Continuous hourly observations of chlorophyll fluorescence, turbidity, and irradiance in Massachusetts Bay (2005 – 2021) reveal variations in phenology of phytoplankton blooms

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Continuous hourly observations of chlorophyll fluorescence, turbidity, and irradiance in Massachusetts Bay (2005 – 2021) reveal variations in phenology of phytoplankton blooms

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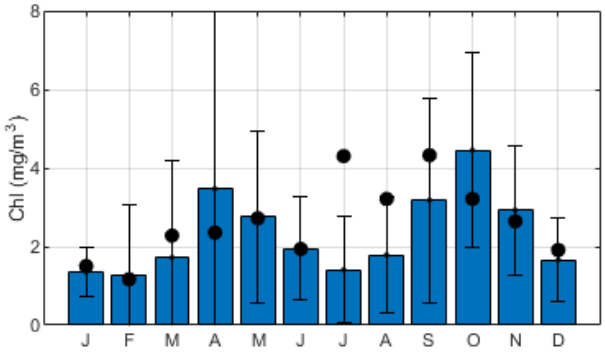
SUMMARY

Since late 2000, MWRA has discharged treated wastewater from its Deer Island Treatment Plant in Boston through a 15 km (9 mi) tunnel into Massachusetts Bay. To help ensure that nutrients in the discharge do not contribute to excess growth of phytoplankton (marine algae), MWRA monitoring includes research vessel surveys to measure phytoplankton conditions approximately monthly. Results show variability has remained within natural ranges, including near the outfall. MWRA augments the monthly surveys with nearly continuous hourly observations, from bio-optical sensors on a buoy in northeastern Massachusetts Bay off Cape Ann. Since 2005, MWRA has contracted Bowdoin College researchers to operate the sensors and provide estimates of chlorophyll and turbidity. Chlorophyll is a pigment unique to phytoplankton, which provides a robust estimate of their concentration. Turbidity is an indicator of water cloudiness due to suspended particles such as sediments and bacteria. University of Maine maintains the buoy, which collects oceanographic observations, and reports the data in real time online (www.neracoos.org) with support from the Northeast Regional Association of Coastal Ocean Observing Systems and MWRA. Bowdoin configures and calibrates the sensors, works with University of Maine to deploy and recover them at sea, arranges manufacturer repair and maintenance, and interprets results in the context of oceanographic conditions. The chlorophyll sensor is a fluorometer that measures the red light emitted (fluoresced) by phytoplankton chlorophyll in response to stimulating blue or green light flashes. As of 2016, Bowdoin has maintained two fluorometers both for redundancy and for additional colors of stimulating light. Redundancy reduces measurement uncertainty and provides some insurance against instrument failure. The additional colors enable the researchers to identify different types of phytoplankton. To maintain high quality of the chlorophyll data they use above-water solar conditions measured by an irradiance sensor.

Results of the 2020-21 observations were generally within the ranges of earlier years and did not indicate unusual water quality. For all years of data, there is a recurring seasonal pattern with spring and fall chlorophyll increases (blue bars in figure) due to phytoplankton blooms. For 2020-21 (black circles in figure), the annual average was similar to earlier years, while the phenology, or timing of the seasonal progression, included slightly lower spring and fall bloom values and slightly higher late summer values. Such features are typical and result from year to year variations in environmental conditions (e.g., sunlight; temperature; and density layering, or stratification). Turbidity, on the other hand, has remained relatively constant, both seasonally within each year and in the long term over 2005-21. This indicates suspended biological particles, such as bacteria, undergo modest seasonal variations with no detectable long-term trend.



Monthly median values of hourly chlorophyll fluorescence: 2020-21 (black circles) and 2005-2021 (blue bars; error bars are standard deviation). The annual mean for 2020-21 was similar to a typical year but its phenology (within-year timing) differed: chlorophyll was slightly lower in spring and higher in summer. Such differences are caused by year-to-year variations in environmental conditions.

