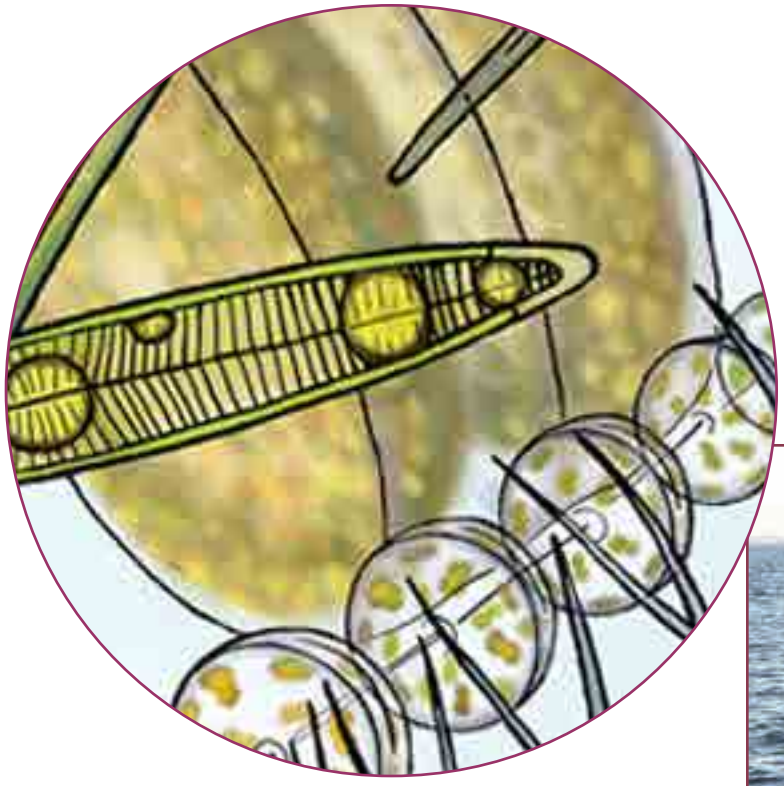
Continuous Observations of Chlorophyll Fluorescence and Other Parameters in Massachusetts Bay 2005 – 2018



Massachusetts Water Resources Authority
Environmental Quality Department
Report 2019-04

Citation:
Roesler CS. 2019. **Continuous Observations of Chlorophyll Fluorescence and Other Parameters in Massachusetts Bay, 2005 - 2018**. Boston: Massachusetts Water Resources Authority. Report 2019-04. 18 p.

Cover image credits from top left:

Phytoplankton illustration: *Haley Viehman, University of Maine*

Moored buoy: *University of Maine*

Continuous observations of chlorophyll fluorescence and other parameters in Massachusetts Bay, 2005 - 2018

Principal Investigator:	Dr. Collin Roesler
Institution:	Bowdoin College Department of Earth and Oceanographic Science
Address:	6800 College Station Brunswick, ME 04011
Phone:	207-725-3842
Email:	croesler@bowdoin.edu

Period of Performance:	1 July 2017 - 30 June 2019

SUMMARY

This report describes work and results from the past two years (July 2017 - June 2019) of MWRA's continuous biological monitoring in Massachusetts Bay. The program's focus is real-time monitoring of water quality, with emphasis on marine algae, to improve MWRA's ability to detect eutrophication-related changes and respond if necessary. This monitoring is required by MWRA's Ambient Monitoring Plan, attached to its National Pollutant Discharge Elimination System permit, for release of treated effluent from the Deer Island Wastewater Treatment Plant into Massachusetts Bay.

MWRA contracts with Bowdoin College to collect, analyze, and report measurements from optical sensors on a buoy sited off Cape Ann in Massachusetts Bay. The University of Maine operates the buoy, with support from the Northeast Regional Association of Coastal and Ocean Observing Systems, and from a separate MWRA contract. Sampling began in 2005 and now consists of 14 years of hourly observations. The primary measurement is chlorophyll, which is a pigment in marine algae measured by fluorometer, and used as a proxy for phytoplankton biomass. Turbidity, the cloudiness of water due to suspended particles, is also measured.

Based on all years of measurements, the typical seasonal cycle in chlorophyll includes elevated concentrations in spring and fall. Turbidity generally has higher values from late winter through spring than the rest of the year, and an early fall peak, and varies more from year to year than chlorophyll. **Results from the most recent years show that conditions were generally typical of other years, and did not indicate unusual water quality.**

To maintain high data quality, Bowdoin improved quality assurance and analysis methods, and implemented them on all years of measurements. The improvements include handling of calibration drift and outliers, and a new method to correct daytime chlorophyll observations, which can be biased up to 50 percent low by non-photochemical quenching. This occurs when the normal response of chlorophyll to light is saturated by high light levels, reducing its fluorescence. By yielding useful measurements during daytime in addition to nighttime, the new correction substantially increases temporal coverage. The correction method uses tidal currents and the fact that horizontal gradients in algae are common. It estimates chlorophyll during daylight, when observations are biased, using the tidal phase and concentrations recently measured at tidal cycle extremes during unbiased conditions at night.

Measurements of light conditions, initiated in 2016 and relevant to interpretation of the phytoplankton and turbidity results, continued through this reporting period.

To augment the chlorophyll measurements and help characterize the phytoplankton community composition, Bowdoin used ratios of fluorescence at different wavelengths, as made possible by a multi-channel fluorometer. Results suggest community dominants were diatoms during the largest blooms in spring and fall, cryptophytes during a summer bloom, and cyanobacteria and dinoflagellates during periods of lower chlorophyll concentrations.

March 2018 turbidity levels were among the highest on record, caused by naturally occurring sediment resuspension unrelated to the outfall, due to a series of historically extreme storms.

