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Meteorological and Limnological Precursors to Cyanobacterial Blooms in Seneca and Owasco Lakes, New York, USA

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Abstract: Meteorological and water quality data were collected in offshore and nearshore settings over 4 years in the oligotrophic–mesotrophic Owasco and Seneca Lakes in order to assess cyanobacteria bloom (CyanoHABs) spatial and temporal variability and precursor meteorological and water quality conditions. CyanoHABs were detected from August through mid-October in both lakes. Blooms were temporally and spatially isolated, i.e., rarely concurrently detected at 3 (4.2%) or more of the 12 sites, and blooms (75.6%) were more frequently detected at only 1 of the 12 sites in the 10 min interval photologs. Both lakes lacked consistent meteorological and water quality precursor conditions. CyanoHABs were detected during the expected calm (<1 kph), sunny (600–900 W/m^2), and warm water (>23 °C) episodes. However, more CyanoHABs were detected during overcast/shady (<250 W/m^2) and windier (1 to 20 kph) and/or in cooler water (16 to 21 °C). More importantly, the majority of the sunny, calm, and/or warm water episodes did not experience a bloom. This suggests that nutrient availability was essential to trigger blooms in these two lakes, and we speculate that the nutrients originate from the decomposition of nearshore organic matter and runoff from the largest precipitation events.

Keywords: cyanobacteria; meteorological conditions; water quality; nutrients; oligotrophic-mesotrophic lakes; finger lakes; spatial variability; temporal variability

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1. Introduction

Over the last several decades, cyanobacterial harmful algal blooms (CyanoHABs) have impacted freshwater ecosystems and local economies throughout the world, e.g., Lake Taihu, China; Lake Erie, North America; Lake Victoria, Africa; and Lake Nieuwe Meer, the Netherlands, e.g., [1–9]. Nutrient loading and global climate change are evoked to explain the recent rise in CyanoHABs, e.g., [1,10–16]. Blooms more frequently impacted shallow, nutrient-rich, water bodies. For example, *Microcystis* blooms were more frequently found in western Lake Erie, which is smaller, warmer, and more nutrient rich than its eastern basin [17]. Sodus Bay on Lake Ontario and Missisquoi Bay on Lake Champlain are additional examples of shallow, warm, nutrient-rich water bodies frequented with late summer CyanoHABs [18–20]. These paradigms are being refined. For example, CyanoHABs are also detected in oligotrophic lakes, and are enhanced by the presence of dreissenid mussels [21–23]. However, challenges still exist in tracking and, more importantly, understanding their spatial and temporal variability, even in well-studied water bodies [1,24,25].

Since 2012, CyanoHABs with high toxins (blue-green algae chlorophyll > 25 mg/L, microcystin > 20 mg/L; New York State Department of Environmental Conservation (NYSDEC)) have been documented in the ultra-oligotrophic to eutrophic Finger Lakes in central and western New York State [26]. These lakes are critical for the regional agricultural–tourism economies and a source of municipal drinking water [27]. Local watershed monitoring groups trained by the NYSDEC have documented numerous blooms with annual mean concentrations of 3600 to 6600 µg/L, and a few samples exceeding 10,000 µg/L, blue-green algae chlorophyll, during the August through mid-October HAB season, which are typically concentrated along the shoreline with limited aerial extent, especially in the oligo-mesotrophic Finger Lakes [28–30]. Dreissenid mussels are in these lakes. The spatial and temporal variabilities make the oligo-mesotrophic Finger Lakes ideal systems to increase our understanding of HAB events in freshwater ecosystems.

Our aim in this study is to present 4 years of nearshore and offshore meteorological and water quality data in Seneca and Owasco Lakes to elucidate the spatial and temporal circumstances for HAB events (Figure 1). Seneca and Owasco Lakes, 2 of the 11 Finger Lakes in western and central New York State, drain a mixture of agricultural (40–50%) and forested (35–40%) landscapes [31]. Both are deep, elongated, north-to-south-orientated, and borderline oligotrophic to mesotrophic systems. Seneca Lake is deeper (198 vs. 54 m), longer (57 vs. 18 km), and wider (maximum of 5.2 vs. 2.1 km) than Owasco Lake. Seneca is warm monomictic, whereas Owasco is dimictic. Seneca also has a smaller watershed-to-lake-surface-area ratio (6.7 vs. 17.4) than Owasco Lake. Both lakes have the invasive dreissenid mussels. Volunteers detected up to 100 CyanoHABs in both lakes during any one season (typically late July through October), which were first documented in 2012 at Owasco and 2015 at Seneca Lake [26,32].

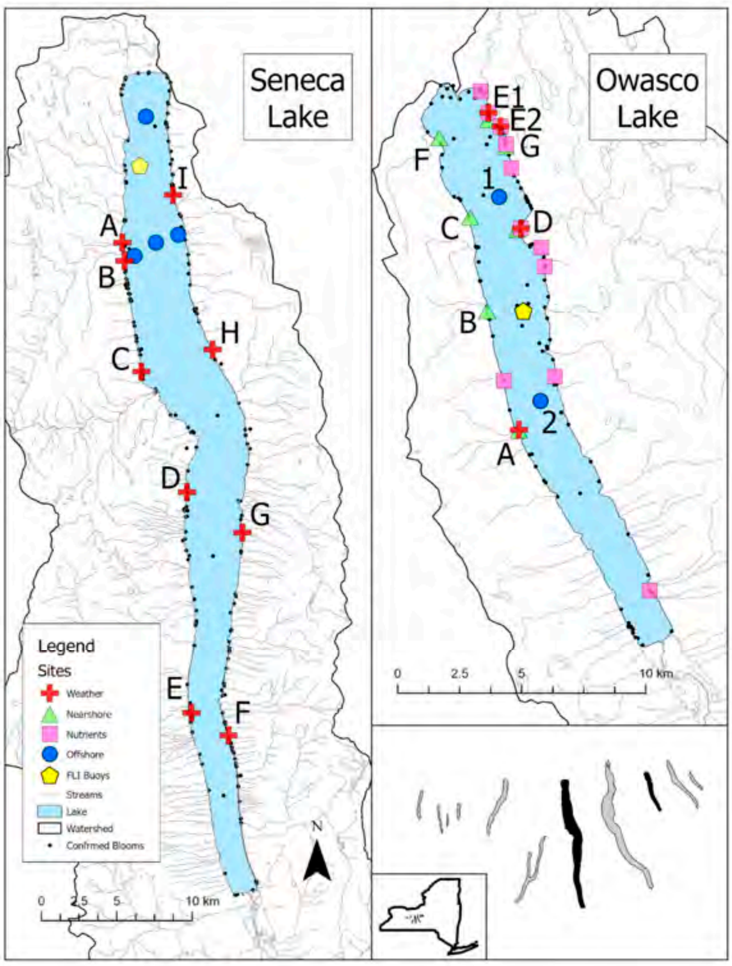


Figure 1. The dock (A–I for Seneca and A–G in Owasco), nearshore, and offshore (1&2 in Owasco) sites in Seneca and Owasco Lakes. The inserts reveal the location of Seneca and Owasco Lakes in the Finger Lakes of central New York, USA.

2. Methods

Meteorological and limnological data were collected at multiple dock sites in Seneca (2019–2021) and Owasco (2019–2022) Lakes during the mid-July through October HAB season (Figure 1, Table 1). At each dock site, an automated camera, a weather station, and a water temperature logger were deployed and water samples collected for nutrient and algal concentrations. A Brinno TLC200 automated camera, deployed approximately 3 m above the lake's surface, recorded 2 m × 3 m to 3.5 m × 5 m images of the lake's surface every 10 min from 0700 to 1800 h to document bloom event timing. An Ambient 10002-WS or WS-2000 Osprey weather station recorded air temperature, rainfall, barometric pressure, humidity, light intensity, wind speed, and wind direction every 30 min. Starting in 2017, a *HOBO* TidbiT MX or *HOBO* U20L-04 logger was placed inside a 2″ PVC pipe and strapped to a dock post in ~1 m of water to measure water temperature every 30 min. Water grab samples from 11 dock sites in 2018 and 4 sites in 2022 in Owasco Lake were analyzed for total phosphorus (TP), soluble reactive phosphate (SRP), nitrate–nitrite (NO_x), total suspended sediment (TSS), and chlorophyll-a concentrations following spectrophotometric limnological techniques [33]. Finally, an in situ Aqua Troll 600 water quality sonde (*YSI/Xylem* EXO2 at FL-20) was deployed at the four dock sites in Owasco Lake from 2020 through 2022 to measure water temperature, conductivity, dissolved oxygen, total, and phycocyanin fluorescence every 30 min. Each sonde was deployed inside a 4″ diameter PVC pipe for the sonde's protection from waves, and strapped to a dock post. The PVC pipes had numerous holes for water flow.

Table 1. Instrument deployment matrix in Owasco and Seneca Lakes.

Instrument	Deployed	Sample Interval	Owasco #Sites						Seneca #Sites		
Dock Sites			2017	2018	2019	2020	2021	2022	2019	2020	2021
Weather Station—Air Temperature, Rainfall, Solar Intensity, Wind Speed, and Direction	August–October	30 min			2	4	4	4	8	8	8
Photographs–Lake Surface	August–October	10 min			2	4	4	4	8	8	8
Water Temperature, ~1 m Depth	August–October	30 min	4	4	2	4	4	4	8	8	8
Sondes, ~1 m Depth, Temperature, Conductivity, Dissolved Oxygen, Total, and Phycocyanin Chlorophyll	August–October	30 min				4	4	4			
Nutrients (TP, SRP, NOx) and TSS, Surface Grabs	August–October	Bimonthly		11				4			
Nearshore Limnology											
Nutrients (TP, SRP, NOx) and TSS, Surface Grabs	August–October	Bimonthly	6	5	5						
Offshore Limnology											

Table 1. *Cont.*

Instrument	Deployed	Sample Interval	Owasco #Sites							Seneca #Sites	
CTD Profile, Plankton Tow, Secchi Depth, Surface, and Bottom Nutrients (TP, SRP, NOx), TSS, Chlorophyll-a	May–October	Monthly–Weekly	2	2	2	2	2	2	4	4	4
Monitoring Buoy	April–October		1	1	1	1	1	1	1	1	1
Metrological Data		30 min									
Water Column WQ Profiles		12 h									
Macrophyte Surveys											
Macrophyte, Quadrat Surveys (0.5 m × 0.5 m)	July						3				
Macrophyte, 897 Rake Tosses, N and S Ends	July–September						x	x			

Weekly limnological data from 4 offshore sites in Seneca Lake and 2 offshore and 7 nearshore (<4 m water depth, 2017–2019) sites in Owasco Lake were collected to compare nearshore and offshore abiotic conditions. CTD (SeaBird SBE-25) profiles, Secchi depths, and plankton tows (80 µm mesh, towed vertically through 20 m of water) were collected at each site. Surface water grab samples were analyzed for TP, SRP, NO_x, TSS, and chlorophyll-a concentrations [33].

A *YSI/Xylem* meteorological and water quality monitoring buoy was deployed in each lake from April through October at an offshore, midlake site. Each buoy collected air temperature, barometric pressure, relative humidity, light intensity, wind speed, and wind direction data every 30 min, and water column profiles using a *YSI/Xylem* EXO2 water quality sonde outfitted with temperature, conductivity, dissolved oxygen, turbidity, chlorophyll, and phycocyanin sensors at noon and midnight every 1.5 m down the water column, starting at 1 m below the surface. Data from a USGS buoy were used in 2020, while the Seneca WQ buoy experienced COVID-delayed repairs.

Finally, preliminary macrophyte surveys were collected at 3 nearshore (<4 m water depth) sites in Owasco Lake in July 2021. Site selection reflected the variability in substrate in the lake from harder cobbles (Site G) to softer macrophyte-covered lake floors (Sites C and D). At each site, triplicate 0.5 m × 0.5 m quadrats were tossed into the water, and scuba divers removed all of the plants in each quadrant. Macrophytes were then separated, identified to species, and weighed wet.

3. Results and Discussion

Data recovery and completeness was good (Table S1). Missed data were typically due to power failures and the inability of the newer meteorological sensors to automatically reconnect to the base station after a power failure at individual sites. These outages were typically skewed towards the beginning (July) or end (October) of the deployment and when blooms were not detected by the cameras. The camera, water temperature loggers, and sonde were recovered early at FL-20 (A) because the homeowner had to remove the dock for winter.

Deployment dates; the number of blooms detected at each site by the cameras and volunteers; and mean, standard deviation, and maximum values of the water and air temperature, wind speed, and light intensity data are shown in the Supplementary Materials (Tables S2 and S3). The data are typically consistent across sites for each parameter, i.e., within 1 standard deviation. For example, the site averaged bloom-season water temperatures for the dock and buoy sites were between 20 and 23 °C (±2 to 3 °C) through the 4 years of the study. Some differences exist. Mean wind speeds were notably faster at the offshore buoy site than the dock sites in each lake, and were small and typically smaller during blooms at the dock sites than other times. Light intensity was slightly elevated during bloom events than other times as well. Finally, deviations detected in the Martin S (E2) meteorological data from the other sites during 2022 were due to missed data, as this site missed 86% of the data during the deployment due to power issues. Each parameter is discussed in more detail below.

The literature indicates that CyanoHABs prefer warm water, sufficient light for photosynthesis and growth, lake stratification, calm or near-calm conditions, and elevated concentrations of nutrients, e.g., [11,34–37]. The onset of CyanoHABs paralleled recent surface water warming and increased anthropogenic nutrient loads related to increased intensity and localization of precipitation events in these lakes due to global climate change [33,35]. Daytime (defined by >0 W/m^2 light intensities) meteorological and water quality data presented here refine these criteria.

Diatoms dominated the phytoplankton mean annual assemblages from the offshore sites. *Diatoma* (spring), *Asterionella* (spring), and *Fragilaria* (fall) species were the three most common diatoms. Other diatom species detected (<1% annual count means) include *Tabellaria*, *Synedra*, and *Melosira*. *Dolichospermum* (formerly *Anabaena*) and *Microcystis* species were the two common forms of cyanobacteria. Low counts of *Dolichospermum* usually appeared first, quickly followed by much larger counts of *Microcystis* during the HAB season. Other cyanobacteria detected (<1% annual count means) include *Stichosiphon* and *Chroococcus*. Varieties of green algae (*Scenedesmus*, *Closteriopsis*, *Staurastrum*, *Pediastrum*, and *Trichiscia*) and dinoflagellates, chrysophytes, and euglenoids (*Chrysosphaerella*, *Dinobryon*, *Epipyxis*, *Ceratium*, and *Colacium*) make up the rest of the community. The counts paralleled FluoroProbe results when they were measured. The 20-year record from the offshore sites indicates that cyanobacteria were always a few percent (<10%) of the annual mean plankton community in both lakes; however, major shoreline blooms were not observed until more recently.

CTD and monitoring buoy data from 1995 (Seneca) and 2005 (Owasco) indicate that surface water temperatures have warmed by ~0.2 °C/year over the past few decades in both lakes (Figure 2). A temperature benchmark of 25 °C was recently attained in these lakes that served as a threshold for the increased dominance of CyanoHABs over other forms of phytoplankton elsewhere [10–12]. Large runoff events delivered significant nutrient loads to both lakes just prior to the first documented reports of Cyanobacteria in both lakes [38,39]. More intense (>5 in/day, >12 cm/day) and more localized rainfall events were more frequent in the past decade [38,40]. Both trends are consistent with global climate change scenarios [41]. Warmer water also promotes faster decomposition of macrophytes and other lake floor organic matter, and provides a potential nutrient source for CyanoHABs and other phytoplankton in these borderline oligotrophic–mesotrophic lakes, e.g., [1,42,43].

