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Effectiveness of a fixed-depth sensor deployed from a buoy to estimate water-column cyanobacterial biomass depends on wind speed

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ABSTRACT

Water quality sondes have the advantage of containing multiple sensors, extended deployment times, high temporal resolution, and telecommunication with stakeholder accessible data portals. However, sondes that are part of buoy deployments often suffer from typically being fixed at one depth. Because water treatment plants are interested in water quality at a depth of the water intake and other stakeholders (ex. boaters and swimmers) are interested in the surface, we examined whether a fixed depth of approximately 1 m could cause over- or under-estimation of cyanobacterial biomass. We sampled the vertical distribution of cyanobacteria adjacent to a water quality sonde buoy in the western basin of Lake Erie during the summers of 2015–2017. A comparison of buoy cyanobacteria RFU (Relative Fluorescence Unit) at 1 m to cyanobacteria chlorophyll *a* (chl*a*) measured throughout the water column showed occurrences when the buoy both under and overestimated the cyanobacteria chl*a* at specific depths. Largest differences between buoy measurements and at-depth grab samples occurred during low wind speeds (< 4.5 m/sec) because low winds allowed cyanobacteria to accumulate at the surface above the buoy's sonde. Higher wind speeds (> 4.5 m/sec) resulted in better agreement between the buoy and at-depth measurements. Averaging wind speeds 12 hr before sample collection decreased the difference between the buoy and at-depth samples for high wind speeds but not low speeds. We suggest that sondes should be placed at a depth of interest for the appropriate stakeholder group or deploy sondes with the ability to sample at various depths.

Introduction

Harmful cyanobacterial blooms are increasing in range, severity, and duration due to anthropogenic nutrient loading and a warming climate (Paerl and Huisman, 2008). The cyanobacterial blooms pose threats to human health due to their ability to produce harmful toxins that can pollute drinking water and shut down recreation associated with lakes and rivers (He et al., 2016; Jetoo et al., 2015; Steffen et al., 2017). Additionally, cyanobacterial blooms from freshwater can be transported to marine systems via rivers and human-made canals and negatively affect marine life (Paerl et al., 2018). Rapid methods for the detection and quantification of cyanobacterial blooms are

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needed to protect drinking water and recreation and to alert potential downstream stakeholders.

Traditional methods to monitor cyanobacterial blooms (and water quality in general) involve grab samples collected from vessels or shore. Grab samples provide a wealth of information on water quality (phytoplankton taxa, nutrient concentrations, toxins) but are limited in spatial area and temporal resolution, and the data from grab samples are delayed due to laboratory analysis. High-resolution auto-samplers have shown that cyanotoxin concentrations can change several fold within a few hours (Miller et al., 2019). Advances in algae and cyanobacteria sensors, which can be deployed *in situ*, can help overcome some of the limitations associated with grab samples (Luo et al., 2017). While there have been several recent studies that investigated the effectiveness of sensors for tracking cyanobacterial bloom biomass (Chaffin et al., 2018; Cotterill et al., 2019), none of the studies have investigated if data obtained from sensors deployed *in situ* can be extrapolated to waters either above or below the sensor.

In situ water quality sensors can be attached to floating offshore buoys or mounted to fixed underwater structures. These sensors are generally affixed at one depth (usually ~ 1 m below the surface of the water); however, stakeholders may be interested in collecting data from other depths. For example, drinking water treatment plant intake pipes are located mid-depth to near the bottom of the lake, whereas recreational beach managers or boaters might be more interested in water quality at the surface. Thus, there is a potential disconnect between stakeholder data requirements and measurements by fixed-depth *in situ* sensors. Moreover, the deferring buoyancy regulation strategies of the various cyanobacteria can further exacerbate disconnect. For example, in calm waters, positively-buoyant cyanobacteria, such as *Microcystis, Dolichospermum*, and *Aphanizomenon*, accumulate near the surface near higher light intensities, whereas, neutrally-to-negatively buoyant cyanobacteria, including *Planktothrix* and *Cylindrospermopsis*, can position themselves in the center of the water column or sink to the bottom in low light intensities (Konopka et al., 1987; Moore et al., 2019; Reynolds et al., 1987). Thus, a data buoy sensor may overestimate cyanobacterial abundance during a surface bloom and underestimate abundance during a *Planktothrix* or a *Cylindrospermopsis* bloom, which could result in over-treatment (inefficient use of treatment chemicals and money) or under-treatment (toxins not completely removed) of drinking water. Additionally, the time scale (minutes to hours) that cyanobacteria respond to wind stress and water column mixing can have further implications for stakeholders (Moreno-Ostos et al., 2009; Wu et al., 2013). Ideally, lake managers and water treatment plant operators deploy multiple sensors at several depths or maintain a vertical-profiling sensor platform (for example, see Wilkinson et al. (2020)) to record cyanobacterial biomasses throughout the water column, but financial resources and logistical constraints may only allow for one sensor at a fixed depth. Therefore, it is critical to understand how cyanobacterial abundance throughout the water column relates to sensor readings from a single-fixed depth.