Introduction

This report describes work and results from the 2021-22 contract period for MWRA's continuous biological monitoring in Massachusetts Bay performed by Bowdoin College researchers. The program focus is real-time monitoring of water quality conditions, with emphasis on marine algae (phytoplankton) through chlorophyll measurements and other suspended particles through turbidity measurements, to improve MWRA's ability to detect changes and respond if necessary. MWRA's Ambient Monitoring Plan, attached to its National Pollutant Discharge Elimination System permit to release treated effluent from the Deer Island Wastewater Treatment Plant into Massachusetts Bay, requires this monitoring.

The program consists of bio-optical observations made at a depth of 3 m on the moored buoy off Cape Ann (Figure 1) operated by University of Maine with support from the Northeast Regional Association of Coastal and Ocean Observing Systems (NERACOOS) and MWRA, referred to as Buoy A01 or Mooring A01. When founded in 2005 it comprised a two-channel sensor measuring chlorophyll fluorescence and turbidity. Chlorophyll fluorescence, the red light emitted by phytoplankton in response to their absorption of light, is an indicator of their concentration in seawater. Turbidity is a measure of cloudiness due to suspended particles. It is used to monitor for the presence of other biological particles such as bacteria that might respond directly to changing nutrient loads. Observations began on October 22, 2005, and there now are approximately seventeen years of hourly observations. In 2016 Bowdoin began also measuring above-water irradiance and multi-channel chlorophyll fluorescence

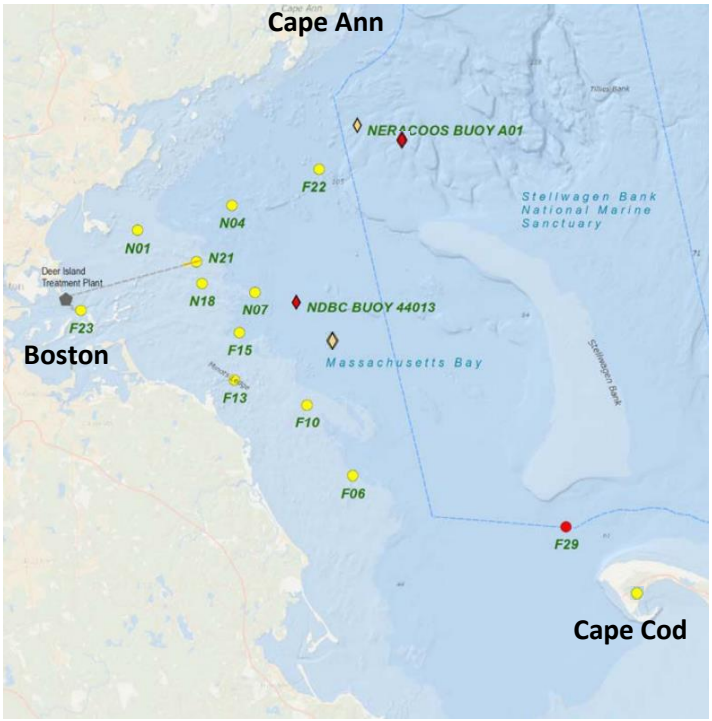


Figure 1. Data in this report are from sensors deployed and operated by Bowdoin College on Buoy A01 (red diamond). The buoy is operated by the University of Maine for the Northeast Regional Association for Coastal and Ocean Observing Systems (NERACOOS). For reference, Deer Island Treatment Plant (gray pentagon), outfall tunnel (dashed gray line), outfall (purple line under station N21), MWRA ship survey monitoring stations (yellow circles), and Boston Buoy 44013 (yellow diamond) operated by the National Data Buoy Center (NDBC) are annotated, as well as Cape Ann, Boston, and Cape Cod.

The focus of this report is presentation of the 2020-21 sampling that has been added to the dataset, brief descriptions of the quality assurance and analysis methods, and bio-optical interpretations of all years of data.

The 2020-21 sampling consists of two deployments. The first deployment, A0143 (each deployment is referred to using the label "A01NN" where NN increases for successive deployments), was from October 2020 to June 2021. The second deployment, A0144, was from June 2021 to November 2021.

