, df = 2, $p = 0.16$, Fig. 4) indicating no climatic control of Secchi.

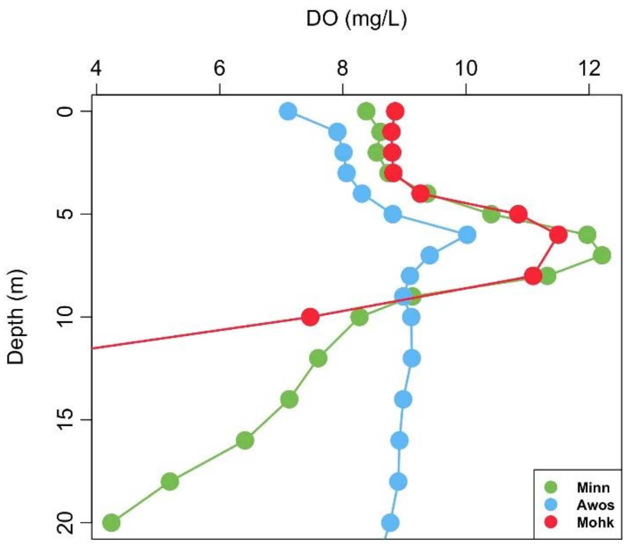

Figure 3. Dissolved oxygen profile taken on 19Jul2017 and 20Jul2017 for Minnewaska, Awosting, and Mohonk. Mohonk has the lowest DO concentration (note the DO concentration is anoxic and Mohonk profiles only reach a maximum depth of 13m). Awosting (max depth 29 m) has the greatest DO concentration at its deepest point as indicative of an oligotrophic lake.

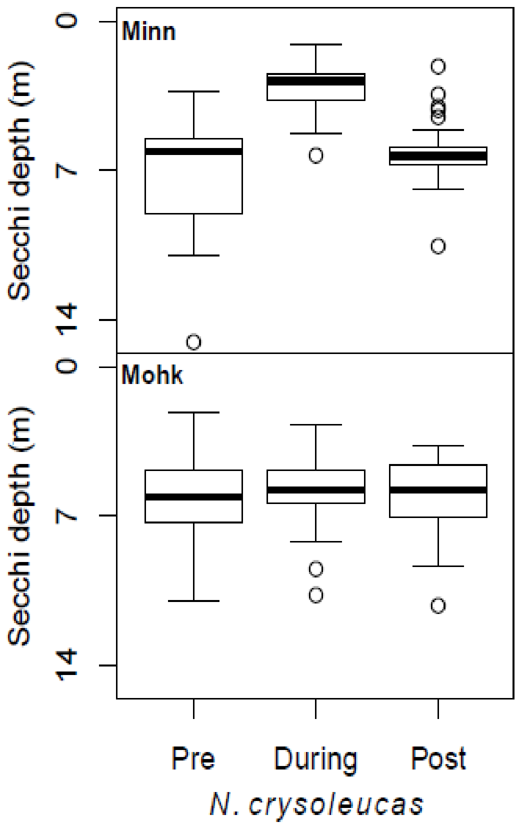

Figure 4. Secchi depth prior to the arrival of *Notemigonus crysoleucas* (Pre, 1995-2007), during *N. crysoleucas* presence (During, 2008-2013), and following the loss of *N. crysoleucas* (Post, 2014-2017) in (a) Minnewaska. (b) Mohonk Secchi depth included as reference during the same time periods. The box is the interquartile range with the median; the whiskers represent the box edges ± 1.5 interquartile range.