Wind speed can impact cyanobacteria and toxin distribution (Huisman et al., 2004; Miller et al., 2019; Moreno-Ostos et al., 2009; Wu et al., 2013) and thus affect the decision-making process of water treatment plant operators. High wind speeds create turbulent mixing of the water column and overpower buoyancy regulation of cyanobacteria resulting in an even spread from surface to the lake bottom. Potential issues for water treatment can arise when a calm day is followed by a windy day. For example, a buoy measures high cyanobacterial biomass due to *Microcystis* near the surface one day on a calm day, but the following day, high winds mix the bloom throughout the water column. Under this scenario, a water treatment plant operator may under-treat the water on a windy day because the buoy indicated a decrease in cyanobacterial biomass, but the intake may draw in more cyanobacteria because the wind mixed the bloom down to the intake pipe. Thus, recent wind events can affect the position of cyanobacteria in the water column, and water treatment operators must be cognizant of such events.

This study was conducted at a buoy site in the western basin of Lake Erie, where the positively-buoyant *Microcystis* dominates the cyanobacterial community during the warm summer months. The objective of this study was to understand how cyanobacterial biomass throughout the water column correspond to data measured by a fixed-depth *in situ* sensor at varying wind speeds. We hypothesized that low wind would allow buoyant cyanobacteria to accumulate at the surface and the buoy data would overestimate cyanobacterial abundance present deeper in the water column and would underestimate cyanobacterial abundance at the surface, whereas high wind speed would mix cyanobacteria throughout the water column and buoy measurements would be representative of cyanobacteria abundance at all depths. Additionally, wind speeds over several durations of time were considered.

1. Material and methods

1.1. Buoy location and data collection

The lake used for this study was Lake Erie, which is the world's 11th largest lake by surface area (Herdendorf, 1982) located on the border of the United States of America and Canada in North America. *Microcystis* blooms have plagued the western basin of Lake Erie every summer since 2002, and the biomass of the bloom is correlated to springtime phosphorus loading from the Maumee River (Bridgeman et al., 2013; Stumpf et al., 2012). Lake Erie *Microcystis* blooms can produce high amounts of microcystins, a very potent class of hepatotoxins (Carmichael, 1992; Gobler et al., 2016). In August 2014, microcystins were detected in the tap water of the City of Toledo, Ohio, USA and nearly 500,000 residents were told not to drink the water (Jetoo et al., 2015; Steffen et al., 2017). The following summer, an array of sensors were deployed throughout Lake Erie to provide real-time cyanobacterial biomass data to serve as an early warning system for cyanobacterial blooms (Chaffin et al., 2018). All of the sensors attached to buoys are fixed at 1 m from the surface.

The buoy used for this study is located about 200 m northwest of Gibraltar Island (Fig. 1), and the depth of the site is 6 m. The buoy was equipped with a YSI 6600v2 (Yellow Springs Instruments, USA) multiprobe sonde during 2015 and a YSI EXO2 sonde during 2016 and 2017. The sonde was suspended in a protective cage beneath the buoy approximately 1 m from the surface. In a parallel study (Chaffin et al., 2018), we presented how we addressed the two different sonde models and how the sondes were calibrated. The buoy sonde recorded cyanobacteria abundance every 15 min as relative fluorescence units (RFU) of phycocyanin.