The automated cameras faithfully detected a total of 68 and 92 days with blooms in Seneca and Owasco Lakes, respectively, during this study (Figure 3). The cameras typically detected more blooms than the local watershed association bloom-watch volunteers at every site (Table S2). Differences are expected, as the camera's 10 min interval photos imaged a small (2 m × 3 m) portion of the lake, whereas each volunteer typically looked for blooms once a week anywhere along their ~1.6 km (1 mile) long segment of shoreline. The volunteers confirmed that the typical bloom was localized and found along the shoreline, i.e., infrequently extending lakeward beyond the end of the docks. Longshore currents transported these localized blooms along the shoreline. In both lakes, blooms were detected from August through mid-October, and more often from 1100 through 1700 (60%). They lasted from 0.2 to 12 h with a mean duration of 3.2 h. Blooms were rarely detected concurrently at 3 or more sites (<4.2%), and were typically detected at only 1 of the 12 sites

(75.6%) during each 10 min photolog interval of the investigation. Thus, the photologs confirmed the spatial and temporal variability of CyanoHABs.

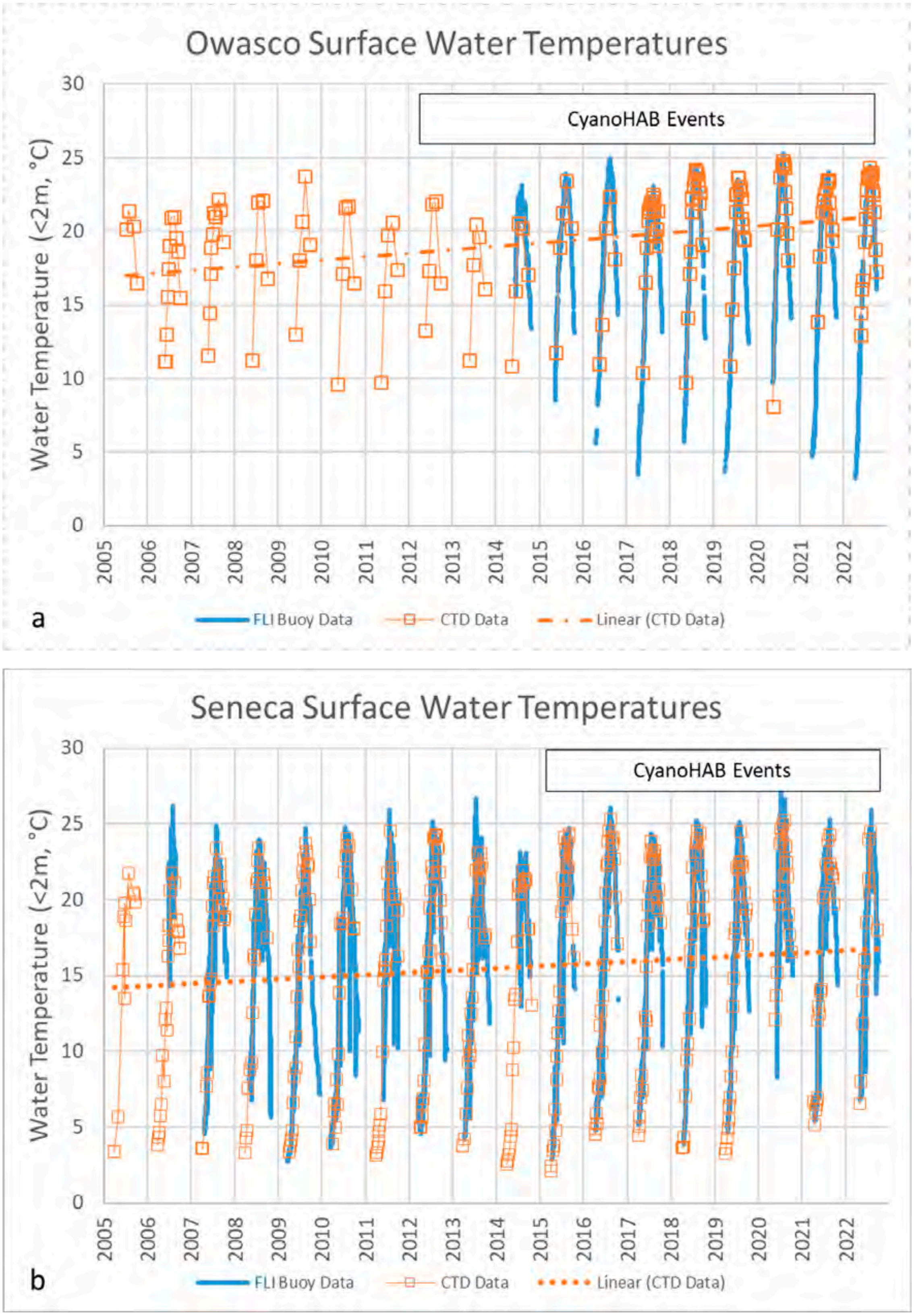
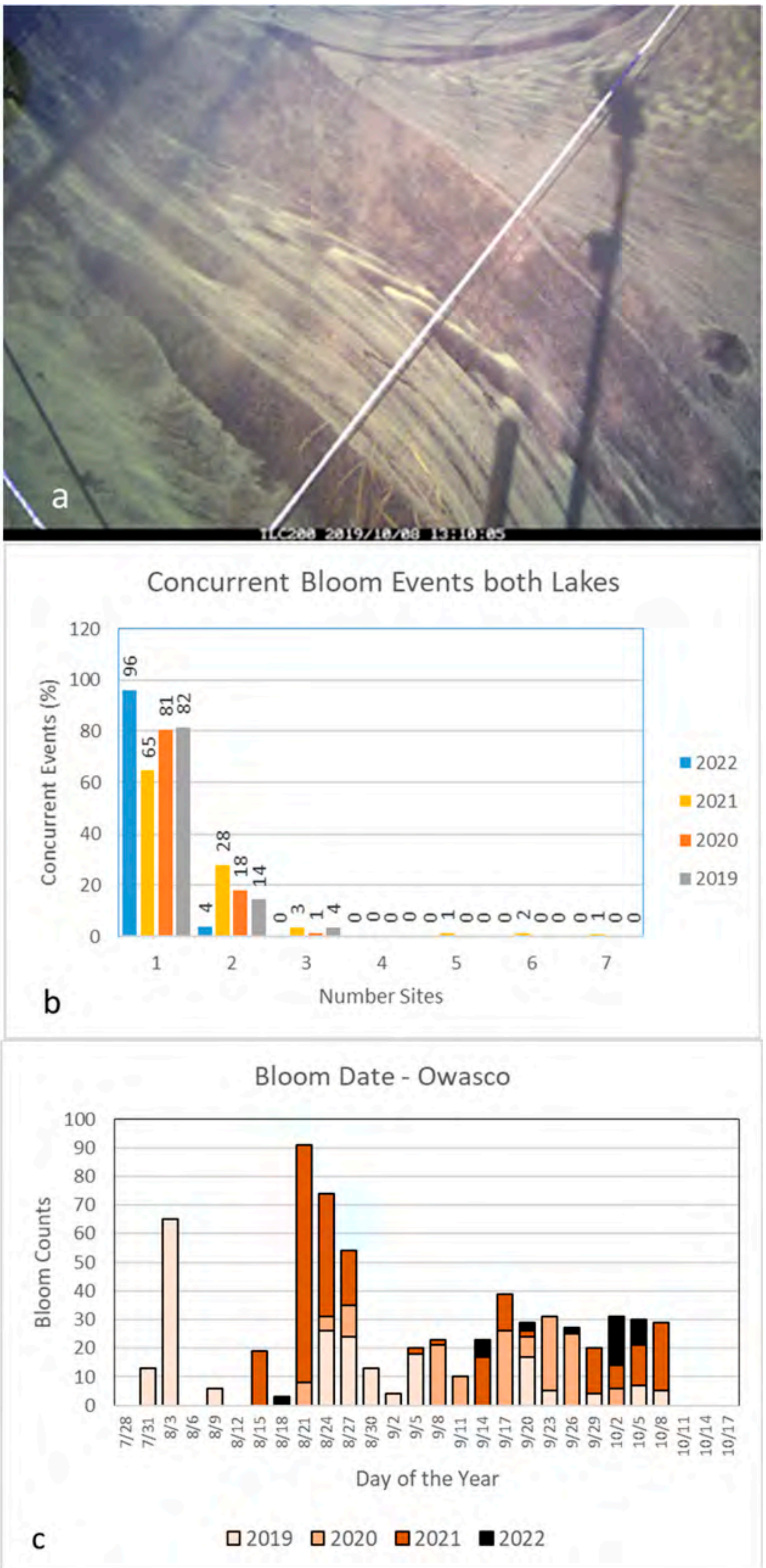


Figure 2. (**a**) Owasco and (**b**) Seneca CTD and monitoring buoy surface (<2 m) mean water temperatures. Years with cyanobacterial bloom sightings are indicated.



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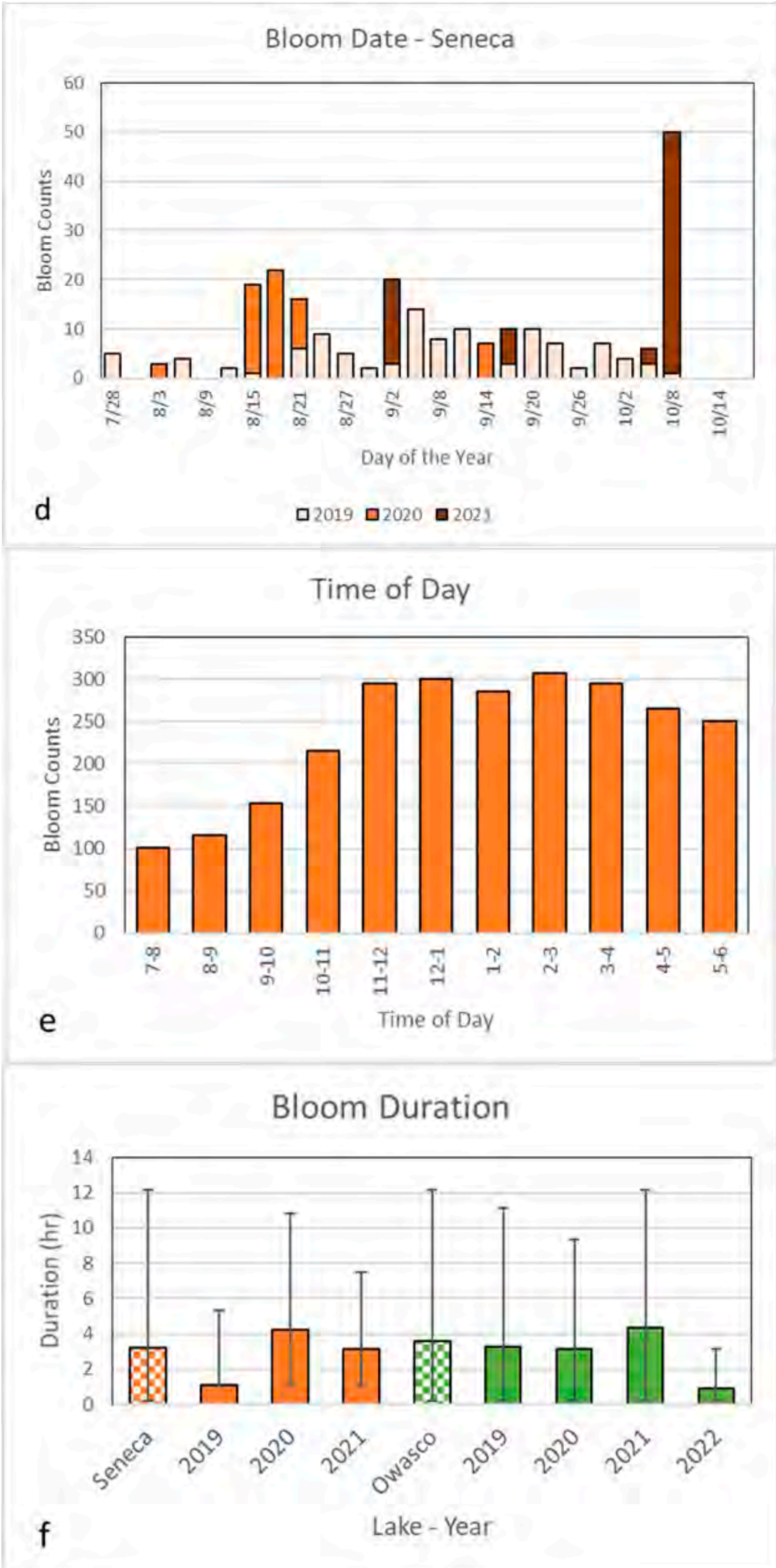
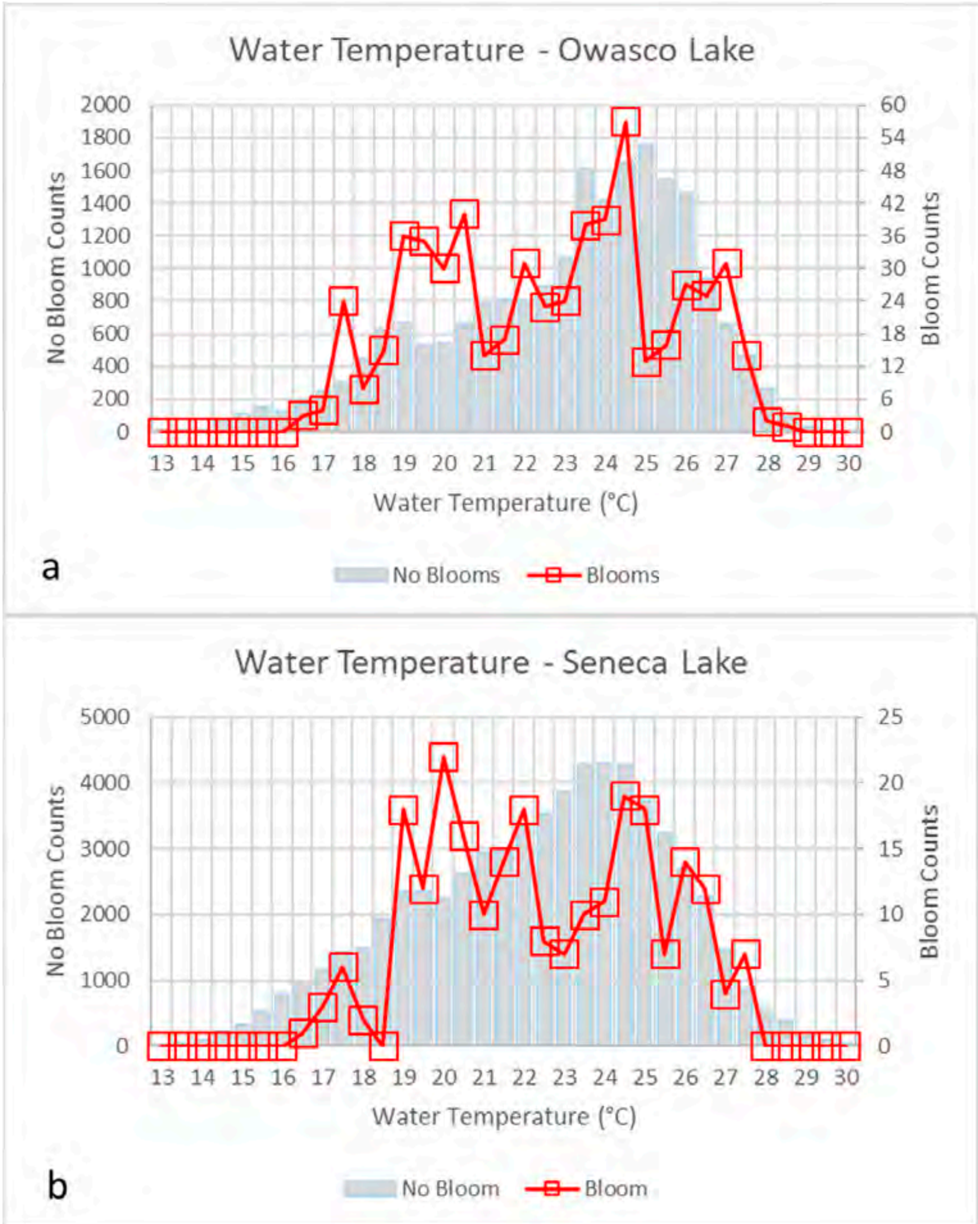


Figure 3. (**a**) Representative photo of a cyanobacterial bloom imaged by the automated camera. (**b**) Percentage of concurrent CyanoHAB events in both lakes (12 sites) by year. Dates for each bloom in (**c**) Owasco and (**d**) Seneca Lakes. (**e**) Time of day for blooms from 7 a.m. through 6 p.m. in both lakes. (**f**) Lake wide mean and annual mean bloom durations in both lakes. The whiskers span the minimum and maximum durations.