Sensors

The WETLabs ECO FLNTU two-channel sensor is the standard bio-optical device that has been deployed on the mooring since 2005 (e.g., Roesler 2016). 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 facility (a subsidiary of SeaBird Electronics) services and calibrates the sensors when they are on shore in between deployments in the field. On the mooring the sensors are integrated into a WETLabs DH4 data handler that provides power to the sensors, controls sampling, archives the raw observations of each hourly burst sampling, and provides hourly mean values to a Campbell Scientific data logger (Table 1). The logger incorporates the optical observations, together with those from all other buoy sensors, into a real-time data stream that is sent via cell phone modem or satellite communications to University of Maine. There, the data stream from the FLNTU is parsed, calibrations are applied to it, and it is made available at the online data portal http://gyre.umeoce.maine.edu/data/gomoos/buoy/html/A01.html and sent to NERACOOS, which also presents it online in real time at their website www.neracoos.org. Since 2016 (deployment A0136), additional bio-optical sensors have been deployed in a stand-alone configuration integrated into the same DH4. Only a subset of their data is transmitted in real time due to limitations on the DH4 and Campbell logger.

Table 1. Components of the optical sensing package on the buoy.

INSTRUMENT	PURPOSE
WETLabs ECO **FLNTU**	Optical sensor, measures chlorophyll fluorescence (470 nm excitation) and turbidity, at 3 m depth.
WETLabs ECO **FL3-WB** ("F3WB")	Optical sensor, measures chlorophyll fluorescence (3 excitation wavelengths), at 3 m depth.
Satlantic OC507-ICSA	Optical sensor, measures solar irradiance; mounted on the buoy tower.
WETLabs DH4	Data handler, collects and stores data from optical sensors; computes mean FLNTU data; transmits means to Campbell Scientific Data Logger, which transmits it in real time to the University of Maine where it is relayed to NERACOOS and posted online.

Each sensor collects measurements for approximately one minute every hour, called a burst sample, which is approximately 60 readings. These data are stored on the DH4, which transmits only the mean sensor values in real time due to limitations of the Campbell software. The full data set is retrieved from the DH4 after the mooring is recovered and the sensors removed from its infrastructure, transported to Bowdoin, cleaned, downloaded and post-processed. These values are analyzed to ensure the mean FLNTU values reported in real time are robust estimates of the bursts, by comparison to their median and standard deviation, and to process the data streams from the remaining optical sensors. Description of the sensor data streams and the information derived from them is detailed in Roesler (2021).

Instrument Calibration. Recent work has concluded that the factory calibrations of the WETLabs ECO model chlorophyll fluorometers are biased by a factor of 2 globally, with regional patterns in the specific values of the bias (Roesler et al. 2017). For this reason, the laboratory calibration for the chlorophyll fluorometer has always been implemented for sensors on Buoy A01, instead of factory calibrations. Details of the calibration are outlined in Roesler (2021). Bowdoin researchers now have the capability to measure the full suite of phytoplankton pigments using high performance liquid chromatography (HPLC) following protocols established by the NASA Goddard Space Flight Center Field Support Group (Van Heukelem and Thomas 2005). This is the state-of-the-art method for pigment identification and quantitation. Such analyses could be performed on water samples collected on the ship survey program at the sampling station closest to Mooring A01 (Figure 1), in order to further improve calibrations.

Data Retrieval for A0143 and A0144

The FLNTU and F3WB sensors both reported hourly observations for the whole extent of deployments A0143 and A0144. The irradiance sensor, OCR507 ICSA S/N 134 stopped reporting data October 29, 2020. There is no indication in the realtime data stream or the DH4 archive file why this happened. The sensor reported normally upon recovery and testing in the laboratory.

The 7-step post-processing protocol for the real-time data for quality control

As explained in detail in prior reports (e.g., Roesler 2020, 2021), a series of processing steps are necessary to maintain the high quality of the dataset.

Step 1. Quality assurance on times recorded by the irradiance sensor.

Step 2. Calibration comparison and correction between sensors.

Step 3. Correction for sensor drift.

Step 4. Identification of and removal of biofouled data.

Step 5. Identification, flagging, and correction of chlorophyll fluorescence observations impacted by non-photochemical quenching (NPQ).