Water grab samples were collected next to the buoy at 1-m depth intervals from surface to a depth of 5 m using a Van Dorn sampler on 36 dates during the cyanobacterial bloom season (July-September) during the years 2015, 2016, and 2017. Small boats (<4 m in length) were used to visit the buoy and collect water within a half meter of the sonde's vertical position. Water from the Van Dorn sampler was poured into 250-

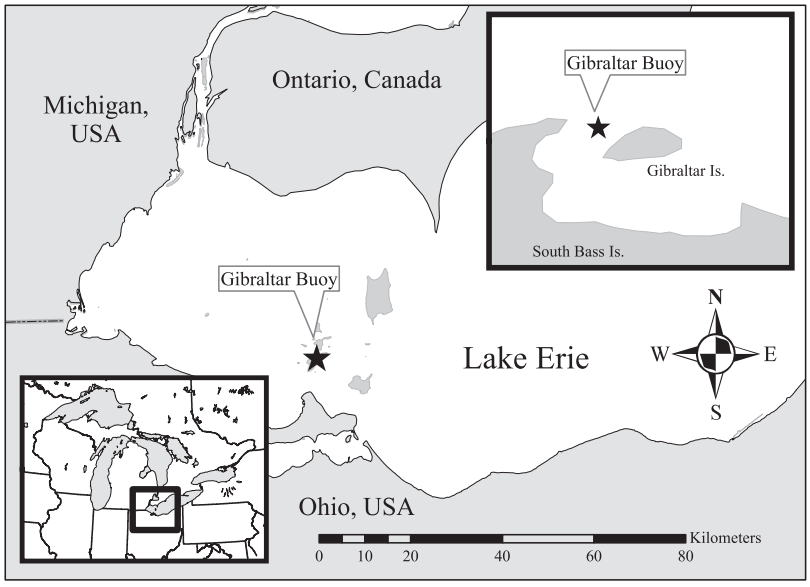

Fig. 1 – Location of the data buoy (black star) in Lake Erie. The upper right shows a zoomed in view of the buoy's location between Gibraltar and South Bass Islands.

mL polycarbonate bottles, and samples were transported to the laboratory in a dark-insulated box. Water was analyzed for algal group-specific chl*a* concentration within 30 min of collection using a FluoroProbe (bbe Moldebanke, Germany) with a bench-top cuvette reader (see Chaffin et al., 2018 for detailed methods). Analyzing dark-adapting water samples before analysis by the FluoroProbe increases the accuracy of the measurements due to the relaxing of non-photochemical quenching (Harrison et al., 2018). Phytoplankton biovolume from the samples collected on July 30, 2015 was quantified with a Flow Cam (Fluid Imaging Technologies, USA; Chaffin et al., 2018).

1.2. *Every-meter phytoplankton and wind data analysis*

Buoy RFU data recorded 60 min prior to sample collection was averaged because the 60-minute average had a stronger correlation between RFU and water sample chl*a*concentrations than did the one measure just prior to sample collection (Chaffin et al., 2018). Because cyanobacterial biomass throughout the water column was determined as cyanobacteria-chl*a* with a FluoroProbe and the data buoy measured cyanobacterial biomass as RFU, buoy RFU data was converted to cyanobacteria-chl*a* with the relationship presented in Chaffin et al. (2018; 27.8 µg chl*a*/L = 1 RFU in 2015 (R^2 = 0.850) and 14.1 µg chl*a*/L = 1 RFU in 2016 and 2017 (R^2 = 0.752)). Next, the percent relative difference (%RD) between the buoy-converted data and every-meter at-depth grab samples data was calculated as:

$$\%RD = \frac{Chla_{@z} - Chla_{buoy}}{Chla_{buoy}} \times 100\%$$

Where $Chla_{@z}$ (µg/L) is the cyanobacteria chl*a* concentration measured at-depth z (0, 1, 2, 3, 4, or 5 m) and $Chla_{buoy}$ is the cyanobacteria chl*a* concentration that was converted from the buoy cyanobacteria RFU data.

Wind speed data were obtained from NOAA's National Buoy Data Center station on South Bass Island (http://www.ndbc.noaa.gov/station_page.php?station=sbio1). The average wind speed 1 hr, 4 hr, 8 hr, 12 hr, and 24 hr before sample collection were calculated. The %RD between buoy and cyanobacteria chl*a* at each depth was plotted against wind speed for each time frame investigated.

2. Results

Buoy measured cyanobacteria RFU and the converted RFU-to-cyanobacteria chl*a* concentrations are displayed in Fig. 2. The highest biomasses of cyanobacteria were recorded during late July 2015 with cyanobacteria-chl*a* peaking at 71.5 µg/L. Much lower cyanobacteria-chl*a* concentrations were observed in 2016 and 2017, with the highest concentrations of 2.5 and 5.0 µg/L, respectively.