Histograms of bloom and no-bloom episodes and bloom/no-bloom ratios versus water temperature, light intensity, wind speed, wind direction, and rainfall revealed similar patterns in both lakes. Blooms were detected when the nearshore water was warm, from 23 to 25 °C (44% of the blooms in Owasco, 33% in Seneca, Figure 4). However, an unexpected peak in bloom counts was observed in cooler nearshore water, cooler than most bloom reports in the literature (16 to 21 °C, 23% of the blooms in Owasco, 33% in Seneca). Blooms in cooler water may reflect the transition into the fall season and/or wind-driven mixing events discussed below. At this range of surface water temperatures, both lakes were stratified, as bottom water temperatures were within a degree of 4 °C year-round as verified by the buoy and CTD data. Larger bloom/no-bloom ratios parallel the peaks in the bloom histograms, suggesting that the two temperature intervals are more ideal for CyanoHABs than other temperatures. For each parameter, the bloom/no-bloom ratios were larger in Owasco Lake, reflecting a larger number of detected blooms by the automated cameras during the deployments.



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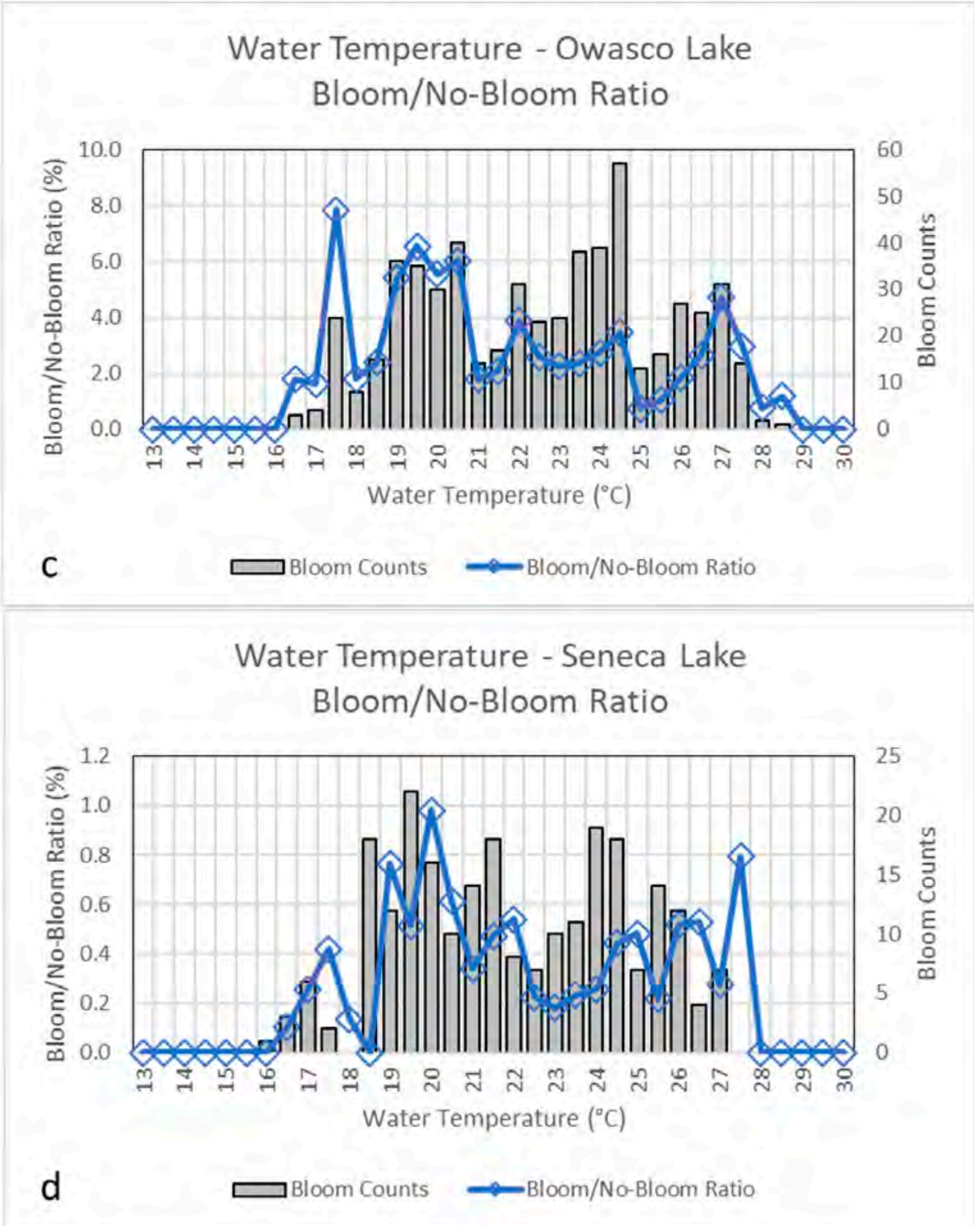
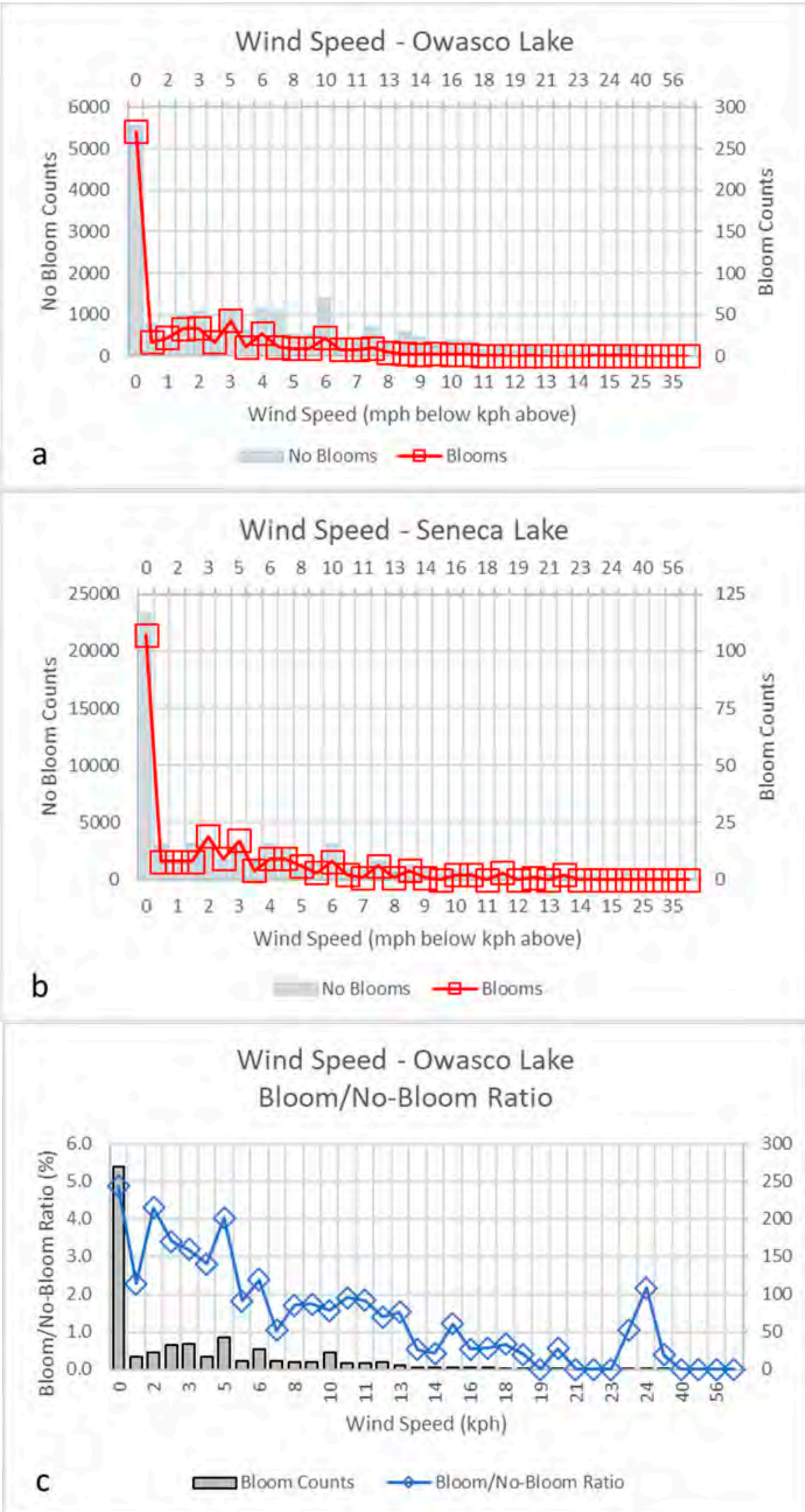


Figure 4. Histograms of surface water temperature during blooms and no blooms and bloom/no-bloom ratios in (**a**,**c**) Owasco and (**b**,**d**) Seneca (identified by the automated cameras). Bloom and no bloom counts are on different scales.

As expected, blooms were frequent during calm, <1 kph, conditions (48% in Owasco, 45% in Seneca, Figure 5). However, over 52% of the blooms were detected at wind speeds of 1 to 20 kph, which were more often blowing onshore. Bloom/no-bloom ratios were generally larger at slower wind speeds, suggesting that CyanoHABs preferred slower wind speeds. The onshore wind direction was unexpected because waves associated with faster winds (e.g., >10 kph, >6 mph) typically retard cyanobacteria buoyancy [37]. Shoreline orientation relative to the offshore wind directions explained some of the spatial variability in blooms in that blooms were more likely along protected, calm shorelines than unprotected shorelines. Blooms were rarely detected (<0.5%) when rain was detected during the previous 30 min of a bloom (Figure 6). The bloom/no-bloom histograms of air temperature revealed similar bell-shaped curves. The most frequent (74%) air temperatures during blooms were from 18 to 27 °C. Larger-bloom/no-bloom ratios parallel the bloom histograms.



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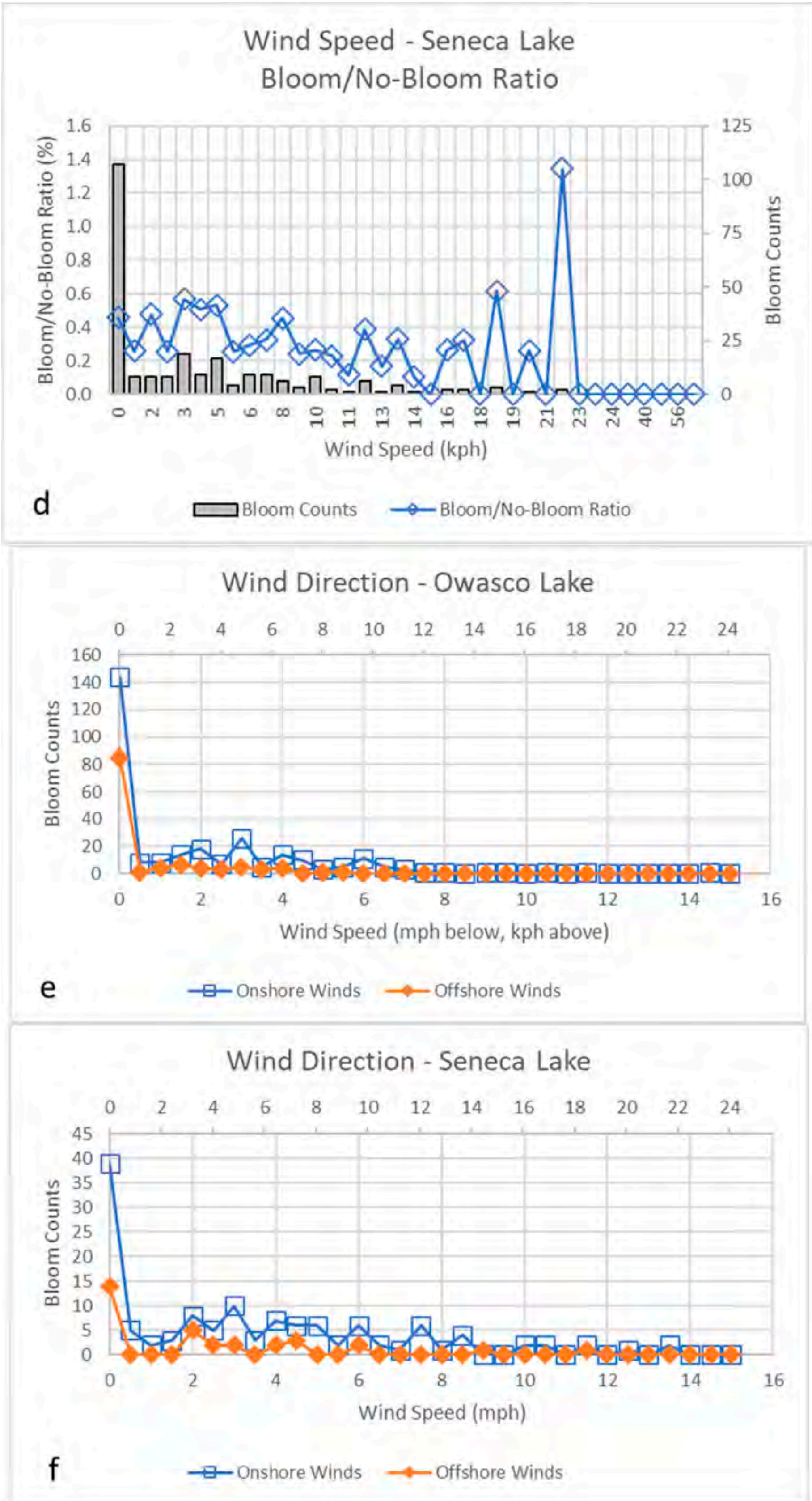