Introduction

The bio-optical observing program for the Cape Ann mooring (Mooring A01, operated by University of Maine for the Northeast Regional Association of Coastal and Ocean Observing Systems) was founded on a two-channel sensor measuring chlorophyll fluorescence and turbidity. Chlorophyll fluorescence, which is a form of light emitted by marine algae when light is incident on them, is an indicator of their concentration in seawater. Turbidity is a measure of cloudiness due to suspended particles. Observations began on October 22, 2005, and there now are approximately fourteen years of hourly observations. Bowdoin implemented new observations of above-water irradiance and multi-channel chlorophyll fluorescence beginning with deployment A0136 in 2016. (Deployments are numbered sequentially, A0136, A0137, A0138, …) The focus of this report is on the incremental addition of the deployments A0137-A0139 to the dataset. Descriptions of the quality assurance and analysis methods, which have been updated and applied to all years of measurements, are included along with bio-optical interpretations of the most recent observations.

Methods

As explained in prior reports (e.g. Roesler 2016) the WETLabs ECO FLNTU two-channel sensor is the standard bio-optical device that researchers have deployed on the mooring since 2005. In order to provide continuous observations with no gaps between deployments, we dedicate two such sensors to the program and swap them on/off the mooring at the start of each deployment, so at all times one is in the field and the other is on shore. The WETLabs factory services and calibrates each of the two FLNTU sensors when it is on shore in between its deployments in the field. On the mooring the FLNTU sensor is integrated into a WETLabs DH4 data handler that provides power to the sensor, controls sampling, archives the raw observations of each hourly burst sampling, and provides hourly mean and standard deviation values to a Campbell data controller. The controller in turn, incorporates current observations into the real-time data stream available via the data portal (http://gyre.umeoce.maine.edu/data/gomoos/buoy/html/A01.html).

Bowdoin deploys additional bio-optical sensors in a stand-alone configuration integrated into the same DH4, but their data are not transmitted in real time, due to limitations on the Campbell software set up. There is a significant time lag for processing of these additional data, as instruments must be recovered from the mooring, transported to Bowdoin College, cleaned, downloaded and post-processed.

The additional sensors include a multi-channel fluorometer, which is a custom made WETLabs ECO Triplet sensor FL3-WB that consists of 3 excitation channels (435nm, 470nm, 532nm) and one emission channel (695nm) to detect fluorescence stimulated by different pigments in chlorophyll of marine algae that absorb in the three wavelength bands. This sensor has been used to detect changes in phytoplankton community composition in Maine Lakes (Proctor and Roesler 2010), the Arabian Sea (Thibodeau et al. 2014), and in the western Mediterranean Sea

(Roesler et al. 2017). Phytoplankton community composition is the relative abundance of different types of phytoplankton present together in seawater, which varies from location to location and temporally, and is an important aspect of water quality and ecological conditions; chlorophyll concentration is a useful measure of marine algae but does not capture phytoplankton community composition. Second, Bowdoin deploys a Satlantic OC507-ICSA seven-channel irradiance sensor on top of the mooring and connected to the subsurface DH4 via a long cable through the well of the float. This sensor is factory calibrated and provides hourly estimates of incident downwelling irradiance ($\mu W\ cm^{-2}$). Third, a Satlantic OC507-ICSW-R10 seven-channel in-water radiance sensor with 10^{o} solid angle detection is deployed in a downward viewing configuration to measure nadir upwelling radiance (μW cm-2 sr-1) at the depth of the bio-optical frame (3m). This sensor was also factory calibrated. There are no anti-biofouling capabilities for this sensor, and due to fouling there was a significant loss of upwelling radiance measurements (see Figure 5D below). While this may potentially limit some ancillary research Bowdoin pursues, it is independent from the chlorophyll observations at the core of the MWRA continuous biological monitoring program, for which anti-biofouling measures were more successful so loss of measurements was minimal.

Bowdoin's recent work has concluded that the factory calibrations of the WETLabs ECO model chlorophyll fluorometers are biased by a factor of 2 (Roesler et al. 2017). For this reason, the laboratory calibration for the chlorophyll fluorometer has always been implemented for Mooring A01 (instead of a factory calibration). Researchers calibrate all fluorometers in the lab prior to deployment using ten dilutions of a monospecific culture of the diatom *Thalassiosira pseudonana* (Proctor and Roesler 2010). They grow the culture in nutrient replete L1 media at an irradiance that maximizes growth rates (i.e. ~300 $\mu Ein\ m^{-2}\ s^{-1}$) and minimizes pigment packaging due to low light acclimation. They harvest the culture in exponential growth with maximal extracted chlorophyll concentrations between 20 mg m^{-3} and 50 mg m^{-3}. This approach to calibration provides a transfer function between sensors and between a single sensor over time, accounting for variations in sensor gain, and also provides conversion of the signal from digital counts (millivolts) to biogeochemical units (mg m^{-3}). Because the excitation wavelength (470 nm) does not directly stimulate chlorophyll fluorescence, it is not possible to calibrate with a standard dilution of purified pigment. In vivo fluorometers take advantage of the energy transference between accessory pigments in the light harvesting complexes to chlorophyll *a* by stimulating accessory pigment absorption at 470 nm. While the fluorescence yield (fluorescence per extracted chlorophyll) varies between species, as a function of environmental acclimation, growth phase, and non-photochemical quenching, each of these sources of variability can be assessed on long-term time scales of observations and thus the impacts can be minimized or exploited for further information (Roesler and Barnard 2013).

Summary of the 5-step post-processing of the real-time data for quality control

Step 1. Correction for sensor drift. Evaluation of the offset between recovery/deployment of sensors that appear in the real time data as step functions. Bowdoin evaluates these offsets by

post recovery calibration or by identification of offset relative to prior and subsequent deployments. They flag the offsets and apply corrections.

Step 2. Removal of biofouled data. Biofouling manifests as a logarithmic signal increase leading to out-of-standard range or to saturating values. Biofouling takes two forms: a smooth signal increase associated with biofilm growth or an extreme hour-to-hour variability due to structural growth on the sensor such as seaweeds that contaminate both the fluorescence and turbidity signals as they waft into the optical sensing volume. Bowdoin flags biofouled observations as either biofilm or structural and remove them from the data stream.

Step 3. Identification, flagging, and correction of chlorophyll fluorescence observations impacted by non-photochemical quenching (NPQ). High levels of incident irradiance induce non-photochemical quenching in the chlorophyll fluorescence observations within the near-surface waters in the euphotic zone. The effect decreases exponentially with depth as the in-water irradiance also decreases exponentially. The onset of NPQ at the surface occurs as early as dawn (e.g., approximately 05:00 in June) and recovery from NPQ is prior to sundown.