Step 6. Removal of single value outliers (SVOs).

Step 7. Identification of values below minimum detection levels (MDLs) and within MDL of zero.

Details and examples for all steps other than #2 can be found in Roesler (2020); details and examples for step #2 can be found in Roesler (2021).

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).

The Appendix provides data string formats:

Table A1 provides the data string for hourly chlorophyll fluorescence data obtained from the FLNTU and F3WB 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 the FLNTU span October 2005 through October 2021 (deployments A0115-A0144), while the observations from the F3WB and irradiance sensors span from July 2016 to October 2021 (deployments A0137-A0144). *Measurements from the most recent deployments exhibit lower variability in both chlorophyll and turbidity, compared to most previous years, but are within the range of observed variations over the whole data record (Figure 2).*

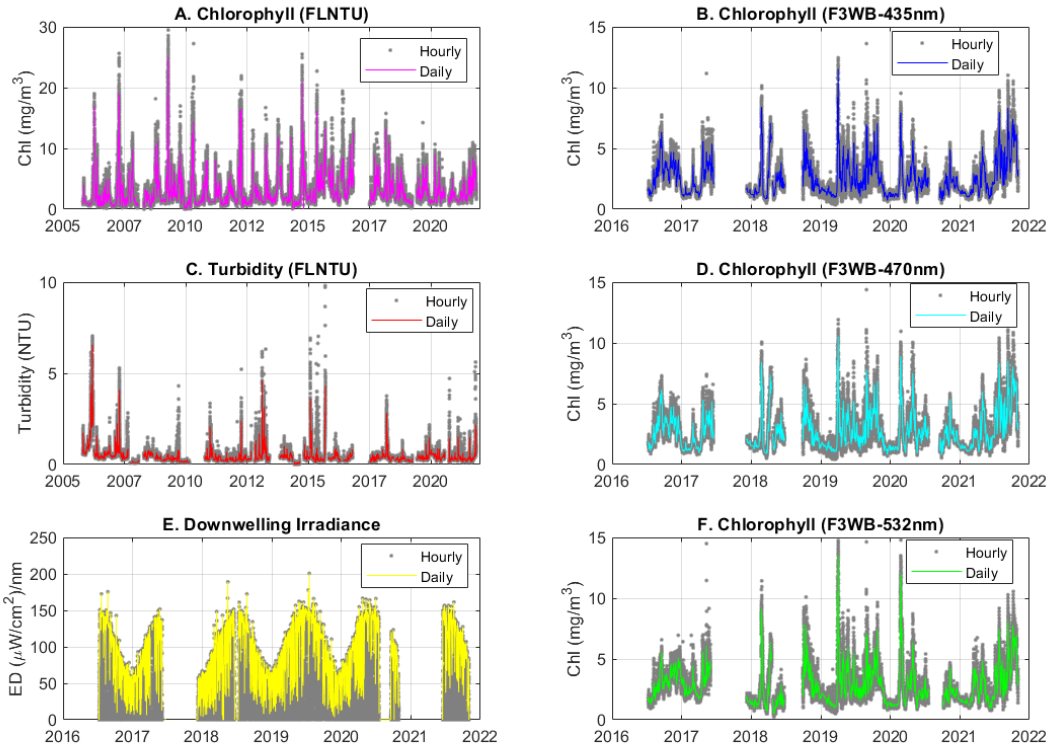


Figure 2. Time series of hourly (gray symbols) and daily (colored lines) observations of chlorophyll fluorescence (A: FLNTU, 2005-2022; B, D, and F: F3WB, 2016-2022), turbidity (C: FLNTU, 2005-2022), and solar irradiance (E: 2016-2022). Daily values are medians for all but irradiance, which is the daily maximum.

Long-term annual climatology. The daily climatological values for the bio-optical time series (Figure 3) clearly show a distinct spring bloom that peaks in early April and lasts about two weeks. Climatologically, the magnitude of the bloom is about 8 mg Chl/m^3. This is followed by a summer lower chlorophyll interval, with increasing chlorophyll beginning at the end of August, peaking in early October at a value of approximately 5 mg Chl/m^3, and declining through the end of December. The lowest chlorophyll concentrations are in the winter months of January through March. The pattern over the last 5 years of F3WB observations indicates that a spring bloom can occur as early as early February and that up to four separate spring blooms can be observed. The fall bloom pattern is much less variable, with a longer duration and a similar magnitude in peak concentration.