Every meter sampling indicated that cyanobacteria were not evenly distributed throughout the water column on some dates but were evenly distributed on other dates (Fig. 3). For example, on July 28, 2015, cyanobacteria chl*a* concentration peaked at 71.5 µg/L at 0 m and declined throughout the water column to 10.5 µg/L at 5 m. An example of cyanobacteria evenly distributed throughout the water column occurred on August 7, 2015, when chl*a* concentration ranged from 11.2 to13.8 µg/L.

Cyanobacterial biovolume measured from each sample on July 30, 2015 (Fig. 4) corresponded to the cyanobacteria-chl*a* concentrations measured on the date (Fig. 3). Total cyanobacterial biovolume measured at depths of 0, 1, and 2 m was about three times greater than biovolume measured at a deeper depth. *Microcystis* biovolume made up more than 85% of the total cyanobacterial biovolume at all depths.

A comparison of buoy RFU converted-cyanobacteria chl*a* to cyanobacteria chl*a* measured throughout the water column with the at-depth grab samples showed that there were occurrences when the buoy both under and overestimated the cyanobacteria chl*a* at specific depths (Fig. 5). Data points that lay above the 1-to-1 line (dotted line) indicate the buoy underestimated cyanobacteria chl*a* concentration at the particular depth, whereas those beneath the 1-to-1 line indicate the buoy overestimated cyanobacteria chl*a* concentration. For example,

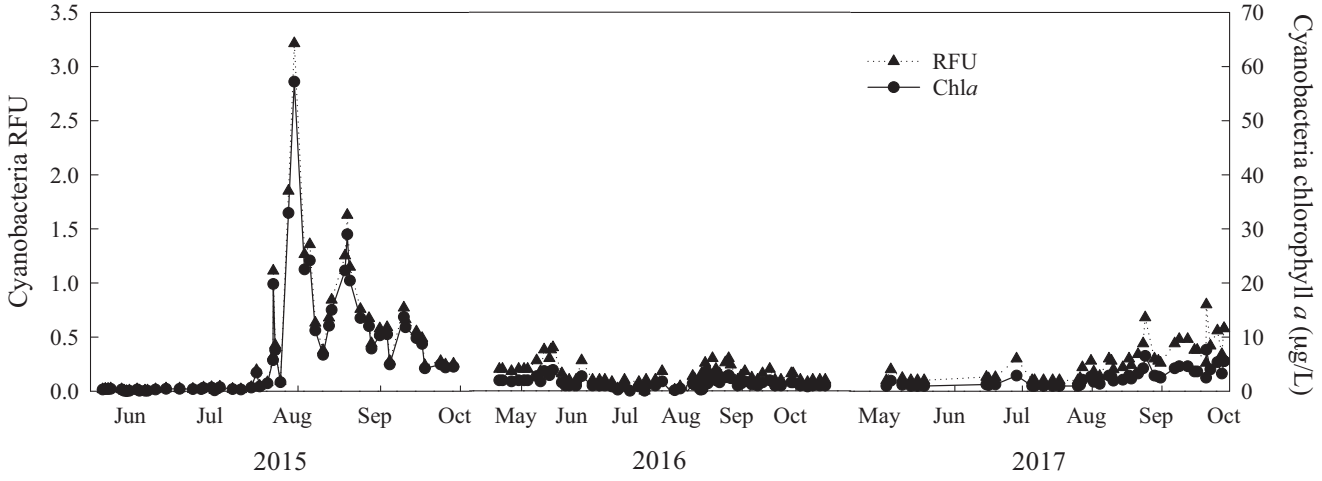

Fig. 2 – Cyanobacteria abundance at the Gibraltar buoy during summers 2015, 2016, and 2017 as phycocyanin relative fluorescence units (RFU) and RFU converted to cyanobacteria chlorophyll *a* concentration.