Previous data submissions have flagged and removed quenched chlorophyll fluorescence observations. Time series analysis of chlorophyll fluorescence from a mooring (deployed for a separate project) in Harpswell Sound in eastern Casco Bay, which is strongly impacted by tidal advection, led to the observation that the fluorescence also has large variations associated with advection of phytoplankton populations that occur at high tide and low tide times. These two endmember populations varied slowly over time (detected semi-diurnally) while the hourly fluorescence signal varied between them due to conservative mixing between the two endmembers. These signals were convolved with the NPQ reduction in fluorescence as well. With the goal of identifying and monitoring the individual growth dynamics of the two phytoplankton communities, Bowdoin developed a method to deconvolve the diel quenching (Figure 1 B and E) and semi-diurnal tidal advection (Figure 1 C and F) sources of variability in the hourly time series (Figure 1A and D). This was inspired because interpolating nighttime observations over the daytime hours to remove the quenched daytime observations revealed strong variations in chlorophyll concentration over the nighttime hours (Figure 1D). The method is summarized using the calibrated fluorescence time series from the deployments A0137-A0139 (Figure 2).

The steps are: (1) selection of the unquenched nighttime fluorescence observations from a time series (Figure 2A); (2) selection of fluorescence values observed at high tide and low tide, the times of which are identified as the zeroes in differentiated alongshore surface current measurements (made with the Aanderaa current meter) (Figure 2B); (3) creation of the intersection of the two time series (i.e., the high and low tide unquenched fluorescence observations, Figure 2C); (4) interpolation of the missing endmember values (for example, if the endmember for high tide occurred during the day) assuming that the variations in the endmember fluorescence values varied slowly over 12 hours (the population is slowly varying);

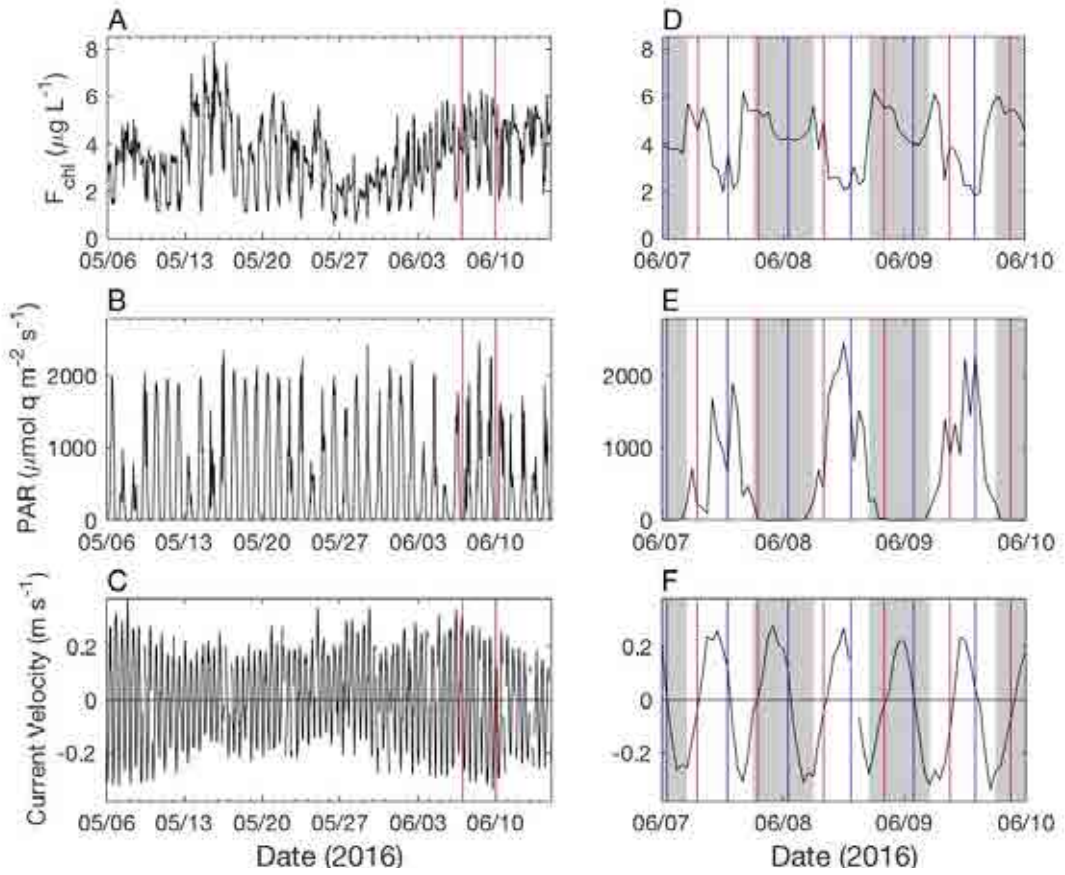


Figure 1. Six-week (left panels) and three-day (right panels) time series of hourly observations from the mooring in Harpswell Sound in 2016: F_{chl} (A and D), Photosynthetically Active Radiation (PAR) (B and E) and alongshore current velocity measured at 1.5 m (C and F). The timing of the three-day time series is indicated with vertical red lines on the six-week time series. On the three-day time series, nighttime intervals indicated by shaded bars, high and low tide times indicated by blue and red lines, respectively. *From Carberry et al. 2019.*

and (5) estimating the hourly variations at the mooring by assuming a cosinusoidal pattern of conservative mixing between the high and low tide communities (Figure 2D and Figure 3). This work was done with an undergraduate student, Luke Carberry, and the technician, Susan Drapeau, in the Bowdoin lab and has been published in *Limnology and Oceanography Methods* (Carberry et al., 2019).

Although the Cape Ann Mooring does not undergo the same tidal dynamics as Harpswell Sound, there is a clear semidiurnal tidal signal in the surface currents and thus some of the observed fluorescence variability is due to tidal advection. The method estimates the hourly time series of calibrated chlorophyll fluorescence in order to retrieve an unquenched signal during the daylight hours (Figure 4). It is clear that it generally provides excellent fit to the nighttime observations. The exceptions appear to be times when conservative mixing between high and low tide endmembers, which the method assumes is applicable, is not upheld.