There is not a strong seasonal signal in turbidity (Figure 3C). Values are typically of order 1 NTU. However, some years there are larger values occurring in late winter, with rare events in fall. These events correspond to storms when stratification is weakening in the fall or at a minimum in the winter. There does not seem to be a biological signal in the turbidity.

The seasonal pattern in the daily maximal solar radiation clearly demonstrates the effect of latitude (Figure 3E) as the dominant source of variation. Within that framework, variations are associated with clouds; spring and early summer months show significant cloud impacts, as does November. The clearest months are August – October, and December – January, associated with high-pressure systems at this latitude.

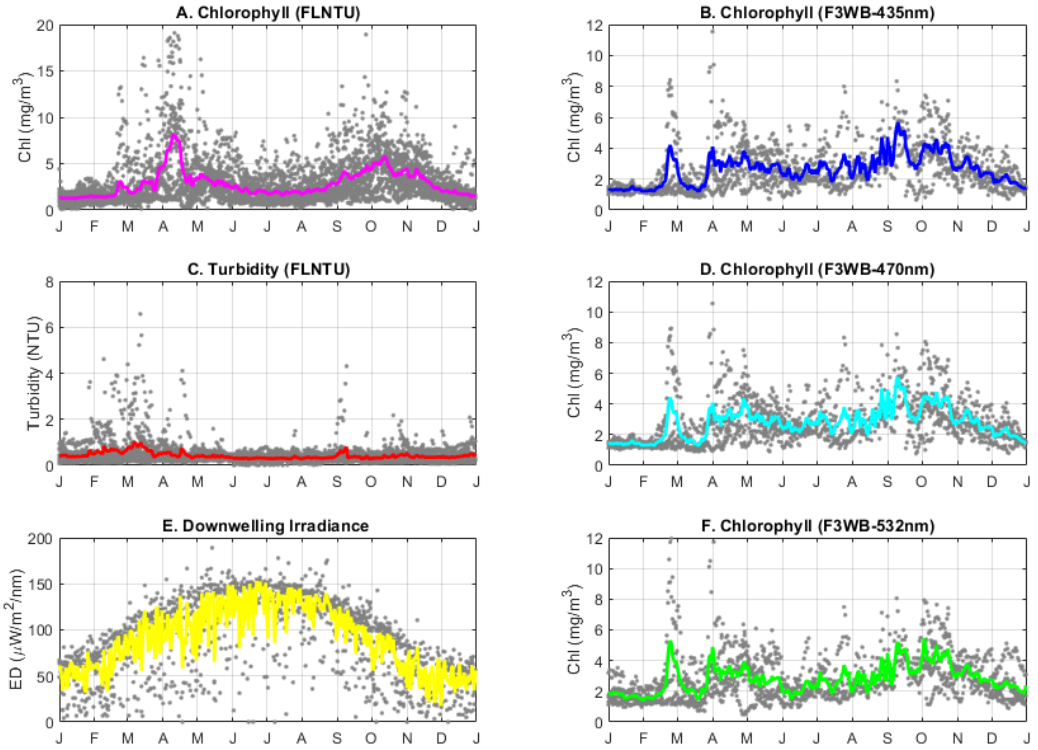


Figure 3. Daily observations (gray symbols) and climatological means (colored lines) for the bio-optical time series for chlorophyll fluorescence (A, B, D, F), turbidity (C), and solar irradiance (E).

Monthly climatological means for the bio-optical time series are shown in Figure 4. The spring bloom chlorophyll peak occurs in April and the fall bloom peak in October. The mean value of the April bloom is smaller than the fall bloom, partly due to the division of data between April and May, and its standard deviation is larger (Figure 4A). This 2020-21 measurements show magnitudes of the spring and fall blooms lower than climatological values. In addition, the spring bloom occurred in March, rather than April, and the fall bloom occurred in September rather than October. In contrast, the summer values in July – September were larger than the climatological values, a statistically significant increase in July occurred in the F3WB observations of 2020-21 compared to the available prior 5 years.