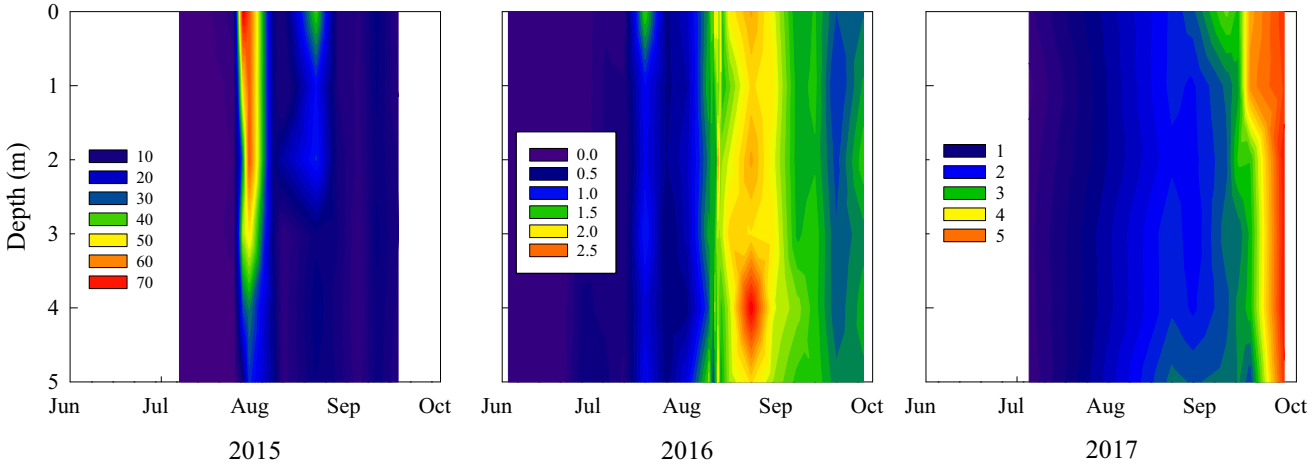

Fig. 3 – Isopleths of cyanobacteria chlorophyll *a* concentration (µg/L) measured at every meter from the surface to 5 m throughout summers 2015, 2016, and 2017. Note the difference in chlorophyll *a* concentration scale among the three years.

on July 28, 2015, the buoy estimated the cyanobacteria chl*a* concentration to be 32.9 µg/L, but the 0 m and 1 m cyanobacteria chl*a* concentrations exceeded the buoy estimate (71.5 and 51.2 µg/L, respectively), whereas the 5 m cyanobacteria chl*a* concentration was much less than the buoy (10.5 µg/L). Overall, the buoy tended to underestimate cyanobacteria chl*a* concentrations at 0 m while overestimating the deeper cyanobacteria chl*a* concentrations.

Wind speed data was used to determine if the percent relative difference (%RD) observed between cyanobacteria chl*a* concentrations measured by the buoy and measured in the at-depth grab samples could be explained (Fig. 6). The greatest range of wind speed occurred 1 hr before sampling (0.85 to 10.25 m/sec), and the wind speed range decreased when more extended time frames were considered. There was high %RD across the range of the 1-hr window before sample collection (Fig. 6a), which indicates that cyanobacteria position in the water column was not affected by wind over a short time. As more extended time frames were considered, the %RD decreased with increased wind speed.

Averages of %RD for each depth were calculated for wind speeds less than and greater than 4.5 m/sec (Table 1). For wind speed averaged 12 hr before sample collection, the %RD between the buoy and 0-meter sample was 52.9% for wind speeds less than 4.5 m/sec, but the %RD between the buoy and 0-m sample decreased to 18.1% for wind speeds greater than 4.5 m/sec. However, the %RD between the buoy and the 5-m sample was 38.9% for low wind speeds and 31.2% for high wind speeds. This indicated that surface chl*a* deviated more from the buoy than bottom chl*a* in low winds, but high winds resulted in the surface chl*a* to be more similar to buoy than bottom chl*a*. The smallest %RD (16.8%) between buoy and the at-depth grab sample occurred at the 1-meter depth during high wind speeds when the buoy data 12 hr before sample collection was average.

3. Discussion

Cyanobacteria can migrate throughout the water column and often concentrate near the surface of the water (Brookes et al., 2003; Ganf et al., 1989; Reynolds et al., 1987). The vertical migration of cyanobacteria can be problematic for *in situ* sensors deployed from buoys and fixed at one depth. Indeed, the chl*a*

Table 1 – The mean of the absolute value of percent relative differences between cyanobacteria chl*a* concentration measured by the data buoy and throughout the water column from grab samples as a function of wind speed less than 4.5 m/sec and greater than 4.51 m/sec and as the time before sample collection.