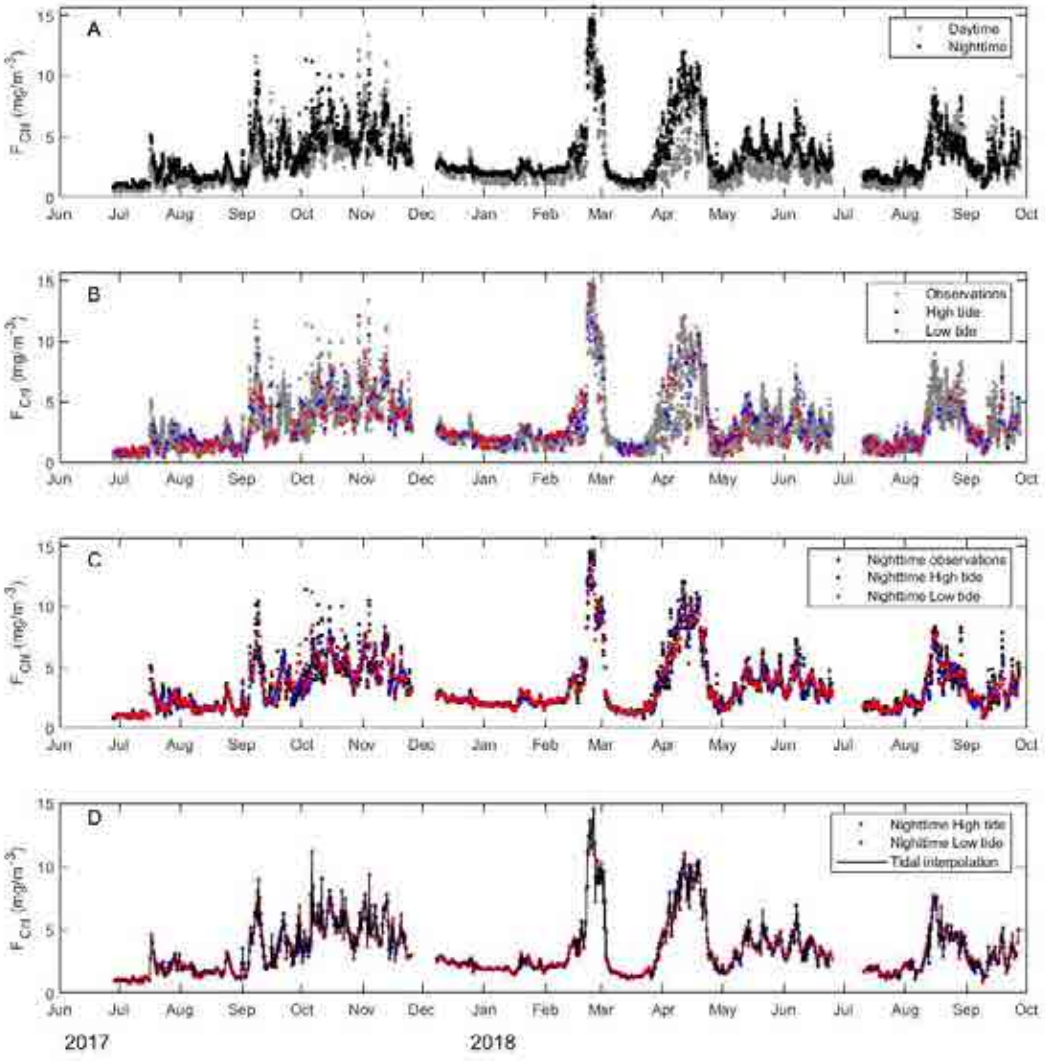


Figure 2. Deployment A0137-A0139 time series of hourly raw in situ F_{chl} observations (grey symbols) and F_{chl} observations (A) coincident with nighttime hours (black symbols), (B) coincident with high tide and low tide (blue and red symbols, respectively), (C) co-occurring unquenched (from A) and high and low tide (from B), and (D) hourly, unquenched, tidally-corrected F_{chl} time series (line), calculated using a cosine function fit to observed and interpolated occurrences of unquenched F_{chl} at high and low tide times in (C).

Step 4. Removal of single value outliers (SVOs). SVOs are identified differences between successive consecutive measurements that exceed the coefficient of variation and are in excess of 15 mg/m^3 (chlorophyll) or 3 NTU (turbidity). SVOs are flagged and removed from the data streams.

Step 5. Identify values below minimum detection levels. The minimum detection levels (MDLs) of the chlorophyll, turbidity, irradiance, and radiance sensors are 0.05 mg/m^3, 0.05 NTU,

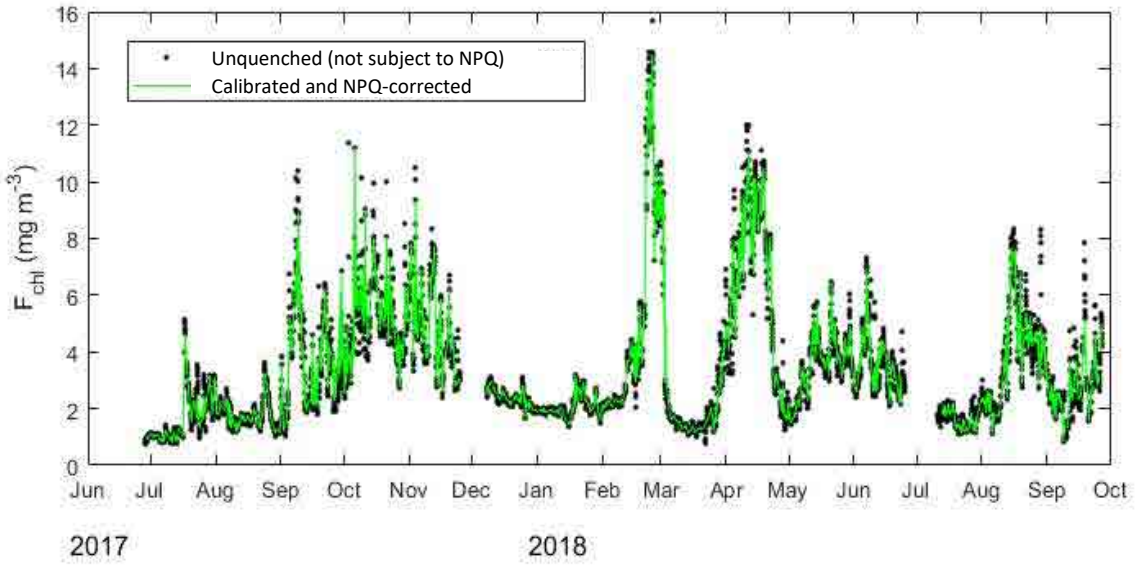


Figure 4. Calibrated and NPQ-corrected F_{chl} time series observations from A0137-A0139 (green line), with unquenched nighttime observations not subject to NPQ (black dots).