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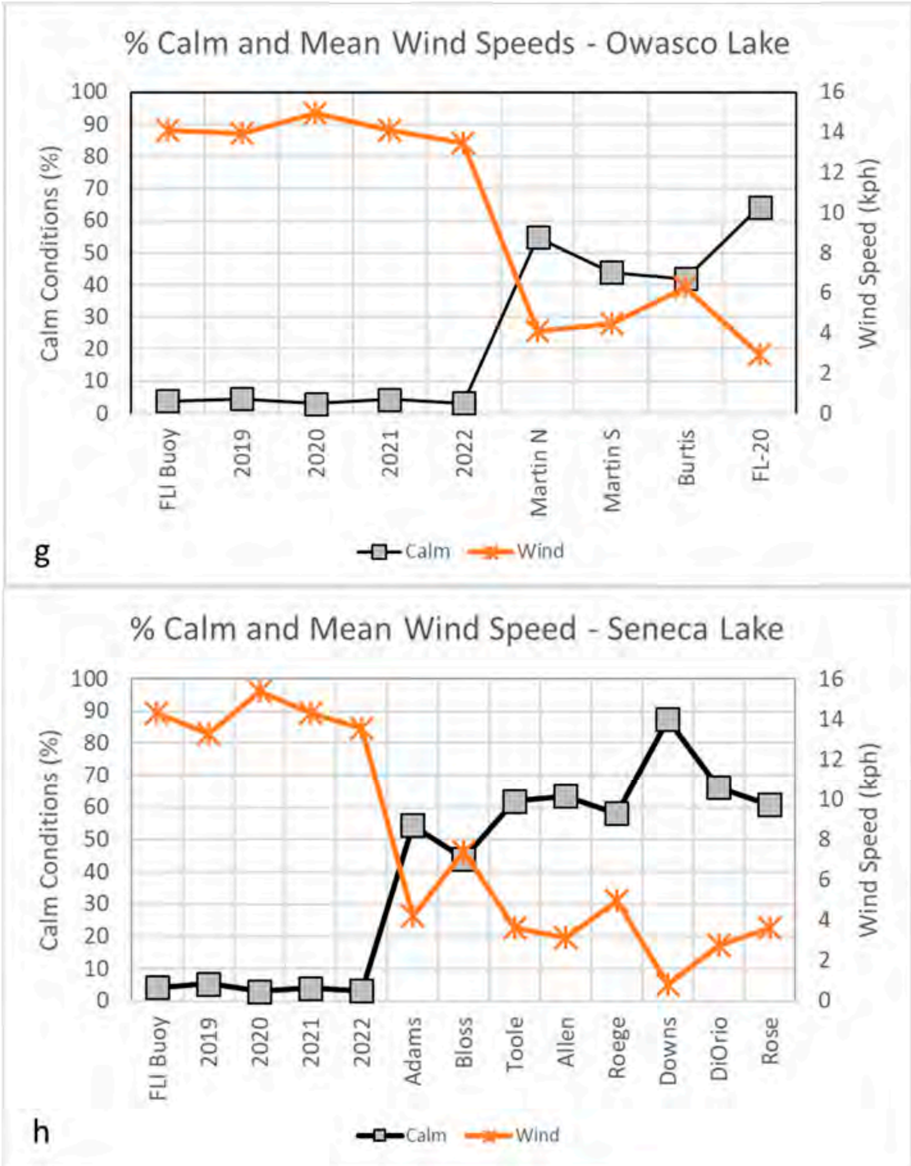
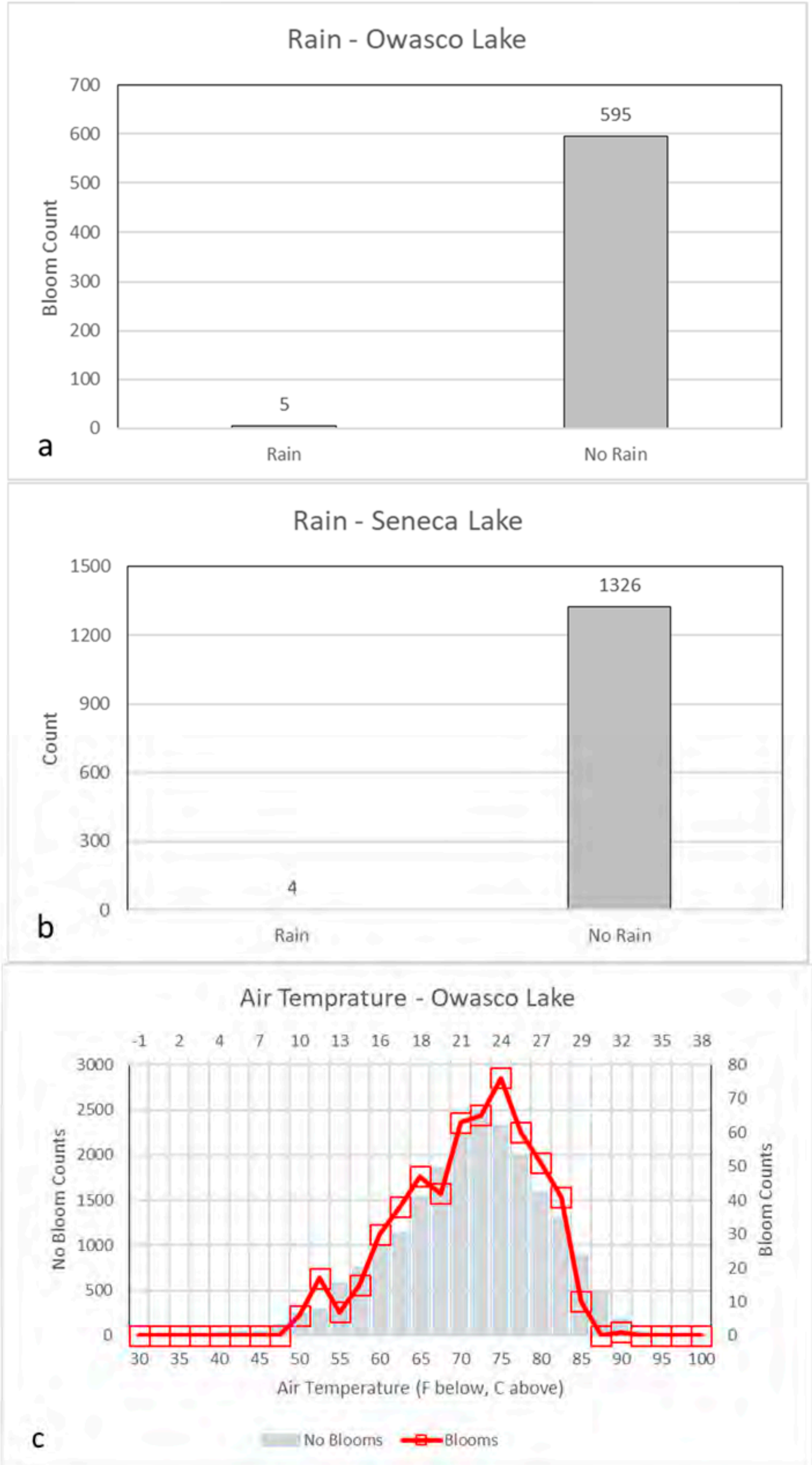


Figure 5. Histograms of wind speed during blooms and no blooms and bloom/no-bloom ratios in (**a**,**c**) Owasco and (**b**,**d**) Seneca Lakes (identified by the automated cameras). Histograms of wind direction during blooms and no blooms in (**e**) Owasco and (**f**) Seneca. Mean HAB season percent calm conditions (<2.5 kph or <1.5 mph) and wind speeds (range: 0–15 kph) at the dock and buoy sites over the course of the study, and annual means for the FLI Buoys in (**g**) Owasco and (**h**) Seneca.

Finally, bloom counts peaked at low light intensities, i.e., from 100 to 200 W/m^2 (25% in Owasco, 35% in Seneca) with a secondary peak at the expected larger light intensities, i.e., sunny conditions, from 600 to 900 W/m^2 (25% in Owasco, 23% in Seneca, Figure 7). For reference, daily light intensities peak just above 1100 W/m^2 during cloud-free days during the HAB season. Some of the low light episodes reflected cloudy weather but others were due to shading by nearby trees, homes, and steep shorelines adjacent to the dock. Bloom/no-bloom ratios were larger at the larger solar intensities, suggesting that CyanoHABs preferred sunny skies. More importantly, 99% of the calm, sunny, warm-water, and/or rain-free episodes did not experience a bloom. It confirms the lack of consistent meteorological or limnological conditions during blooms, and suggests that nutrient availability could be a factor for bloom genesis in these borderline oligotrophic–mesotrophic lakes.



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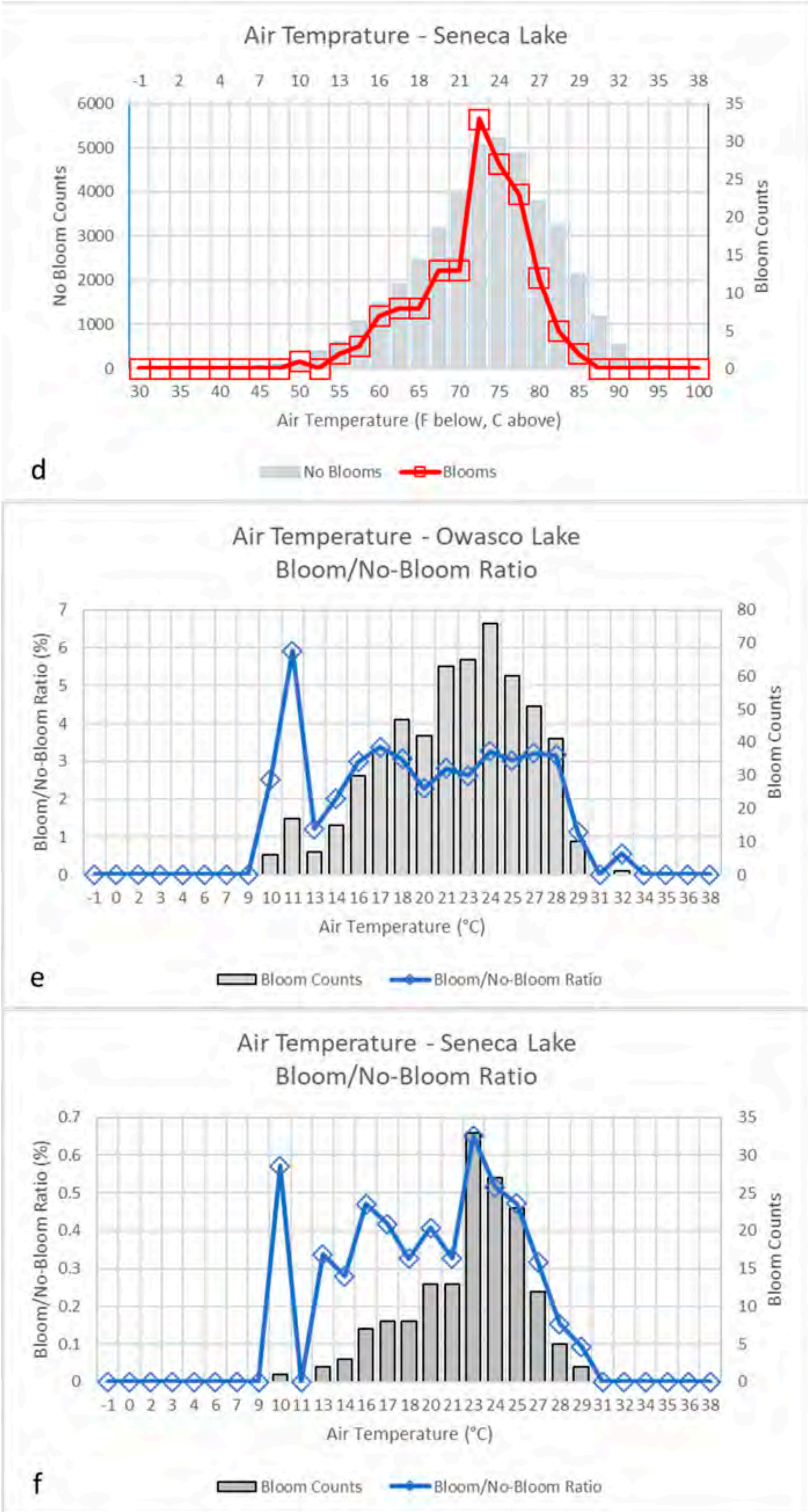

Figure 6. Bloom counts during rainfall and no rainfall events as defined by the preceding 30 min episodes in (**a**) Owasco and (**b**) Seneca. Histograms of air temperature during blooms and no blooms and bloom/no-bloom ratios in (**c**,**e**) Owasco and (**d**,**f**) Seneca (identified by the automated cameras).

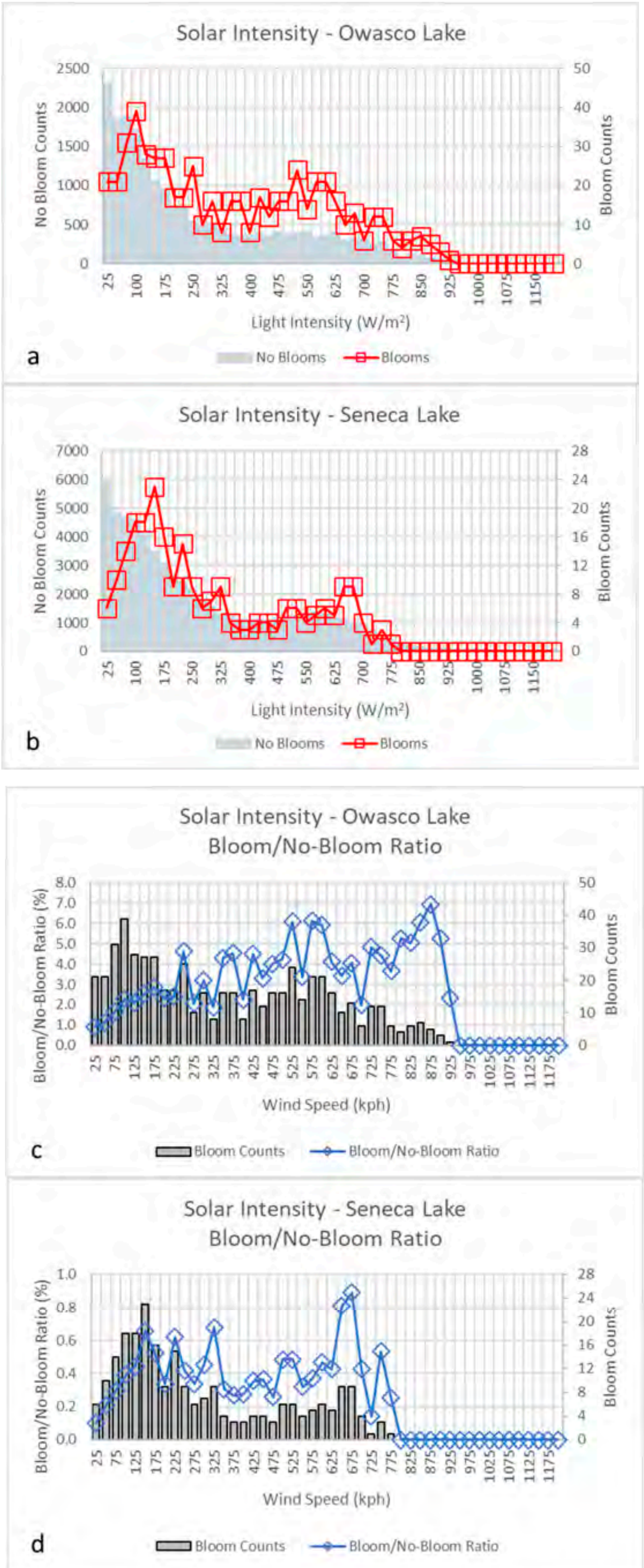

Figure 7. Histograms of light intensity during blooms and no blooms and bloom/no-bloom ratios (identified by the automated cameras) in (**a**,**c**) Owasco and (**b**,**d**) Seneca.