	1 hr		4 hr		8 hr		12 hr		24 hr	
	<4.5 m/sec	>4.5 m/sec	<4.5 m/sec	>4.5 m/sec	<4.5 m/sec	>4.5 m/sec	<4.5 m/sec	>4.5 m/sec	<4.5 m/sec	>4.5 m/sec
0 m	49.8%	29.4%	52.1%	22.9%	50.7%	20.0%	52.9%	18.1%	47.7%	30.0%
1 m	35.6%	27.0%	38.1%	21.3%	37.7%	18.6%	39.3%	16.8%	37.6%	20.7%
2 m	29.2%	32.9%	32.1%	27.4%	32.8%	24.5%	33.3%	24.2%	35.1%	20.1%
3 m	36.9%	32.2%	38.5%	28.7%	38.4%	26.7%	38.8%	27.0%	38.6%	27.5%
4 m	33.9%	35.4%	34.8%	33.7%	35.1%	32.5%	35.9%	31.0%	37.7%	27.0%
5 m	37.9%	34.2%	38.6%	32.4%	38.2%	32.2%	38.9%	31.2%	38.0%	33.2%
Overall	37.2%	31.8%	39.0%	27.7%	38.8%	25.8%	39.8%	24.7%	39.1%	26.4%

concentration measured by the sensor at a depth of 1 m often did not match the chl*a* concentration measured at the surface (above the sonde) or below the sonde at deeper depths (Fig. 5). Therefore, a data buoy's chl*a* data that is recorded from a fixed depth cannot be assumed to be equal to the concentration above or below the sonde.

Wind speed can affect the phytoplankton position in the water column. In light winds and calm water, buoyant cyanobacteria, like *Microcystis*, will concentrate near the surface (Soranno, 1997; Webster and Hutchinson, 1994), whereas, negatively buoyant phytoplankton, such as diatoms, will sink towards the lake bottom (Huisman et al., 2002; Webster and Hutchinson, 1994). In high winds and rough waters, the buoyancy of cyanobacteria and the sinking rate of diatoms is over-powered by the water turbulence, and the phytoplankton will be more evenly distributed throughout the water column (Brookes et al., 2003; Huisman et al., 2002). There were considerable differences of cyanobacteria chl*a* measured by the buoy and the at-depth grab samples during low wind speeds, and the relative difference between the buoy and the at-depth grab samples decreased as wind speed before sampling increased (Fig. 6, Table 1). This indicates that the cyanobacteria became more-mixed throughout the water column and that the buoy estimates of cyanobacteria biomass were more comparable to other depths as the wind speed increased.

The period over which wind speed was averaged affected how to interpret the relationship between buoy and at-depth