0.06 μW m^{-2} and 0.0003 μW m^{-2} sr^{-1}, respectively. Observations below -1*MLD are flagged and removed. Values between -1*MLD and 0, and those between 0 and +1*MLD are kept and independently flagged, for convenience of entering the data in the MWRA database where different value qualifiers are applied to the two ranges. The negative values are not removed because removing negative values that are within one MDL of zero leads to positive biasing of the observed data (Thompson 1998).

Data products provided

In order to give a clear sequence of observations, flagging and correction steps, we provide hourly data arrays including each stage of the post-processing. These are also helpful for optimization of correction schemes for biofouling and NPQ.

Separate data files are submitted for:

- the chlorophyll (Chl) and turbidity (NTU) sensors of the FLNTU,
- each channel of the calibrated ECO F3WB chlorophyll fluorometer (F1 through F3),
- the 7-channel irradiance (ED7), and
- the 7-channel radiance (LU7) sensors.

The Appendix provides data string formats:

- Table A1 provides the data string for hourly chlorophyll fluorescence data obtained from the ECO FLNTU and FL3-WB sensors.

- Table A2 provides the data string format for the hourly turbidity.
- Table A3 provides the data string format for the hourly downwelling irradiance and upwelling radiance data files.
- Table A4 provides a list of the data file names, descriptions, units and array sizes.

The data arrays provided have the Matlab binary storage “mat” file format.

Results and Discussion

Time series bio-optical observations

The time series bio-optical observations from deployments A0137-A0139 span from June 2017 to October 2018 (Figure 5). The calibrated chlorophyll time series (Figure 5A) clearly

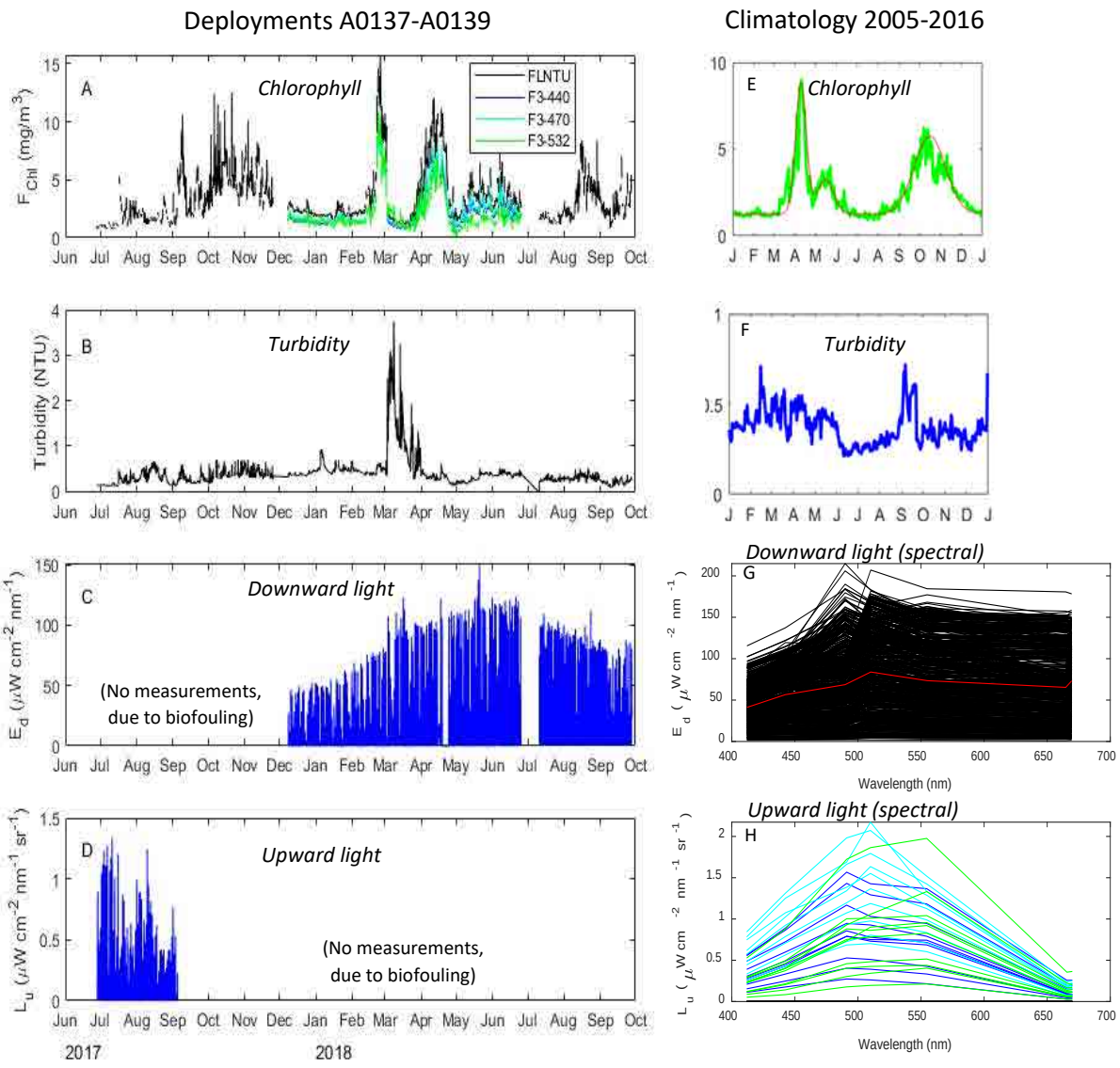


Figure 5. Hourly time series observations of

- **A.)** calibrated chlorophyll fluorescence from the FLNTU and FL3-WB sensors,
- **B.)** turbidity from the FLNTU sensor,
- **C.)** downwelling irradiance $E_d(\lambda)$ at 440 nm from Satlantic OC507-ICSA above water radiometer,
- **D.)** upwelling radiance $L_u(\lambda)$ at 440 nm from Satlantic OC507-ICSW-R10 in-water radiometer.