Cyanobacterial presence across the Sky Lakes – Chlorophyta (green algae) were the most common in all three lakes, followed by Bacillariophyta (diatoms) (Fig. 5). Cyanobacteria were present in only in Mohonk Lake (11% of total) – predominantly Anabaena spp. (Fig. 5). In this study, phytoplankton community composition, measured as phyla diversity, had some association with background nutrient concentrations as Mohonk had the highest of both nutrients. We did not find a prevalence of N-fixing cyanobacteria in the lakes with lower N:P ratios, thereby suggesting N fixation was not occurring at high rates in these lakes at the time of our experiment. However, community composition often changes on a sub-seasonal timescale, where different taxa are more likely to be dominant depending on the environmental and biological factors (Naselli-Flores et al. 2007). There is a need to continue examining the relationships between phytoplankton communities and nutrient concentrations at finer scales that are relevant to seasonal variations in phytoplankton communities and can alter the trajectory of the phytoplankton community composition each season.

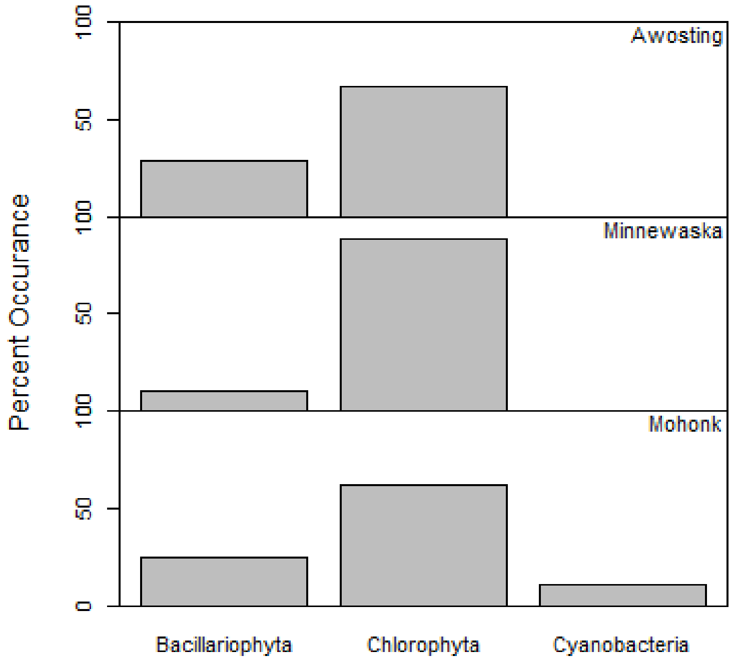

Figure 5. Community composition in three Sky Lakes on the northern Shawangunk Ridge. Three of the more common phyla are shown (bars will not add up to 100%).

Climate change and thermal stratification – Summer surface (epilimnion) is warming at ~0.5°C per decade (Fig. 6) – similarly, epilimnion temperature during peak temperature is rising. The residuals appear to have a periodicity (Fig. 6, inset) that may relate to teleconnections (sub decadal scale climate oscillations like El Nino or North Atlantic Oscillation). Conversely, hypolimnion temperature is cooling at ~0.3°C per decade (Fig. 7). Interestingly, there were two extreme outliers on the figure, the first (1984) and last (2016) years of the dataset that otherwise followed the linear trend tightly. We will be examining these two years more closely to ensure they are real values. The annual maximum stratification is increasing over time at a rate of 2.3 J m^{-2} day^{-1} (Fig. 8). Each year, the overall stability during the stratified period has increased rapidly and by ~40% from 1984 to 2016 (Fig. 9). This suggests that the summer stratification is continually getting stronger over time with implications for freshwater ecosystems. In many lakes, changes in the amount of vertical mixing can also contribute to changes in nutrient dynamics and ultimately lake productivity and changing fisheries (O'Reilly et al. 2003). Warming and increasingly anoxic deep water can both result in increased cyanobacterial recruitment in species that both overwinter in and draw phosphorus from the sediments (e.g., Cottingham et al. 2015). Increasingly warm surface temperatures could favor harmful cyanobacterial algal blooms and transition lakes from less productive towards eutrophic (Paerl and Paul 2012). Oxygen, lake temperature, and water transparency also regulate predator-prey interactions through the vertical distribution and migration of phytoplankton and zooplankton and thereby modify availability of refugia from predation (e.g., Hansson et al. 2016).