Nutrient concentrations in surface water grab samples collected at dock, nearshore, and offshore sites in Owasco Lake revealed similar concentration means and ranges of total phosphorus (14 µg/L, P), soluble reactive phosphate (0.7 µg/L, P) and nitrate–nitrite (0.6 mg/L, N, Figure 8). Estimated concentrations of phosphorus in the CyanoHABs using measured cyanobacteria bloom concentrations and mean algal Redfield ratios were approximately 10 to 100 times larger than the water column concentrations detected in these lakes, e.g., [44]. The low nutrient concentrations and minimal spatial variability in those concentrations indicate that the water column lacks sufficient nutrients to support the detected bloom biomass. Perhaps a unique series of precursor events are required to initiate a nearshore spike in nutrients and subsequently a bloom.

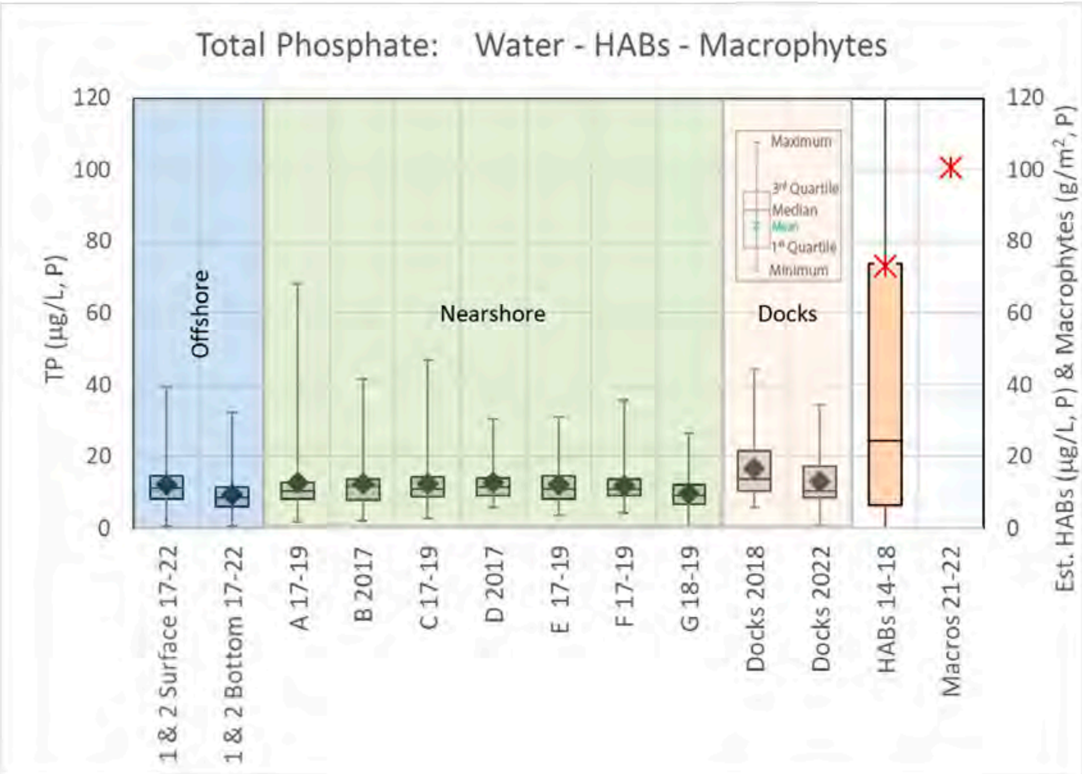

Figure 8. Box (25%, 50%, 75%) and whisker (minimum and maximum) plots and mean concentrations (◆) of surface water, grab sample, total phosphate concentrations at offshore (1 and 2), nearshore (A–G), and dock sites in Owasco Lake, compiling all available data from each site. Estimated P-concentration means from measured HAB samples (∗) and nearshore macrophyte biomass (note the scale change from µg/L to g/m^2) are also shown. The preliminary macrophyte data precluded plotting the "25, 50, 75% box".

Numerous blooms were detected after the heaviest rain events over the course of the study and consistent with findings elsewhere, e.g., [1,7,11,45] (Figure 9). In Owasco Lake, the 18–20 August 2021 event preceded blooms at 3 of 4 sites around Owasco Lake. Blooms were not detected around Seneca Lake during these dates because this intense precipitation event was localized to the Owasco watershed [40]. This atypical and very localized event provided over 20 cm of rain and 50% of the seasonal nutrient and suspended sediment loads in the second largest basin in the watershed [40]. Lake levels rose by ~1 m and delivered nearshore rotting organic debris to the water column. Atypical localized and intense rain events are becoming the new normal as global temperatures continue to rise [41]. However, blooms were not detected after most, i.e., smaller (<2 in, 5 cm) rain events.

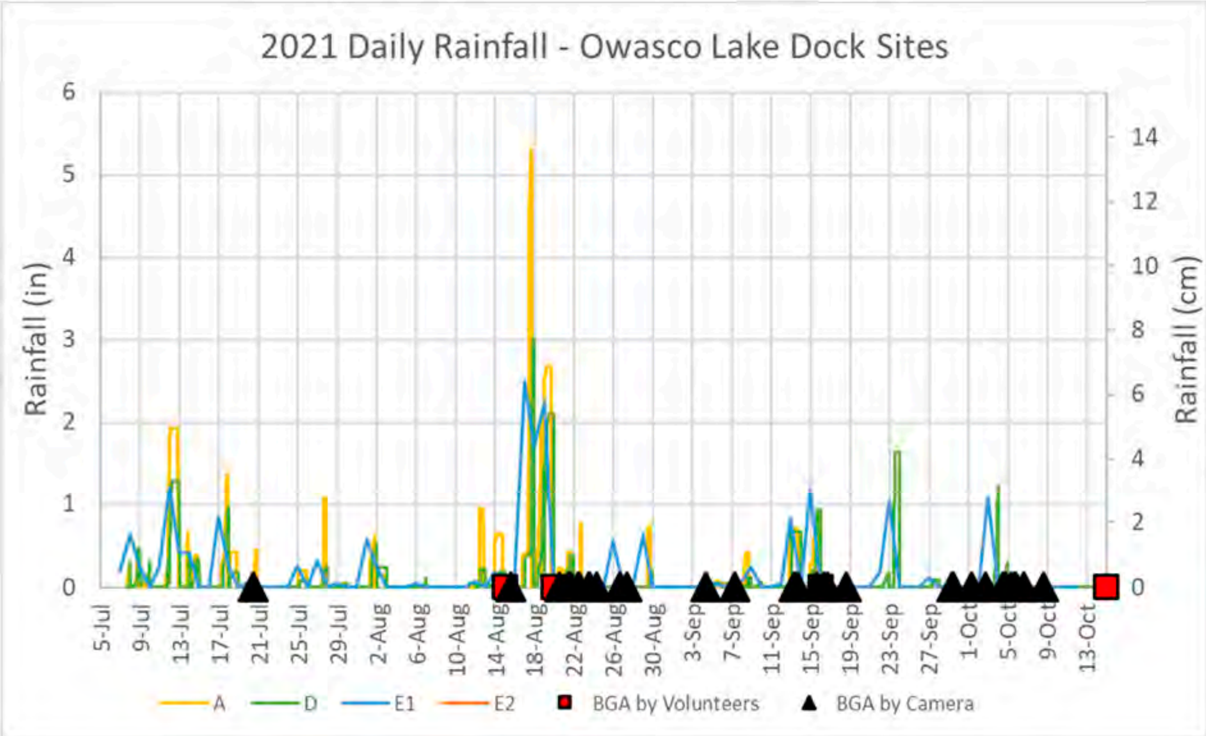

Figure 9. Daily rainfall and its temporal relationship with blooms detected at the four Owasco Lake dock sites in 2021.

Blooms were also detected on the first calm day after a strong wind event, e.g., daylong, sustained winds greater than 15 kph (Figure 10). For example, the 2020 peak in bloom counts during October in Seneca Lake were associated with the first calm days after many days with strong winds (Figure 2). We hypothesize that the strong winds and associated waves uprooted macrophytes and other organic debris leading to biomass accumulation along the downwind shoreline. The decaying biomass could provide a viable supply of nutrients for the blooms. In support, two sites, Site C in Seneca Lake, and FL-20 (A) in Owasco Lake, experienced significantly fewer strong wind events and smaller seasonal mean wind speeds than the other sites in these lakes (Figure 5). Site C experienced the third fewest blooms in Seneca Lake, and the FL-20 (A) site experienced the fewest blooms in Owasco Lake. This indicates that a lack of strong wind events hampered bloom development during the subsequent calm day. For Owasco, the FL-20 (A) site lacks an extensive shallow-water shelf (15 m wide compared to >100 m wide in the northern Owasco Lake), as the lake floor descends quickly to the deepest and aphotic parts of the lake just offshore of the dock. Thus, the FL-20 (A) site has less benthic biomass to decompose and supply nutrients for blooms.

Surface water temperatures revealed consistent spatial and temporal variability in water temperatures during each year of the study (Figure 11). The first major, i.e., mid-August, bloom event of the season in both lakes were detected a week or so after the summer peak in temperatures at ~25 °C, and more importantly, after a 2 to 3 °C multi-day dip in surface water temperatures. The temperature dip was initiated by strong winds that mixed cooler hypolimnetic water to the surface and/or were associated with a rain event that brought cooler rainwater to the lake, and presumably delivered nutrients from the watershed to the surface waters of the lake. We also hypothesize that strong winds released nutrients from the decaying organics along the shoreline and/or stored in the nearshore sediments. The amount of organic debris and nutrient cycling is presumably augmented by the presence of dreissenid mussels nearshore [46]. The delay after the peak in water temperatures may reflect the time required to stimulate benthic communities leading to faster bacterial decomposition of organic debris along the shoreline. The prevailing southerly winds would accumulate the organic detritus to the northern shorelines, and is consistent with more blooms detected along the northern shorelines. It suggests that the warm water, wind/rain event, and subsequent temperature dip sequence defined a series of events to initiate a bloom in these lakes. Unfortunately, subsequent blooms during 2017 and a few other years were less dependent on the warmer water, wind/rain, and temperature dip sequence.

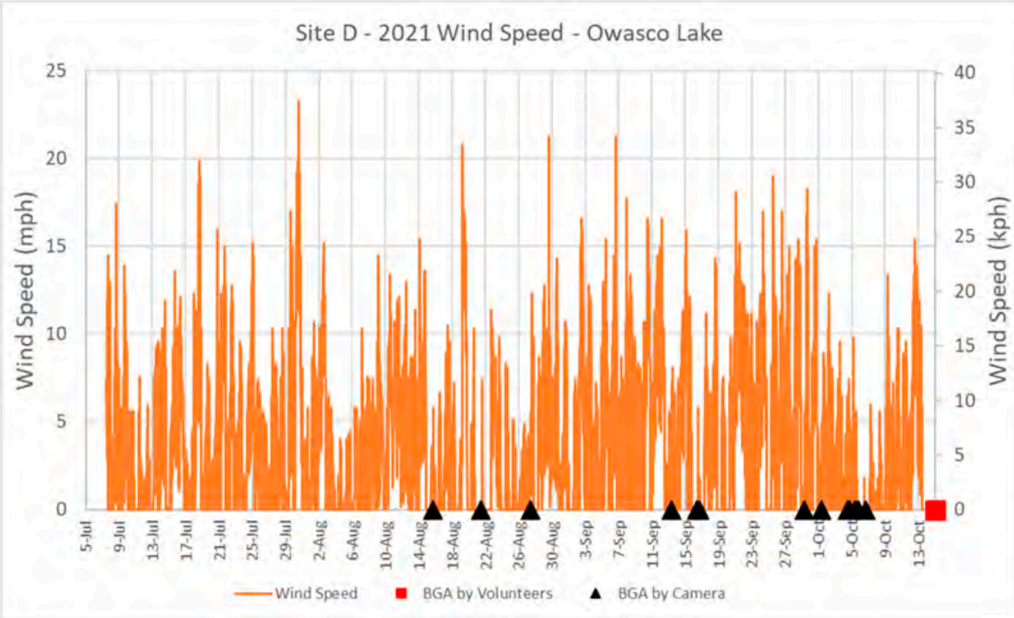

Figure 10. Wind speeds at the Burtis dock site (near Site D), Owasco Lake, and its temporal relationship with blooms detected at this site in 2021.

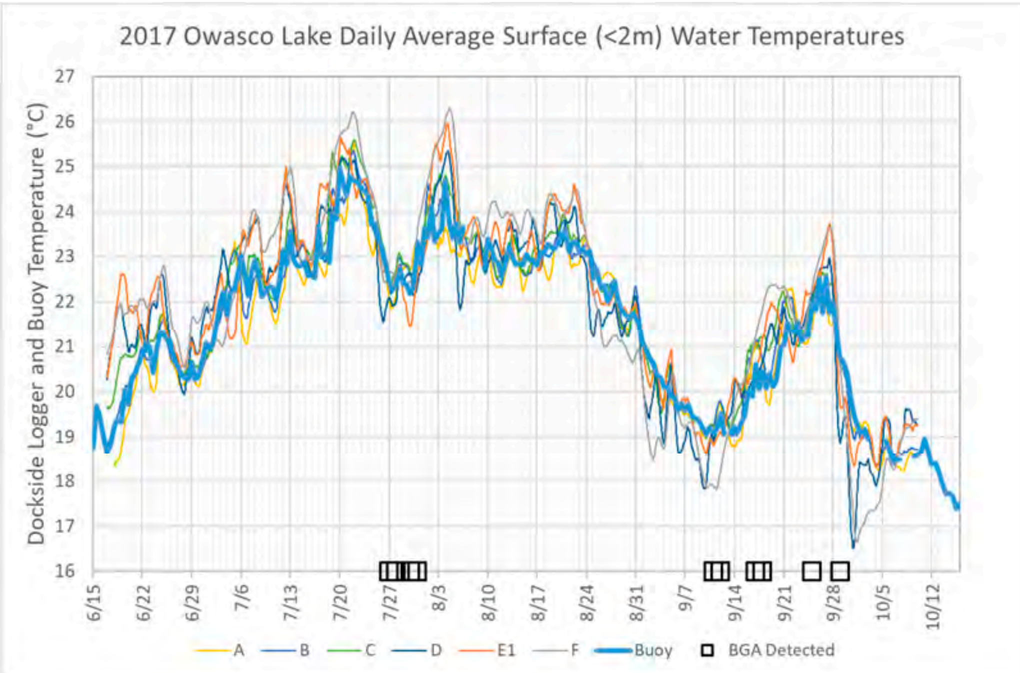

Figure 11. Surface water (<2 m) temperatures and its temporal relationship with blooms at the four dock sites in Owasco Lake during 2017.