Long term seasonal climatology (2005-2016) for **E.)** chlorophyll and **F.)** turbidity.

Noon-time **G.)** $E_d(\lambda)$ (median red) and **H.)** $L_u(\lambda\ \mathrm{nm})$ wavelength of max blue (490), cyan (510), green (555).

demonstrates a large fall bloom September through December 2017, and a shorter fall bloom in August 2018 (although there is the suggestion of increasing chlorophyll at the end of September 2018, indicating a possible additional fall bloom). The wintertime concentrations are low until the occurrence of an intense and short-lived bloom at the end of February. (A similar early bloom was observed in 2012 in February due to early warming-induced surface stratification.) A longer-lived bloom occurred in April 2018 and a third lower magnitude bloom during May and June. The Oct-Nov 2017 and Apr 2018 blooms are comparable to what would be expected based on the long-term annual climatology (Figure 5E) but the others are significantly different from it. The 2018 springtime turbidity peak (Figure 5B) is significantly larger than would be expected based on the climatology (Figure 5F), and corresponds to a series of storms with extreme wind and wave conditions (e.g., https://www.climate.gov/news-features/event-tracker/nor%E2%80%99easters-pummel-us-northeast-late-winter-2018). Other than that event, the recent turbidity measurements are consistent with climatology. The main factor controlling the incident irradiance and upwelling radiance time series (Figure 5C and 5D, respectively) at this latitude is the seasonal solar cycle. The spectra of the incident irradiance varies in magnitude (Figure 5G) but not strongly in spectral shape. However, the upwelling radiance spectrum (Figure 5H) does vary in spectral shape due to changing contributions by blue absorbing materials such as phytoplankton, and other organic particles and dissolved matter. The wavelength of maximal radiance shifts from blue (442 nm) to green (555 nm).

Non-photochemical quenching dependence on irradiance

Once the corrected fluorescence is computed, one can quantify the fraction of quenching in the daytime observations. The fractional NPQ increases as irradiance increases (Figure 6) with NPQ reducing fluorescence by up to 50% under high irradiance conditions. Although there is substantial variability in the relationship, it is possible to estimate the fraction for each irradiance bin and thus characterize the median response. The median value of the observed to corrected fluorescence is one up until approximately 15 $\mu W/cm^2$ irradiance levels, above that light level the quenching reduces fluorescence approximately linearly until about 90 $\mu W/cm^2$, above which the quenching fraction remains constant.

Multi-channel fluorescence as indicator of evolving phytoplankton community composition

The WETLabs FL3-WB, three-excitation single emission chlorophyll fluorometer was deployed during A0136 and A0138 (Figure 7A). The intensity of the chlorophyll fluorescence in response to each excitation wavelength varies as the associated absorption coefficient at that wavelength varies, and thus as the pigment composition varies. Thus, fluorescence ratios are comparable to pigment absorption ratios. The daily resolved fluorescence ratio time series evidenced slowly varying taxonomic succession; because the raw fluorescence for each channel is calibrated to the diatom *Thalassiosira pseudonana*, ratio values of 1.0 are indicative of diatom domination (Figure 7B), while variations from 1.0 indicate variations in pigment composition relative to the diatom signal.

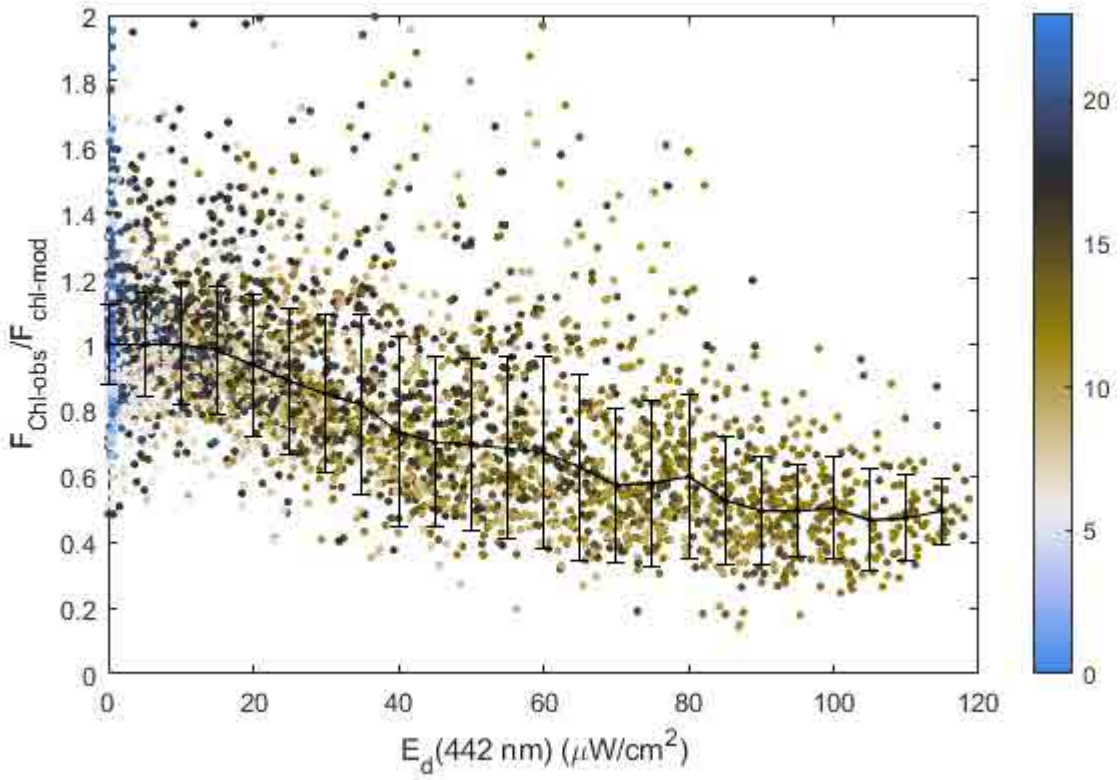


Figure 6. Ratio of hourly, calibrated fluorescence observations to corrected, hourly, calibrated fluorescence values as a function of hourly incident irradiance at 442 nm color coded by local time of day. Black line represents the median ratio value for 5-$\mu W/cm^2$ bins, error bars are bin standard deviation values.