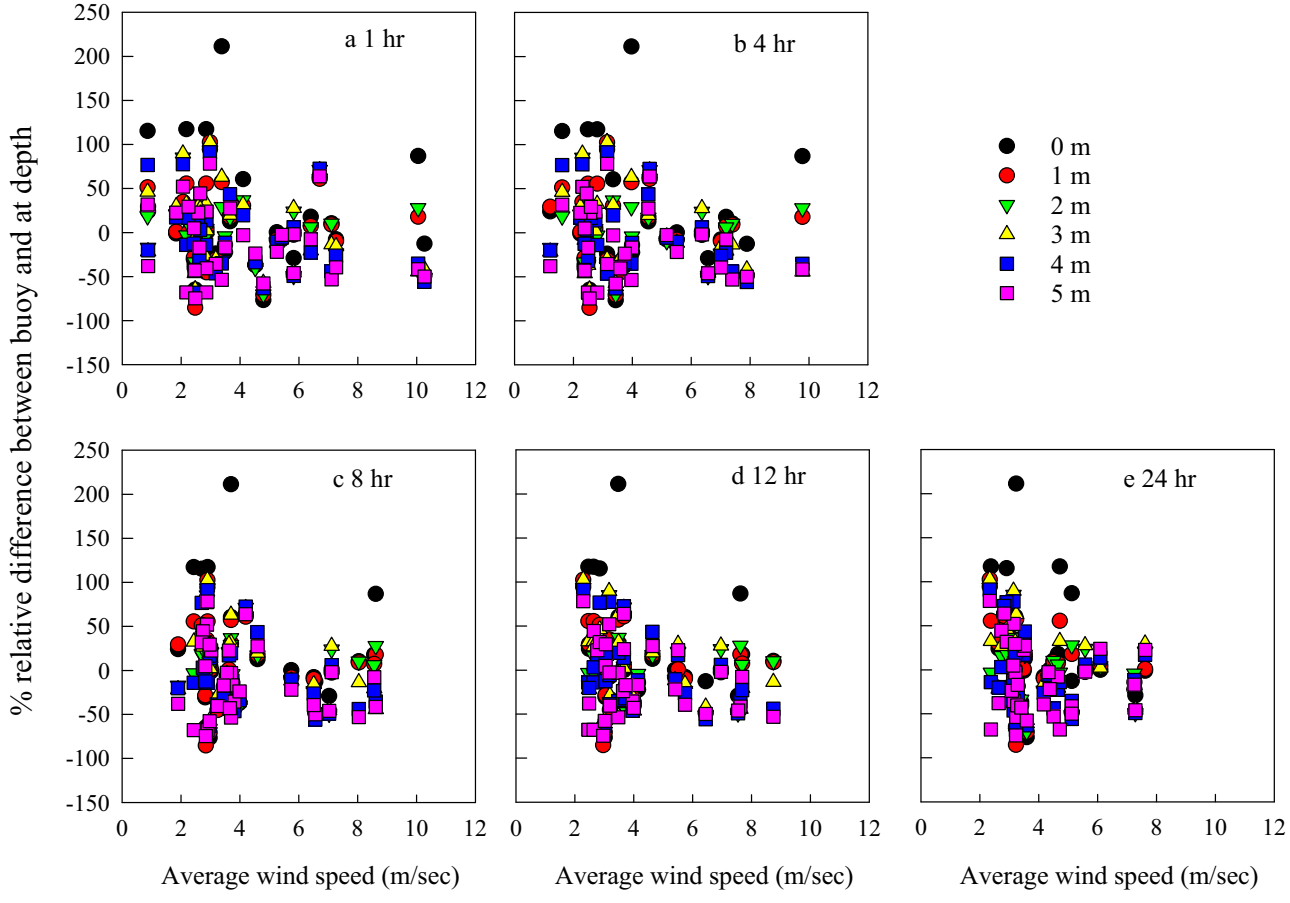

Fig. 6 – The percent relative difference (%RD) between cyanobacteria chlorophyll *a* concentration measured by the data buoy and throughout the water column as a function of wind speed.

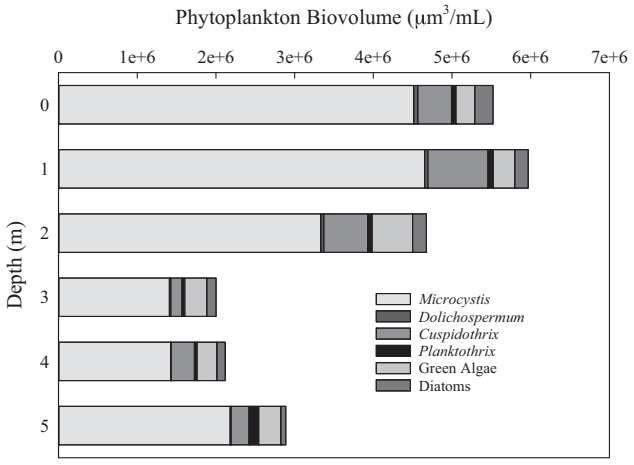

Fig. 4 – Phytoplankton biovolume measured throughout the water column on July 30, 2015, at the Gibraltar Island data buoy.

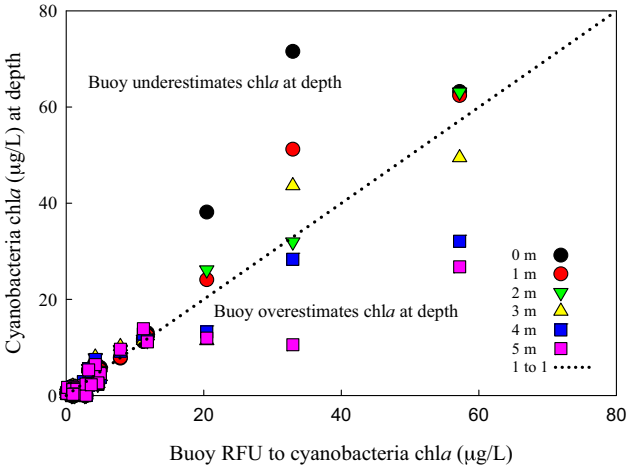

Fig. 5 – The relationship between buoy measured cyanobacteria chlorophyll *a* concentration and cyanobacteria chlorophyll *a* concentration throughout the water column. Data points that lay above the 1 to 1 line (dotted line) indicate the buoy underestimated chlorophyll *a* concentration, whereas those beneath the 1 to 1 line indicate the buoy overestimated chlorophyll *a* concentration.