The day-to-day change in water temperature, wind speed, light intensity, air temperature, and rainfall over a 24 h period was investigated to explore these temporal relationships. The mean of both 2 and 4 h windows during each sample point was subtracted from the mean of the 2 and 4 h windows exactly 24 h before the sample point. This was calculated over the entire dataset, counting if the sample time was during a bloom or not. The differences were compiled for each lake and plotted as a percentage of the differences less than 0 to the total dataset and its subsequent deviation from 50% (Figure 12). For example, 0% (50–50) indicates an equal number of declines or increases in the environmental variable over the 24 h period. A less-than-zero temperature difference indicates that the data point mean temperature was warmer than during a previous 24 h window. Blooms occur after the water warms (65%), the air warms (65%, in Owasco only), wind speed decreases (40%), light intensity increases (65%), and rainfall declines (10%) from the previous day in both lakes. Temporal trends through the bloom season in the percent difference were not observed in these parameters. The no-bloom differences are typically separated by 15% from bloom comparison. It suggests that the change in these environmental variables impacts the timing for many blooms. The wind speed and rainfall results are consistent with the earlier findings, yet water and air temperature and light intensity appear less consistent. However, these percentages are within 15% of 50%, and thus do not exclude the opposite trend.

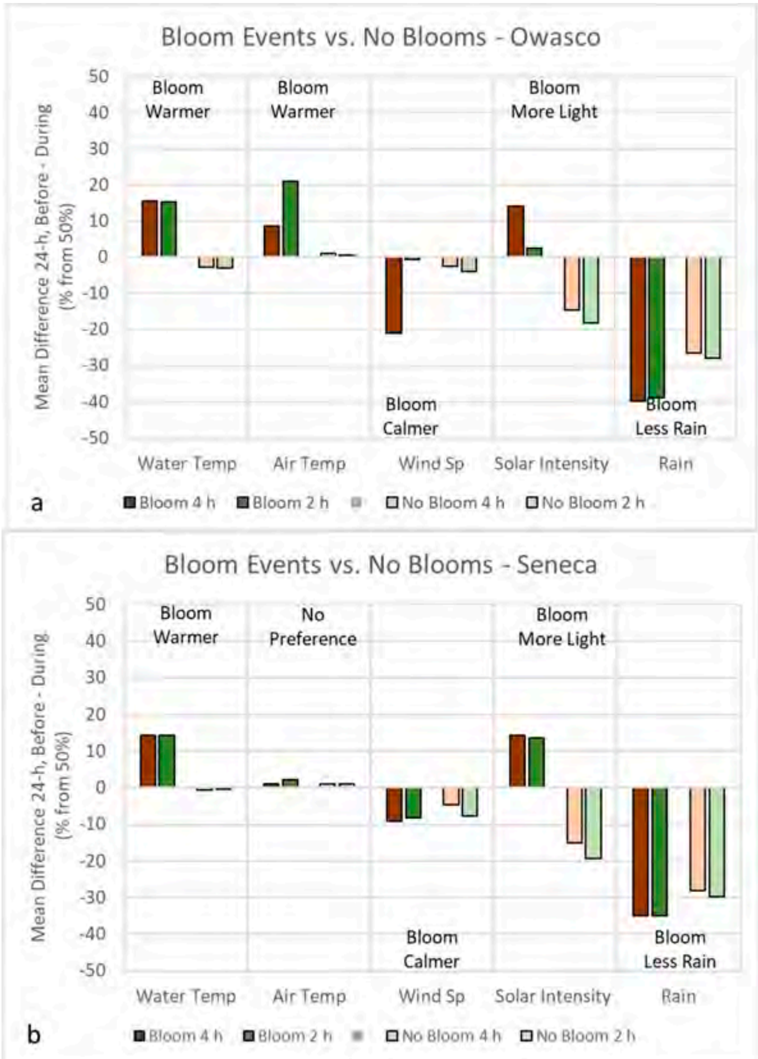

Figure 12. Percent difference in water temperature, air temperature, wind speed solar intensity, and rainfall over a 24 h period tabulated for bloom or no-bloom events in (**a**) Owasco and (**b**) Seneca Lakes.

The nutrient availability hypothesis for cyanobacteria blooms is supported by six observations and preliminary macrophyte biomass data. First, approximately 100 mL of distilled water was added to 50 mL of surficial sediments in 125 mL flasks, swirled, and placed on a windowsill in full sunlight. The sediments were collected by ponar dredge from water depths of 5 to 50 m at 8 different sites in Owasco Lake. Within a week, cyanobacteria bloomed in every flask. It indicates that appropriate concentrations of resting cysts and nutrients were present in the mud. The swirl, aka wind event, released both for a bloom. Second, total phosphorus and total organic carbon concentrations in these sediment samples ranged from 60 to 140 mg P/g dry sediment and 1 to 6% dry wt., respectively. These concentrations are sufficient to support a typical bloom of cyanobacteria and consistent with findings elsewhere [47]. Third, cyanobacteria are frequently observed near decaying macrophyte accumulations along the shoreline and floating macrophyte mats in the open water. This suggests that decomposing organic material is supplying nutrients for cyanobacterial growth, and is consistent with the unexpected detection of blooms during onshore winds in these lakes and internal nutrient sources supporting cyanobacterial blooms elsewhere, e.g., [14,48,49]. It also suggests a potential remediation practice for these lakes; namely, remove shoreline accumulations of macrophytes and other organic materials before they decompose.

Fourth, intense nearshore biological activity was discerned from the dockside sonde data. Sonde dissolved oxygen (DO) concentrations revealed a diel cycle at all four dock sites that was not observed offshore (Figure 13). DO concentrations were largest during the daytime when the water was warmer, smallest at night when the water was cooler, and interpreted as intense daytime net photosynthesis and nighttime respiration in nearshore settings. Between the 4 Owasco dock sites, Burtis Pt. (D) had the largest diel change in DO concentrations, FL-20 (A) had the smallest diurnal change in DO, and the two Martin sites (E1 and E2) were in between. It parallels the mean width of 120, 15, 60, and 70 m, respectively, of the offshore shallow water shelves (<4 m water depth) at each site and, thus, the aerial extent of macrophyte beds and benthic algae (e.g., chara, starry stonewort).

Fifth, during the second week of September 2021, DO concentrations decreased to anoxia or close to anoxia on several occasions, and occurred when the deployment pipe was clogged with macrophytes (Figure 13). The DO decrease is interpreted as respiration resulting from bacterial decomposition of the decaying macrophytes in the deployment pipe. The occasional increase in DO reflects the replenishment of lake water into the pipe enclosure. For a few days after the initial decreased DO, total chlorophyll and phycocyanin concentrations increased. We suspect that cyanobacteria growth was stimulated by the release of nutrients by bacterial respiration. The blooms were restricted to the deployment pipe as they were not observed in the adjacent automated camera. The anoxic conditions may have also released ferrous iron, a suspected micronutrient for CyanoHABs [50,51].

Sixth, preliminary macrophyte surveys revealed populations that were dominated by brittle and other naiads, starry stonewort, chara, small and other pondweeds, and Eurasian watermilfoil (Figure 14). Brittle naiads dominated site C, chara site D, and starry stonewort site G. Quadrat mean macrophyte masses ranged from 3800 to 10,000 g wet/m^2. Assuming an estimated water content of 90% and typical phosphorus contents of 0.2% (dry weight), this equates to 1 to 2 g of phosphorus/m^2 of lake floor (Figure 8). Even if only 0.01% of this biomass decomposed along the shoreline in any given year, this yields more than enough phosphorus to spur a typical CyanoHABs bloom in these lakes, assuming a 4 m water depth. It compares nicely with a three- to fivefold increase in water column TP concentrations after decomposing common macrophytes in controlled settings [43]. The northerly locations that have more extensive shallow-water shelves presumably generate more nutrients for CyanoHABs. It parallels more frequent blooms along the northerly shoreline. These observations and preliminary data suggest that large rain events, wind, and decomposition of macrophytes and other biomass are likely nutrient sources for the HAB events. Clearly, more work is required to better quantify macrophyte densities by adding monitoring sites, investigating the percentage of biomass decomposed each year, and understanding the biomass and nutrient recycling by other organisms, e.g., zebra and quagga mussels, on the lake floor to confirm this nutrient source hypothesis for these borderline oligotrophic to mesotrophic lakes.

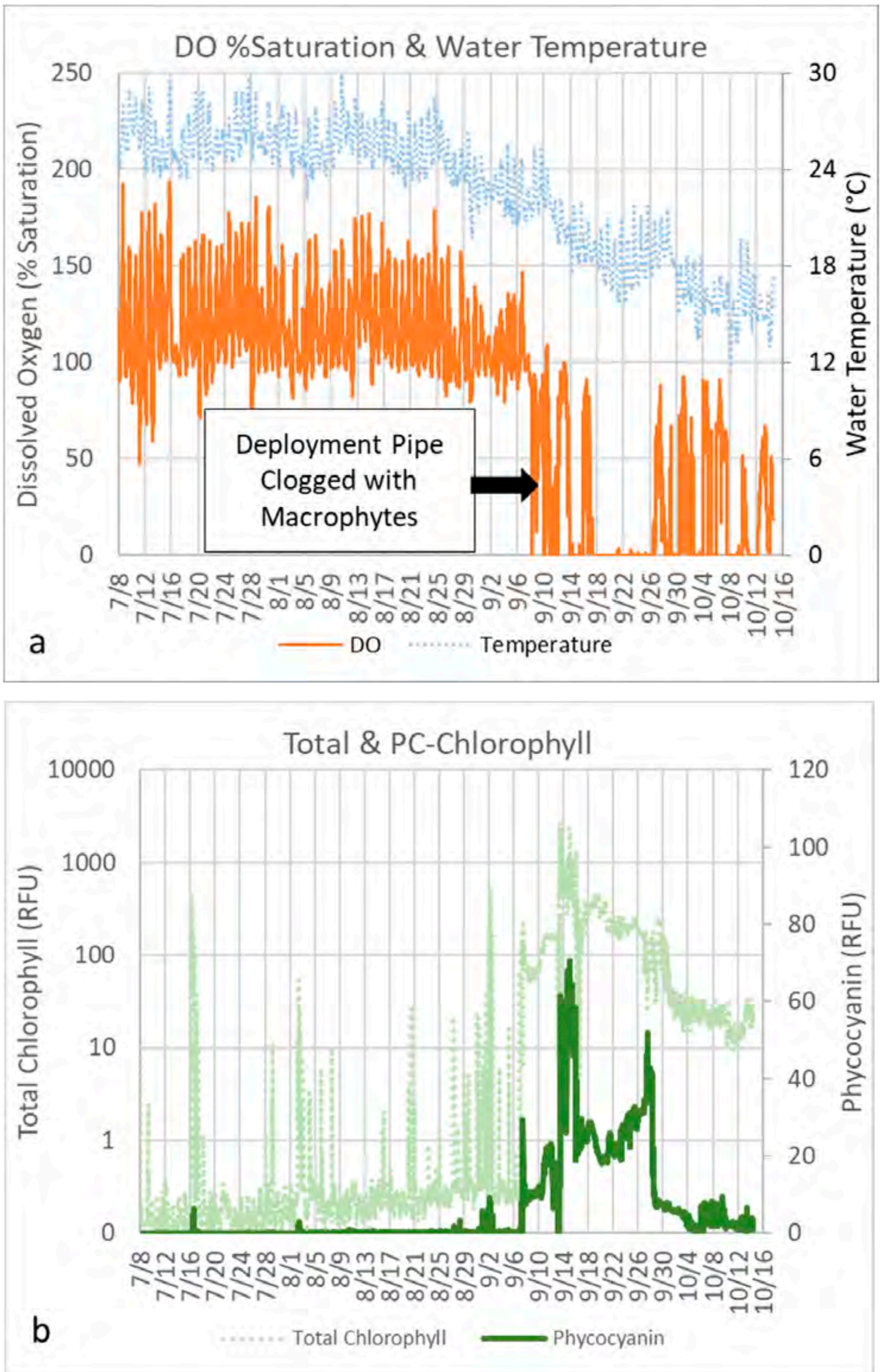

Figure 13. (**a**) Dissolved oxygen (DO) and water temperature and (**b**) total chlorophyll and phycocyanin pigment concentrations from Martin S (E2) in Owasco Lake during 2020.

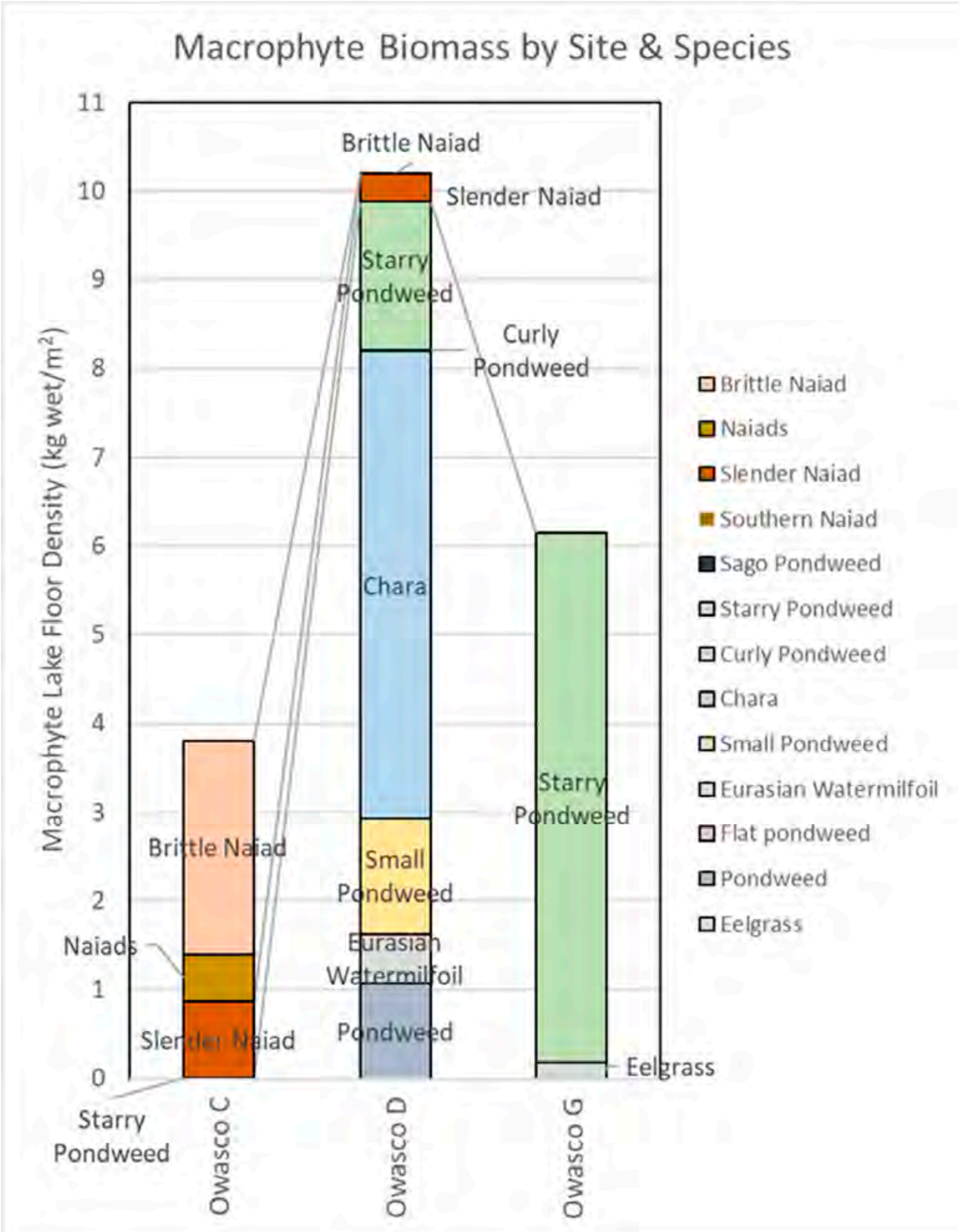

Figure 14. Preliminary nearshore macrophyte biomass (kg wet/m^2) in Owasco Lake during 2021.