Surprisingly, the phenology of stratification (initialization of stratification each spring, day of turnover each fall, day of peak stratification each summer) did not change significantly over the last 33 years. Similarly, the length of stratification (mean=206 days) did not change over time. The patterns here can be applied to other lakes and used to make predictions about future climate scenarios and the effects of the interaction between climate change and teleconnection on lake ecosystems, especially Sky Lakes.

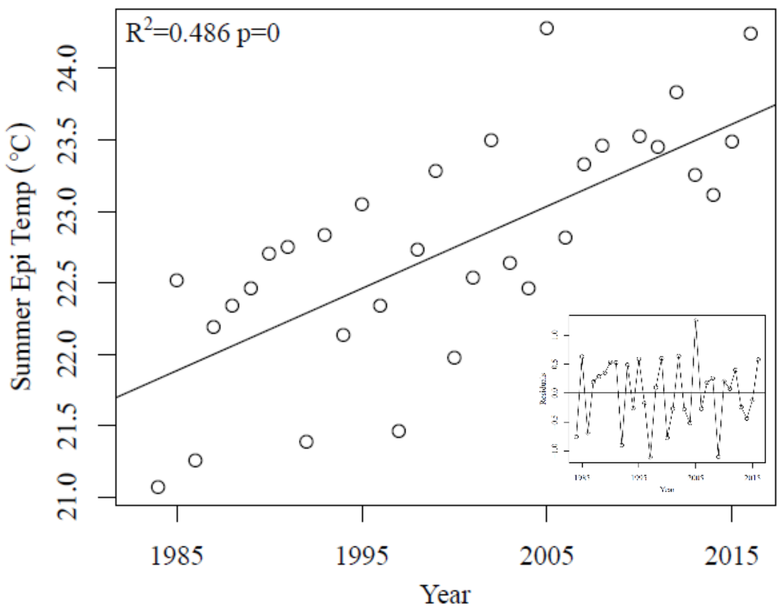

Figure 6. Summer annual average of epilimnion (1m – 3m) temperature in Mohonk over the last 33 years including significant linear regression (R^2 and p-value on graph). Residuals from the trend line are shown in the inset.

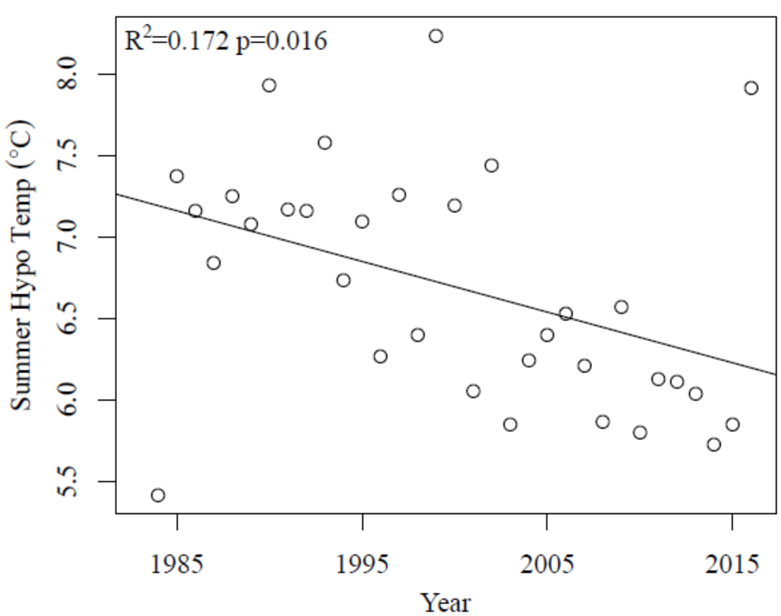

Figure 7. Summer annual average of hypolimnion (10m – 12m) temperature in Mohonk over the last 33 years including significant linear regression (R^2 and p-value on graph).