Ratio-ratio data display is used to identify fluorescence 'fingerprints' characteristic of each pigment-based taxonomic group. The data clusters are associated with specific phytoplankton groups using High Pressure Liquid Chromatography (HPLC) pigment analysis and diagnostic pigments for each taxonomic group (i.e., fucoxanthin for diatoms, peridinin for dinoflagellates, etc.). A recent time series analysis from the Mediterranean Sea yielded similar ratio-ratio patterns over an annual cycle, and there were associated monthly high performance liquid chromatography (HPLC) samples to identify the phytoplankton composition of the clusters. The Mediterranean Sea results, as well as laboratory observations of multichannel fluorescence measurements of specific phytoplankton cultures, provide some insight into the phytoplankton community evolution at Mooring A01 (Figure 7C). These inferred community patterns indicate that the two early blooms comprise diatoms, the summer bloom dominated by cryptophytes, while lower chlorophyll concentration conditions are dominated by cyanobacteria and dinoflagellates (Figure 7D). In order to validate these results it would be useful to have samples collected for HPLC analysis. This would involve collecting water samples, filtering them onto glass fiber filters and freezing them until analysis. Bowdoin plans to have the capability for this

analysis beginning fall 2019 and may consider carrying it out, as an exploratory research augmentation of the ongoing routine continuous biological measurements program.

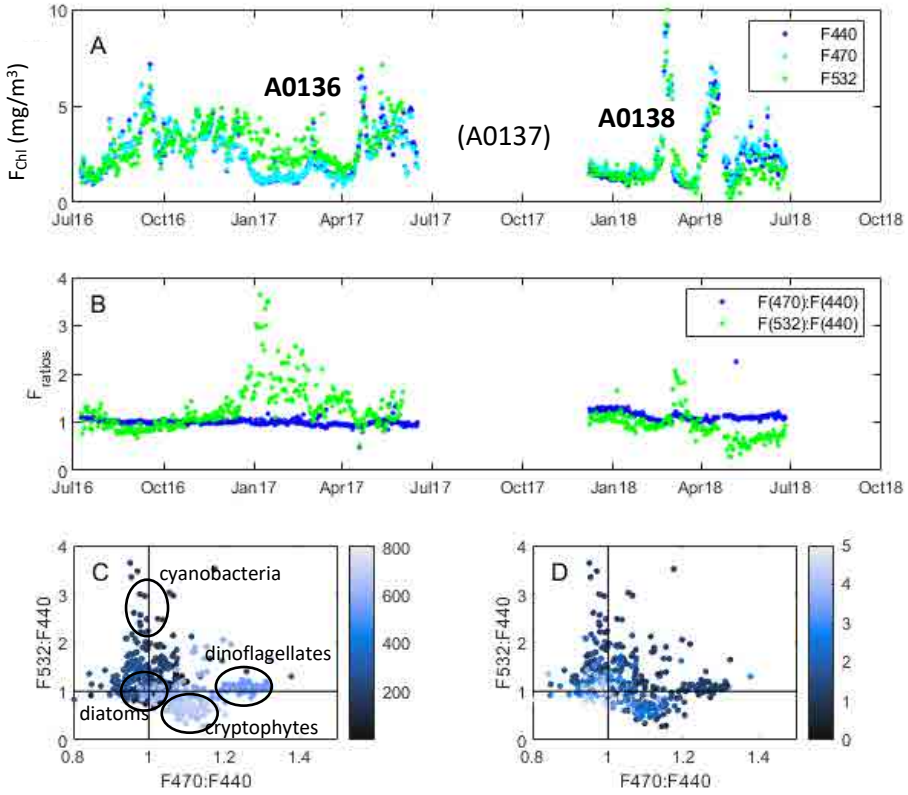


Figure 7. Time series of daily-average observations from multi-channel fluorometer. (Multi-channel fluorometer was not included on deployment A0137.) **A.)** Calibrated fluorescence emission from 440nm, 470 nm, and 532 nm excitation (blue, cyan, and green, respectively). **B.)** Fluorescence ratios. **C.)** Ratio versus ratio graphs color-coded by day since July 7, 2016. **D.)** Ratio vs ratio graphs color-coded by calibrated chlorophyll concentration [mg m^{-3}]. Ratio values of one are indicated by lines in C and D, the intersection of which is calibrated to the diatom *Thalassiosira pseudonana.* Circled clusters of observations in C, and corresponding ratio-ratio values, were identified by dominant pigment-based taxonomy from Mediterranean multi-channel fluorescence time series and HPLC diagnostic pigment-based taxonomy.

References

Carberry, L., C. S. Roesler, and S. L. Drapeau. 2019. Correcting in situ chlorophyll fluorescence time series observations for non-photochemical quenching and tidal variability reveals non-conservative phytoplankton variability in coastal waters. Limnol. Oceanogr. Methods. DOI: 10.1002/lom3.10325

Proctor, C. W., and C. S. Roesler. 2010. New insights on obtaining phytoplankton concentration and composition from in situ multispectral Chlorophyll fluorescence. Limnology and Oceanography: Methods **8:** 695-708.

Roesler, C. S. 2016. In Situ Chlorophyll Fluorescence Observations on NERACOOS Mooring A01: Revised Data Flagging and Changing Phenology. Boston: Massachusetts Water Resources Authority. Report 2016-15. 11 p.