measurements of cyanobacteria chl*a*. In the 1-hr before sampling period, large relative differences between the buoy and the at-depth grab samples occurred at high wind speeds (greater than 4.5 m/sec; Fig. 6a), which likely indicates that the high winds that started just recently before sampling and there was not enough time to mix the water column. The decreases in relative difference between buoy and chl*a* at depth became more apparent when 12 and 24 hr of wind speed data were considered (Fig. 6d and e), and indicates that cyanobacteria vertical position was more affected by long-term (12+ hr) than short-term (< 1 hr) at high wind speeds. On the contrary, at low wind speed (< 4.5 m/sec), the relative differences between the buoy and the at-depth grab samples remained similar across the time of averaging wind speeds (Table 1).

The relationship between buoy and surface (0 m) cyanobacteria chl*a* was different from the relationship between the buoy and deep chl*a* (5 m). Under calm winds, surface and buoy chl*a* differed by 52.9%, which indicated that buoyant cyanobacteria migrated above the buoy's water quality sonde (˜ 1.0 m in depth). Thus low cyanobacteria chl*a* buoy data would have misled data users during the presence of noticeable scum at the surface. Contrary to low winds, the smallest difference between the buoy data and chl*a* at the surface and 1 m (18.1% and 16.8%, respectively) was recorded under high winds, and thus surface buoy measurements are most accurate at high wind speeds because water turbulence inhibits surface scum formation. Our results agree with those of Bosse et al. (2019), who found that under high winds (>4.9 m/sec), vertical stratification of cyanobacteria in the western basin of Lake Erie decreased. Furthermore, the results agree with Fang et al. (2019) who showed that chl*a* measured in surface samples was 35% greater than samples integrated throughout the water column at low wind speeds less than 2.0 m/sec, but surface chl*a* was only 17% greater than samples taken throughout the water column at wind speeds greater than 8.0 m/sec. Additionally, Golnick et al. (2016) compared four commonly-used water sample collection methods in side-by-side fashion in Lake Erie and found good agreement in measured chl*a* concentration among the methods (< 9% difference for entire 82-sample data set); however, during calm conditions that allowed for surface scums, the surface-to-2 m sample method had chl*a* concentrations nearly double that of the other three methods that included deeper water containing lower cyanobacteria biomass. Likewise, in Lake Taihu, Wu et al. (2013) showed cyanobacteria were evenly distributed throughout the water column when wind speeds exceeded 6 m/sec and concentrated at the surface in calmer winds. However, in our study, the difference between the buoy data and chl*a* at the 5 m was less affected by wind speed (%*RD* 38.9% at low wind speeds and 31.2% at high wind speeds). Thus, there is going to be an error associated with using surface buoy data as a surrogate for cyanobacteria biomass at deeper depths. For example, a water treatment plant operator cannot assume surface buoy biomass data is proportional to biomass being drawn into the plant from deeper depths, and the difference cannot be corrected for by wind speed.

Cyanobacteria biomasses (Fig. 2; Chaffin et al., 2018) and their toxins (Miller et al., 2019) can change several fold over just a few hours. These large differences are driven by the horizontal patchiness of surface scums and water currents and wind transporting the cyanobacteria (Wu et al., 2013). Additionally, this study suggested at low wind speeds that there is a large disconnect between cyanobacteria biomass measured by a sensor fixed at one depth and biomass measured from water samples at other depths due to the uneven vertical distribution. This disconnect presents challenges to stakeholders because cyanobacteria biomasses and toxins can change faster at unmonitored depths than a sensor fixed at one depth would indicate.

In summary, we suggest that sondes should be placed at the depth of interest for the appropriate stakeholder group (*e.g.*, water treatment plants, beach managers) or that sondes with the ability to profile the water column (Brentrup et al., 2016; Wilkinson et al., 2020) be deployed. Additionally, researchers who wish to use data buoys with sensors fixed at one depth to estimate cyanobacterial biomass throughout the water column need to account for potential overestimation of cyanobacterial biomass due to the cyanobacteria's ability to concentrate near the surface. Although there are logistical and financial ramifications of such decisions, the increased ability of the sonde to give the relevant information to the

stakeholder group and protect human health should outweigh such factors. Finally, stakeholders need to be cognitive of the lack of correlation between cyanobacterial biomass measurements and cyanotoxin concentrations.

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