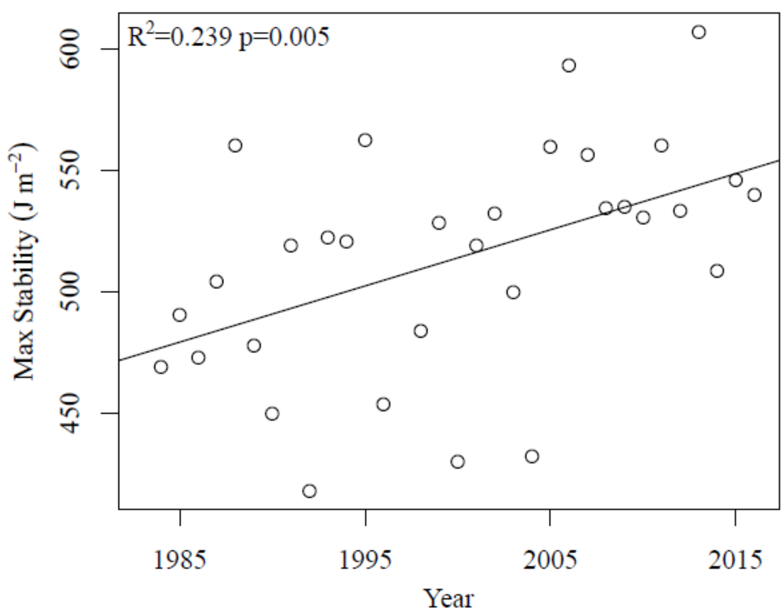

Figure 8. Maximum annual Mohonk Lake Schmidt stability of stratification over the last 33 years including significant linear regression (R^2 and p-value on graph).

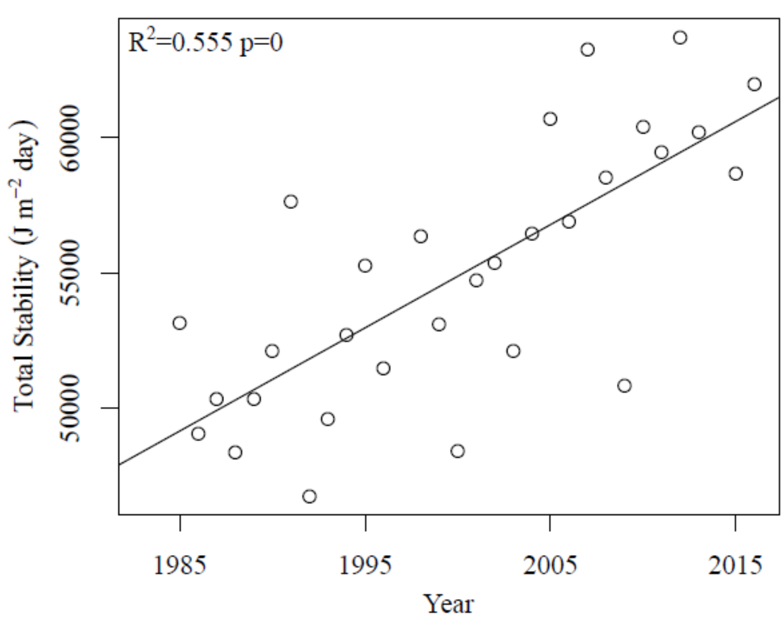

Figure 9. Total Mohonk Lake Schmidt stability integrated throughout the stratified period annually over the last 33 years including significant linear regression (R^2 and p-value on graph).

Outreach documentaries – Two documentaries were produced by Alana Roolart and Conor Donachie, SUNY New Paltz Digital Media and Journalism undergraduate students, who filmed and edited each one. The first documentary focuses on the climate change related warming in Mohonk Lake and is titled 'Northeastern sentinels of climate change - Mohonk Lake.' The second documentary relates to the ecology of Lake Minnewaska and is titled 'Acid rain and ecological change - a brief history of Lake Minnewaska.' The two documentaries can be seen on the Richardson lab YouTube channel and are being used as outreach for these projects.

https://www.youtube.com/watch?v=Su_YWq0WZIM

https://www.youtube.com/watch?v=gjm6bR6S-ZE

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