4. Conclusions

Nearshore cyanobacterial blooms favored calm, sunny, and warm conditions. However, they were not detected on every calm, sunny, and warm day. Blooms were also detected on overcast, cool, and windy days. The first blooms of the season happened a few days after the summer peak in water temperatures, occasionally following a significant dip (~2 °C) in water temperatures. Nearshore, water column, nutrient concentrations (TP, SRP, and NO_x) from surface grabs were similar to offshore data and insufficient to support bloom events. Potential nutrient sources for blooms may result from significant precipitation events and/or the decomposition of nearshore and shoreline organic matter, e.g., dead macrophytes, nearshore sediment organics augmented by dreissenid mussels, and earlier CyanoHABs. Onshore winds released the nutrients from these nearshore and shoreline sources to supply the typical shoreline-hugging cyanobacterial blooms in these lakes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15132363/s1, Table S1: Data Recovery and Completeness in Owasco & Seneca Lakes (% Deployment); Table S2. Deployment Dates and Blooms Detected by Cameras & Volunteers; Table S3. Data Means, Standard Deviations and Maximum Values.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare that they have no competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Ho, J.; Michalak, A. Challenges in tracking harmful algal blooms: A synthesis of evidence from Lake Erie. *J. Great Lakes Res.* **2015**, *41*, 317–325. [CrossRef]
2. Johnk, K.D.; Huisman, J.; Sharples, J.; Sommeijer, B.; Visser, P.M.; Stroom, J.M. Summer heatwaves promote blooms of harmful cyanobacteria. *Glob. Chang. Biol.* **2008**, *14*, 495–512. [CrossRef]
3. Anderson, D. Approaches to monitoring, control and management of harmful algal blooms (HABs). *Ocean Coast Manag.* **2009**, *52*, 342–347. [CrossRef]
4. Qin, B.Q.; Zhu, G.W.; Gao, G.; Zhang, Y.L.; Li, W.; Paerl, H.W.; Carmichael, W.W. A drinking water crisis in Lake Taihu, China: Linkage to climatic variability and lake management. *Environ. Manag.* **2010**, *45*, 105–112. [CrossRef]
5. Chawira, M. Monitoring Blue-Green Algae in the Ijsselmeer Using Remote Sensing and In-Situ Measurements. Available online: http://essay.utwente.nl/84860/1/chawira.pdf (accessed on 31 March 2022).
6. Sitoki, L.; Kurmayer, R.; Rott, E. Spatial variation of phytoplankton composition, biovolume, and resulting microcystin concentrations in the Nyanza Gulf (Lake Victoria, Kenya). *Hydrobiologia* **2012**, *691*, 109–122. [CrossRef]
7. Michalak, A.E.; Anderson, E.J.; Beletsky, D.; Boland, S.; Bosch, N.S.; Bridgeman, T.B.; Chaffin, J.D.; Cho, K.; Confesor, R.; Dalglu, I.; et al. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 6448–6452. [CrossRef] [PubMed]
8. Ma, J.; Qin, B.; Paerl, H.; Brookes, J.; Hall, N.; Shi, K.; Zhou, Y.; Guo, J.; Li, Z.; Xu, H.; et al. The persistence of cyanobacterial (*Microcystis* spp.) blooms throughout winter in Lake Taihu, China. *Limnol. Oceanogr.* **2016**, *61*, 711–722. [CrossRef]
9. Smith, R.B.; Buss, B.; Sawyer, D.; Depew, D.; Watson, S.B. Estimating the economic costs of algal blooms in the Canadian Lake Erie basin. *Harmful Algae* **2019**, *87*, 101624. [CrossRef]
10. Weyhenmeyer, G.A. Warmer winters: Are planktonic algal populations in Sweden's lakes affected? *Ambio* **2001**, *30*, 565–571. [CrossRef]
11. Paerl, H.W.; Huisman, J. Climate change: A catalyst for global expansion of harmful cyanobacterial blooms. *Environ. Microbiol. Rep.* **2009**, *1*, 27–37. [CrossRef]
12. Elliot, J.A. Is the future blue-green? A review of the current model predictions of how climate change could affect pelagic freshwater cyanobacteria. *Water Res.* **2012**, *46*, 1364–1371. [CrossRef]
13. Huisman, J.; Codd, G.A.; Paerl, H.A.; Ibelings, B.W.; Verspagen, J.; Visser, P.M. Cyanobacterial blooms. *Nat. Rev. Microbiol.* **2018**, *16*, 471–483. [CrossRef] [PubMed]
14. Jankowiak, J.; Hattenrath-Lehmann, T.; Kramer, B.; Ladds, M.; Gobler, C. Deciphering the effects of nitrogen, phosphorus, and temperature on cyanobacterial bloom intensification, diversity, and toxicity in western Lake Erie. *Limnol. Oceanogr.* **2019**, *64*, 1347–1370. [CrossRef]
15. Ho, J.C.; Michalak, A.M. Exploring temperature and precipitation impacts on harmful lagal blooms across continental US lakes. *Limnol. Oceanogr.* **2020**, *65*, 992–1009. [CrossRef]
16. Tewari, K. A review of climate change impact studies on harmful algal blooms. *Phycology* **2022**, *2*, 244–253. [CrossRef]

17. Kitchens, C.; Johengen, T.; Davis, T. Establishing spatial and temporal patterns in Microcystis sediment seed stock viability and their relationship to subsequent bloom development in Western Lake Erie. *PLoS ONE* **2018**, *13*, e0206821. [CrossRef] [PubMed]
18. Perri, K.A.; Sullivan, J.M.; Boyer, G.L. Harmful algal blooms in Sodus Bay, Lake Ontario: A comparison of nutrients, marina presence, and cyanobacterial toxins. *J. Great Lakes Res.* **2015**, *41*, 326–337. [CrossRef]
19. McCarthy, M.; Gardner, W.; Lehmann, M.; Guindon, A.; Bird, D. Benthic nitrogen regeneration, fixation, and denitrification in a temperate, eutrophic lake: Effects on the nitrogen budget and cyanobacteria blooms. *Limnol. Oceanogr.* **2016**, *61*, 1406–1423. [CrossRef]
20. Gonzales, C. New York Sea Grant: Harmful Algal Blooms News—Update on Harmful Algal Blooms in Sodus Bay, Lake Ontario, May 2021. Available online: https://seagrant.sunysb.edu/articles/t/update-on-harmful-algal-blooms-in-sodus-bay-lake-ontario-harmful-algal-blooms-news (accessed on 31 March 2022).
21. Raikow, D.F.; Sarnelle, O.; Wilson, A.E.; Hamilton, S.K. Dominance of the noxious cyanobacterium *Microcystis aeruginosa* in low-nutrient lakes is associated with exotic zebra mussels. *Limnnol. Oceanogr.* **2004**, *49*, 482–487. [CrossRef]
22. Sarnelle, O.; Wilson, A.E.; Hamilton, S.K.; Knoll, L.B.; Raikow, D.F. Comploex interactions between the zevra mussel, Dreissena polymorpha, and the harmful phytoplankter, Microcystis aeruginosa. *Limnol. Oceanogr.* **2005**, *50*, 896–904. [CrossRef]
23. Reini, K.L.; Brookes, J.D.; Carey, C.C.; Harris, T.D.; Ibelings, B.S.; Morales-Williams, A.M.; De Senerpont Domis, L.N.; Atkins, K.S.; Isles, P.D.; Mesman, J.P.; et al. Cyanobacterial blooms in oligotrophic lakes: Shifting the high-nutrient paradigm. *Freshwater Biol.* **2021**, *66*, 1846–1859. [CrossRef]
24. Chorus, I.; Bartram, J. *Toxic Cyanobacteria in Water: A Guide to Their Public Health Consequences, Monitoring and Management*; CRC Press Routledge: Boca Raton, FL, USA, 1999.
25. Graham, J.L.; Loftin, K.A.; Ziegler, A.C.; Meyer, M.T. *Guidelines for Design and Sampling for Cyanobacterial Toxin and Taste-and-Odor Studies in Lakes and Reservoirs*; U.S. Geological Survey (U.S. Geological Survey): Reston, VA, USA, 2008.
26. Gorney, R.M.; June, S.G.; Stainbrook, K.M.; Smith, A.J. Detections of cyanobacteria harmful algal blooms (cyanoHABs) in New York State, United States (2012–2020). *Lake Res. Manag.* **2023**, *39*, 21–36. [CrossRef]
27. Shonbrun-Siege, C. HABs, Science and Public Opinion: Where's the Disconnect? Available online: https://www.cayugalake.org/wp-content/uploads/clwn_nn_3_18_full_color_web_version_1.pdf (accessed on 31 March 2022).
28. Mathews, D.; Matt, M.; Mueller, N.; June, S. Citizen science advances the understanding of cyanoHABs in New York State Lakes. *Lakeline* **2021**, *41*, 32–36.
29. Prestigiamcomo, A.R.; Gorney, R.M.; Hyde, J.B.; Davis, C.; Clinkhammer, A. Patterns and impacts of cyanobacteria in a deep, thermally stratified, oligotrophic lake. *AWWA Water Sci.* **2022**, *5*, e1326. [CrossRef]
30. Armstrong, A.; Stedman, R.; Sweet, S.; Hairston, N. What Causes Harmful Algal Blooms? A Case Study of Causal Attributions and Conflict in a Lakeshore Community. *Environ. Manag.* **2022**, *69*, 588–599. [CrossRef]
31. Callinan, C. Water Quality of the Finger Lakes. New York State Department of Environmental Conservation Report. 2001. Available online: http://www.dec.ny.gov/lands/25576.html (accessed on 5 January 2023).
32. DEC HABs Website. Available online: https://www.dec.ny.gov/chemical/77118.html (accessed on 5 March 2022).
33. Wetzel and Likens. *Limnological Analyses*, 3rd ed.; Springer: New York, NY, USA, 2000.
34. Cayelan, C.; Ibelings, B.; Hoffmann, E.; Hamilton, D.; Brookes, J.D. Eco-physiological adaptations that favor freshwater cyanobacteria in a changing climate. *Water Res.* **1993**, *46*, 1394–1407. [CrossRef]
35. Tang, D.; Kawamura, H.; Oh, I.; Baker, J. Satellite evidence of harmful algal blooms and related oceanographic features in the Bohai Sea during autumn 1998. *Adv. Space Res.* **2006**, *37*, 681–689. [CrossRef]
36. Mantzouki, E.; Visser, P.M.; Bormans, M.; Ibelings, B.W. Understanding the key ecological traits of cyanobacteria as a basis for their management and control in changing lakes. *Aquat. Ecol.* **2016**, *50*, 333–350. [CrossRef]
37. Zhang, Y.; Loisesle, S.; Shi, K.; Han, T.; Zhang, M.; Hu, M.; Jing, Y.; Lai, L.; Zhan, P. Wind effects for floating algal dynamics in eutrophic lakes. *Remote Sens.* **2021**, *13*, 800. [CrossRef]
38. Halfman, J.D. Decade-scale water quality variability in the eastern Finger Lakes, New York. *Clear Waters* **2017**, *47*, 20–32.
39. Halfman, J.D.; Dumitriu, I.; Cleckner, L.B. *The 2021 Water Quality Monitoring Report*; Finger Lakes Institute, Hobart and William Smith Colleges: Owasco Lake, NY, USA, 2022. Available online: http://people.hws.edu/halfman/Data/Halfman%202021%20Owasco%20Water%20Quality%20Report.pdf (accessed on 5 January 2023).
40. Jones, T.; Halfman, J.D. Spatial and Temporal Change in Large Rainfall Events in the Central Finger Lakes. In Proceedings of the New York State Federation of Lake Associations Annual Conference Poster Presentation, Lake George, New York, USA, 28–30 April 2022. Available online: https://nysfola.org/past-conferences/ (accessed on 28 April 2021).
41. Easterling, D.; Kunkel, K.E.; Arnold, J.R.; Knutson, T.; LeGrande, A.N.; Leung, L.R.; Vose, R.S.; Waliser, D.E.; Wehner, M.F. Precipitation change in the United States. In *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program*; Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., Dokken, D.J., Stewart, B.C., Maycock., T.K., Eds.; U.S. Global Change Research Program: Washington, DC, USA, 2017; pp. 301–335.
42. Li, Z.; Xu, Z.; Yang, Y.; Stewart, R.I.A.; Urrutia-Cordero, P.; He, L.; Zhung, H.; Hansson, L.A. Heat waves alter macrophytes derived nutrients released under future climate warming scenarios. *Environ. Sci. Technol.* **2021**, *21*, 1049–1058. [CrossRef]
43. Zhang, F.; Li, R.; Tang, L.; Wang, J.; Shen, C.; He, X.; Feng, J.; Li, R.; Li, N. Effects of submerged macrophytes decomposition on water quality. *Nat. Environ. Pol. Technol.* **2022**, *21*, 1049–1058. [CrossRef]

44. DEC HABS Action Plan Owasco Lake. 2020. New York State Department of Environmental Conservation. Available online: https://www.dec.ny.gov/docs/water_pdf/owascohabplan.pdf (accessed on 5 January 2023).
45. Philips, E.; Badylak, S.; Nelson, N.; Havens, K. Hurricanes, El Niño and harmful algal blooms in two sub-tropical Florida estuaries: Direct and indirect impacts. *Sci. Rep.* **2020**, *10*, 1910. [CrossRef]
46. Shen, C.; Liao, Q.; Bootsma, H.A. Modelling the influence of invasive mussels on phosphorus cycling in Lake Michigan. *Ecol. Model.* **2020**, *416*, 108920. [CrossRef]
47. Brannon, M.A.; Scholz, C.A.; Driscoll, C.T. Shallow sediment as a phosphorus reservoir in an oligotrophic lake. *JGR Biosci.* **2023**, *128*, e2022JG007029. [CrossRef]
48. Paerl, H.W.; Gardner, W.S.; Havens, K.E.; Joyner, A.R.; McCarthy, M.J.; Newell, S.E.; Qin, B.; Scott, J.T. Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate warming and anthropogenic nutrients. *Harmful Algae* **2016**, *54*, 213–222. [CrossRef] [PubMed]
49. Xu, H.; McCarthy, M.J.; Paerl, H.W.; Brooks, J.D.; Zhu, G.; Hall, W.S.; Qin, B.; Zhang, Y.; Zhu, M.; Hamplel, J.; et al. Contributions of external nutrient loading and internal cycling of cyanobacterial bloom dynamics in Lake Taihu, China. Implications for nutrient management. *Limnol. Oceanogr.* **2021**, *66*, 1492–1509. [CrossRef]
50. Sorichett, B.J.; Creed, I.F.; Trick, C.G. Evidence for iron-regulated cyanobacteria predominance in oligotrophic lakes. *Freshwater Biol.* **2014**, *59*, 679–691. [CrossRef]
51. Molot, L.A.; Watson, S.B.; Creed, I.F.; Trick, C.G.; McCabe, S.K.; Verschoor, M.J.; Sorichettei, R.J.; Powe, C.; Venkiteswaran, J.J.; Schiff, S.L. A novel model for cyanobacteria bloom formation: The critical role of anoxia and ferrous iron. *Freshwater Biol.* **2014**, *59*, 1323–1340. [CrossRef]