Roesler, C. S. and A. H. Barnard, 2013. Optical proxy for phytoplankton biomass in the absence of photophysiology: Rethinking the absorption line height. Methods Oceanogr. 7: 79-94. Doi:10.1016/j.mio.2013.12.003 .

Roesler, C. S., J. Uitz, H. Claustre, E. Boss, X. Xing, E. Organelli, N. Briggs, A. Bricaud, C. Schmechtig, A. Poteau, F. D'Ortenzio, J. Ras, S. Drapeau, N. Haëntjens, and M. Barbieux, 2017. Recommendations for obtaining unbiased chlorophyll estimates from in situ chlorophyll fluorometers: A global analysis of WET Labs ECO sensors. Limnol. Oceanogr. Methods, 15: 572–585. doi:10.1002/lom3.10185.

Thibodeau, P. S., C. S. Roesler, S. L. Drapeau, S. Prabhu Matondkar, J. I. Goes, and P. J. Werdell. 2014. Locating Noctiluca miliaris in the Arabian Sea: An optical proxy approach. Limnology and Oceanography **59:** 2042-2056.

Thompson, M. (1998). Perspective: Do we really need detection limits? Analyst 123(2): 405-407.

Appendix. Data file formats.

Table A1. Format of the hourly observational data file for chlorophyll fluorescence data arrays, including those derived from FLNTU and FL3-WB sensors.

Column	ID	Value/Range	Comment
1	Year	2005-2016	
2	Month	1-12	
3	Day	0-31	
4	Hour	0-25	
5	Minute	0-60	
6	Second	0-60	
7	Date.Time	732607 - 737335	Matlab format
8	Raw Fchl	-1.63 – 162.56	Raw hourly mean
9	Flag_Offset	0, 1	Between deployments
10	Fchl_corr_offset		Corrected for offsets
11	Flag_Biofouling1	0, 1	Biofilm
12	Flag_Biofouling2	0, 1	Structural
13	Fchl_corr_biofouling	NaN	Values removed
14	Flag_NPQ	0, 1	NPQ
15	Fchl_corr_NPQ	-0.04 28.6	Values corrected (Carberry et al. 2019)
16	Flag_SVO	0, 1	Single value outlier
17	Fchl_corr_SVO	NaN	Values removed
18	Flag_MLD1	0, 1	<-Minimum level detection
19	Flag_MLD2	0, 1	-MLD to 0
20	Flag_MLD3	0, 1	0 to +MLD
21	Fchl_corr	-0.04 to 29.47 /NaN	Cumulative removal/correction
22	Deployment	15 – 39	Deployment number
23	ECO-FLNTU S/N	001-9999	Sensor serial number, FLNTU

Table A2. Format of the hourly observational data file for Turbidity.

Column	ID	Value/Range	Comment
1	Year	2005-2016	
2	Month	1-12	
3	Day	0-31	
4	Hour	0-25	
5	Minute	0-60	
6	Second	0-60	
7	Date.Time	732607 - 737335	Matlab format
8	Raw Turbidity	-0.59 to 25.95	
9	Flag_Offset	0, 1	
10	Turb_corr_offset		Corrected for offsets
11	Flag_Biofouling1	0, 1	Biofilm
12	Flag_Biofouling2	0, 1	Structural
13	Turb_corr_biofouling	NaN	Values removed
14	Flag_SVO	0, 1	Single value outlier
15	Turb_corr_SVO	NaN	Values removed
16	Flag_MLD1	0, 1	<-Minimum level detection
17	Flag_MLD2	0, 1	-MLD to 0
18	Flag_MLD3	0, 1	0 to +MLD
19	Turb_corr	-0.05 to 9.81 /NaN	Cumulative removal/correction
20	Deployment	15 - 39	Deployment number
21	ECO-FLNTU S/N	001-9999	Sensor serial number, FLNTU

Table A3. Format of the hourly observational data file for downwelling irradiance (ED) and upwelling radiance (LU).

Column	ID	Value/Range	Comment
1	Year	2005-2016	
2	Month	1-12	
3	Day	0-31	
4	Hour	0-25	
5	Minute	0-60	
6	Second	0-60	
7	Date.Time	732607 - 737335	Matlab format
8-14	Raw Ed(7)	-0.60 25.95	
15	Flag_Offset	0, 1	
16-22	Ed(7)_corr_offset		Corrected for offsets
23	Flag_Biofouling	0, 1	Biofouling
24-30	Ed(7)_corr_biofouling	NaN	Values removed
31	Flag_SVO	0, 1	Single value outlier
32	Flag_MLD1	0, 1	<-Minimum level detection
33	Flag_MLD2	0, 1	-MLD to 0
34	Flag_MLD3	0, 1	0 to +MLD
35	Flag Cal	0, 1	Indicates multiplicative scaling
36-42	Ed(7)_final	NaN	Cumulative removal/correction
43	Deployment	15 - 39	Deployment number
44	OCI_507_SN	001-9999	OCI 507 sensor serial number

Table A4. List of submitted data arrays

Array Name	Description	Units	Array size (row x columns)	Format
H_Chl_2018_v1	hourly chlorophyll fluorescence, FLNTU	mg/m3	112289x23	Table A1
H_NTU_2018_v1	hourly turbidity	NTU	112289x21	Table A2
H_F1_2018_v1	Hourly chlorophyll fluorescence 435 nm excitation, F3WB	mg/m3	18649X23	Table A1
H_F2_2018_v1	Hourly chlorophyll fluorescence 470 nm excitation, F3WB	mg/m3	18649X23	Table A1
H_F3_2018_v1	Hourly chlorophyll fluorescence 532 nm excitation, F3WB	mg/m3	18649X23	Table A1
H_ED_2018_v1	Hourly spectral irradiance, 7 channels	μW/cm2/nm	18376x44	Table A3
H_LU_2018_v1	Hourly spectral radiance, 7 channels	μW/cm2/sr/nm	18406x44	Table A3
ED7wave_2018	Irradiance central wavelength	nm	7x1	n/a
LU7wave_2018	Radiance central wavelength	nm	7x1	n/a

Massachusetts Water Resources Authority
100 First Avenue • Boston, MA 02129
www.mwra.com
617-242-6000