Supplementary Materials

Table S1. Data Recovery and Completeness in Owasco & Seneca Lakes (% Deployment)

Owasco	Weather Station	Water Temperature	Camera	Sondes	Buoy - Met	Buoy - WQ
2019 - Martin N (E1)	2.0	0.0	0.0	n.a.	0.0	0.9
2019 - Burtis Pt (D)	0.1	0.0	0.0	n.a.		
2020 - Martin N (E1)	0.1	0.0	0.0	0.0	0.0	0.9
2020 - Burtis Pt (D)	0.1	0.0	0.0	0.0		
2020 - Martin N (E1)	45.5	0.0	0.0	0.1		
2020 - FL-20 (A)	23.5	23.4	25.0	64.4		
2021 - Martin N (E1)	0.5	0.0	0.0	0.0	0.0	1.9
2021 - Burtis Pt (D)	0.1	0.0	19.0	0.0		
2021 - Martin S (E2)	21.6	0.0	0.0	0.0		
2021 - FL-20 (A)	24.7	24.5	26.0	0.0		
2022 - Martin N (E1)	2.0	0.0	0.0	0.0	1.0	0.9
2022 - Burtis Pt (D)	0.0	0.0	21.3	0.0		
2022 - Martin S (E2)	86.2	3.3	0.0	3.8		
2022 - FL-20 (A)	37.9	0.0	0.0	0.0		
Owasco Combined	17.5	3.7	6.5	5.7	0.3	1.2
Seneca						
2019 - I	0.1	0.0	0.0	n.a.	0.0	4.3
2019 - H*	0.0	0.0	0.0	n.a.		
2019 - G	0.2	0.0	1.0	n.a.		
2019 - F*	0.2	0.0	0.0	n.a.		
2019 - B	0.4	0.0	17.0	n.a.		
2019 - C	2.3	0.0	74.0	n.a.		
2019 - D	1.4	0.0	0.0	n.a.		
2019 - E	2.0	0.0	0.0	n.a.		
2020 - I	0.2	0.0	32.6	n.a.	0.0	0.5
2020 - H	0.1	0.0	74.4	n.a.		
2020 - G	0.4	0.0	0.0	n.a.		
2020 - A	14.0	12.7	8.1	n.a.		
2020 - B	0.2	0.0	1.2	n.a.		
2020 - C	0.5	0.0	30.2	n.a.		
2020 - D	1.6	0.0	0.0	n.a.		
2020 - E	0.2	0.0	47.7	n.a.		
2021 - I	1.7	0.0	0.0	n.a.		
2021 - H	0.0	0.0	0.0	n.a.		
2021 - G	0.7	0.0	29.3	n.a.		

2021 - A	0.1	0.0	0.0	n.a.	0.0	2.8
2021 - B	0.2	0.0	0.0	n.a.		
2021 - C	0.0	0.0	13.8	n.a.		
2021 - D	0.1	0.0	17.4	n.a.		
2021 - E	0.0	0.0	32.1	n.a.		
Seneca Combined	1.1	0.5	15.8	n.a.	0.0	2.5

*Site Moved

Table S2. Deployment Dates and Blooms Detected by Cameras & Volunteers

Year	Lake	Site	Deployment Dates	Dock Cameras	Volunteers w/in 1 Mile
2019	Seneca	FLI Buoy	Spr - Fall		
		I	6/23 - 10/7	3	1
		H*	6/21 - 10/8	2	0
		G	6/21 - 10/7	0	1
		F*	6/21 - 10/8	1	0
		B	6/22 - 10/8	1	2
		C	6/21 - 10/4	2	2
		D	6/24 - 10/6	2	1
		E	6/24 - 10/11	1	3
		Blooms All Sites		12	10
2020	Seneca	USGS Buoy	Spr - Fall		
		I	7/8 - 10/10	5	2
		H	7/8 - 10/10	0	0
		G	7/9 - 10/10	0	0
		A	7/8 - 10/9	0	0
		B	7/8 - 10/10	1	0
		C	7/8 - 10/10	1	0
		D	7/22 - 10/10	0	0
		E	7/9 - 10/9	0	1
		Blooms All Sites		7	3
2021	Seneca	FLI Buoy	Spr - Fall		
		I	7/26 - 10/27	9	1
		H	7/24 - 10/27	4	0
		G	7/12 - 10/27	3	2
		A	7/12 - 10/27	7	5
		B	7/12 - 10/27	5	9
		C	7/12 - 10/27	1	8
		D	7/12 - 10/27	4	4
		E	7/12 - 10/27	8	7
		Blooms All Sites		41	36
2019	Owasco	FLI Buoy	Spr - Fall		
		Martin N (E1)	6/26 - 10/3	10	3
		Burtis (D)	6/26 - 10/9	14	1
		Blooms All Sites		24	4
2020	Owasco	FLI Buoy	Spr - Fall		

		Martin N (E1)	7/7 - 10/14	9	1
		Martin S (E2)	7/9 - 8/31	17	2
		Burtis (D)	7/7 - 10/14	12	0
		FL-20 (A)	7/7 - 9/18	0	0
		Blooms All Sites		38	3
2021	Owasco	FLI Buoy	Spr - Fall		
		Martin N (E1)	7/7 - 10/12	10	2
		Martin S (E2)	7/28 - 10/13	7	2
		Burtis (D)	7/7 - 10/13	10	1
		FL-20 (A)	7/7 - 9/17	3	0
		Blooms All Sites		30	5
2022	Owasco	FLI Buoy	Spr - Fall		
		Martin N (E1)	7/20 - 10/5	3	2
		Martin S (E2)	9/24 - 10/5	1	1
		Burtis (D)	7/20 - 10/5	3	0
		FL-20 (A)	7/20 - 10/5	2	0
		Blooms All Sites		9	3

*Site Moved

Table S3. Data Means, Standard Deviations, and Maximum Values

Year	Lake	Site	Water Temperature, °C	Wind Speed, kph	Air Temperature, °C	Light Intensity, W/m²
			mean ± sd, max	mean ± sd, max	mean ± sd, max	mean ± sd, max
2019	Seneca	FLI Buoy	20.2 ± 5.3, 26.2	14.3 ± 8.1, 42.9	21.6 ± 4.9, 43.7	225.6 ± 311.1, 1260.6
		I	21.4 ± 3.1, 33.2	4.2 ± 5.8, 33.5	19.3 ± 4.8, 32.6	82.3 ± 121.4, 703.9
		H*	21.4 ± 2.8, 27.5	9.2 ± 9.6, 41.0	19.4 ± 4.7, 32.8	128.5 ± 190.6, 748.4
		G	21.3 ± 2.3, 26.7	3.4 ± 5.4, 47.5	19.3 ± 4.8, 33.4	309.8 ± 501.4, 2761
		F*	21.8 ± 3.0, 27.2	3.2 ± 5.2, 42.2	19.0 ± 5.1, 33.4	120.7 ± 187.3, 880.5
		B	21.7 ± 2.7, 28.7	5.3 ± 8.2, 68.7	19.5 ± 5.0, 33.5	116.9 ± 173.0, 1027.6
		C	21.6 ± 2.6, 28.1	1.2 ± 1.9, 17.2	19.4 ± 5.0, 33.1	114.0 ± 189.5, 944.7
		D	21.4 ± 2.5, 28.3	2.2 ± 3.8, 32.0	19.1 ± 4.7, 32.2	90.5 ± 140.0, 786.8
		E	20.8 ± 2.3, 27	3.5 ± 5.6, 34.6	19.3 ± 4.8, 33.1	396.3 ± 619.1, 3328
		Blooms All Sites	21.2 ± 2.6, 26.7	0.8 ± 1.4, 21.6	21.0 ± 2.9, 28.4	252.7 ± 185.4, 751.1
2020	Seneca	USGS Buoy	23.0 ± 3.3, 26.7	15.4 ± 8.8, 55.8	20.6 ± 5.0, 33.3	228.1 ± 312.9, 1254.5
		I	22.4 ± 4.0, 26.5	4.7 ± 6.3, 39.9	20.3 ± 5.5, 33.8	97.7 ± 142.1, 805
		H	22.2 ± 3.7, 28.8	9.0 ± 9.4, 56.2	20.4 ± 5.4, 33.7	168.1 ± 234.1, 938.3
		G	22.1 ± 3.4, 29.0	4.2 ± 5.8, 39.6	20.3 ± 5.5, 32.7	156.1 ± 221.1, 933.1
		A	22.7 ± 4.5, 30.6	3.3 ± 4.9, 35.6	19.3 ± 5.8, 33.9	153.2 ± 221.1, 941.0
		B	22.9 ± 3.6, 29.8	5.4 ± 9.3, 76.3	20.3 ± 5.7, 34.4	150.4 ± 205.1, 857.6
		C	22.8 ± 3.7, 28.9	0.5 ± 1.6, 19.5	20.2 ± 5.9, 34.6	143.3 ± 197.7. 961.7
		D	22.4 ± 3.6, 29.2	3.0 ± 4.4, 28.0	20.1 ± 5.5, 34.1	125.6 ± 186.9, 797.5
		E	21.6 ± 3.5, 28.7	3.9 ± 5.6, 36.0	20.2 ± 5.7, 35.6	157.4 ± 212.8, 1000.0
		Blooms All Sites	24.9 ± 1.7, 27.4	6.4 ± 5.4, 21.6	22.4 ± 2.8, 36.5	211.1 ± 146.4, 672.5
2021	Seneca	FLI Buoy	21.4 ± 3.1, 26.7	14.3 ± 8.1, 42.9	21.6 ± 4.9, 43.7	225.6 ± 311.1, 1260.6
		I	21.9 ± 3.1, 28.8	4.2 ± 5.8, 33.5	19.3 ± 4.8, 32.6	82.3 ± 121.4, 703.9
		H	21.6 ± 2.9, 33.3	9.2 ± 9.6, 41.0	19.4 ± 4.7, 32.8	128.5 ± 190.6, 748.4
		G	21.2 ± 2.8, 26.9	3.4 ± 5.4, 47.5	19.3 ± 4.8, 33.4	309.8 ± 501.4, 2761
		A	20.8 ± 2.8, 27.5	3.2 ± 5.2, 42.2	19.0 ± 5.1, 33.4	120.7 ± 187.3, 880.5

		B	22.3 ± 2.8, 27.4	5.3 ± 8.2, 68.7	19.5 ± 5.0, 33.5	116.9 ± 173.0, 1027.6
		C	22.1 ± 2.9, 27.0	1.2 ± 1.9, 17.2	19.4 ± 5.0, 33.1	114.0 ± 189.5, 944.7
		D	21.6 ± 2.9, 27.6	2.2 ± 3.8, 32.0	19.1 ± 4.7, 32.2	90.5 ± 140.0, 786.8
		E	20.8 ± 2.9, 27.6	3.5 ± 5.6, 34.6	19.3 ± 4.8, 33.1	396.3 ± 619.1, 3328
		Blooms All Sites	21.3 ± 2.4, 26.4	3.8 ± 4.8, 5.3	20.7 ± 4.4, 28.4	345.4 ± 238.1, 658.0
2019	Owasco	FLI Buoy	21.7 ± 3.1, 25.9	14.0 ± 8.2, 54.4	20.1 ± 4.3, 31.6	195.8 ± 267.9, 1129.0
		Martin N (E1)	22.1 ± 3.0, 28.7	3.4 ± 4.8, 48.6	20.1 ± 4.5, 35.0	153.4 ± 231.6, 898
		Burtis (D)	22.0 ± 3.0, 29.0	6.0 ± 6.5, 39.6	19.3 ± 5.0, 34.8	190.6 ± 277.1, 1025
		Blooms All Sites	23.7 ± 2.8, 27.6	4.3 ± 4.8, 24.5	22.0 ± 4.2, 28.8	480.6 ± 261.7, 909.8
2020	Owasco	FLI Buoy	20.8 ± 4.3, 26.6	15.0 ± 8.4, 48.7	20.2 ± 5.2, 33.1	194.7 ± 262.3, 1014.0
		Martin N (E1)	22.6 ± 3.8, 28.7	4.9 ± 6.2, 38.5	19.7 ± 5.8, 35.0	144.0 ± 215.6, 898
		Martin S (E2)	22.7 ± 3.7, 28.6	4.8 ± 5.2, 29.4	22.5 ± 3.6, 31.7	175.5 ± 261.0, 914.8
		Burtis (D)	22.3 ± 4.0, 39.0	6.9 ± 7.5, 50.0	19.4 ± 5.9, 34.8	164.8 ± 240.6, 1025
		FL-20 (A)	24.3 ± 2.0, 28.2	3.0 ± 4.0, 39.4	21.1 ± 4.3, 33.1	201.0 ± 299.7, 1179.4
		Blooms All Sites	20.5 ± 2.0, 28.2	2.4 ± 3.9, 23.3	19.9 ± 4.4, 31.4	346.2 ± 210.4, 736.2
2021	Owasco	FLI Buoy	22.1 ± 2.0, 25.6	14.2 ± 7.8, 43.6	20.5 ± 3.7, 30.5	168.7 ± 239.0, 1031.0
		Martin N (E1)	22.4 ± 2.2, 28.2	3.9 ± 5.2, 32.0	20.0 ± 4.3, 35.0	116.3 ± 177.4, 884
		Martin S (E2)	22.4 ± 2.2, 28.9	4.9 ± 5.0, 29.1	19.7 ± 4.2, 31.9	127.5 ± 207.5, 911.7
		Burtis (D)	22.3 ± 2.5, 28.1	5.9 ± 6.7, 37.5	19.8 ± 4.3, 33.9	127.8 ± 180.4, 897.1
		FL-20 (A)	23.0 ± 1.2, 27.5	2.7 ± 3.7, 39.4	20.4 ± 3.8, 30.8	158.3 ± 238.7, 1041.9
		Blooms All Sites	22.4 ± 2.6, 26.3	2.2 ± 3.4, 18.3	21.5 ± 4.0, 27.8	213.3 ± 161.8, 631.3
2022	Owasco	FLI Buoy	22.5 ± 2.7, 25.6	13.4 ± 6.8, 37.0	20.0 ± 5.0, 32.6	176.6 ± 246.7, 1044.0
		Martin N (E1)	23.2 ± 2.8, 29.0	4.1 ± 5.2, 29.9	19.5 ± 5.5, 32.1	124.5 ± 189.7, 814.6
		Martin S (E2)	23.4 ± 2.5, 29.3	3.7 ± 5.7, 22.4	11.8 ± 3.8, 19.2	67.9 ± 135.6, 783.4
		Burtis (D)	22.7 ± 3.1, 28.1	6.3 ± 6.9, 43.1	19.4 ± 5.6, 32.9	119.4 ± 167.3, 804.9
		FL-20 (A)	22.9 ± 2.3, 27.4	3.1 ± 4.1, 22.4	19.5 ± 5.7, 32.9	142.9 ± 226.3, 950.9
		Blooms All Sites	20.1 ± 2.7, 25.7	3.6 ± 4.9, 19.5	16.0 ± 4.4, 25.8	327.4 ± 172.1, 635.5

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