The seasonal pattern in turbidity in 2021 was essentially flat through the year (Figure 4C), however, there is substantial variability January through April when winter storms drive events in increased turbidity. September also appears to be a month of higher variability.

The monthly pattern in solar irradiance in 2021 (Figure 4E) reveals slightly higher peak irradiance in June, and slightly lower peak irradiance in November. The hourly patterns in irradiance indicate this is consistent with increased cloudiness late spring to early summer compared to the summer and fall months. Note that the missing irradiance data prior to June in Figure 4A is due to a data processing issue and efforts are underway to determine if good data quality are obtainable.

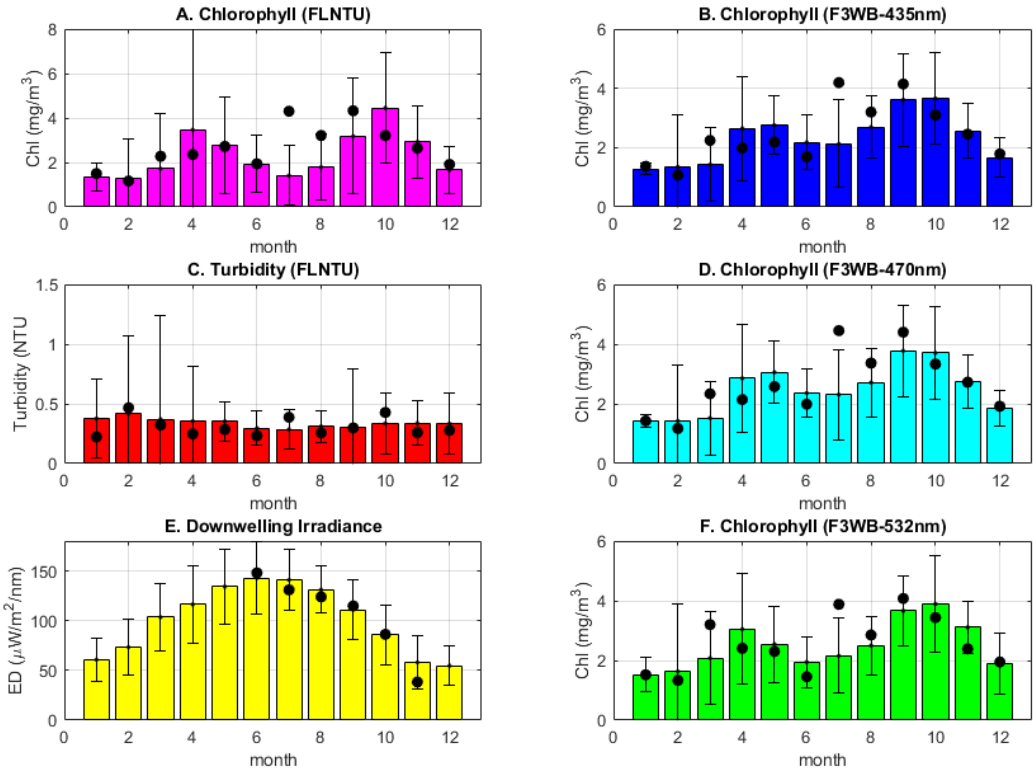


Figure 4. Monthly median (colored histogram bars; all years) values of chlorophyll fluorescence (A, B, D, F), turbidity (C), and solar irradiance (E); error bars indicate standard deviation. Observed monthly median values for the 2020-21 data (A0143 and A0144) are shown as black symbols.

Overall, there is no significant trend in the annual median values of chlorophyll or turbidity at Mooring A01 over the last 17 years. Annual median values of chlorophyll reveal an increasing period from 2005-2009, relatively constant interval from 2010-2014, a peak in 2015, slight decrease in 2016, and relatively constant values from 2017 - 2021 (Figure 5A). A consistent pattern appears in the F3WB chlorophyll time series (Figure 5 B, D, and E). The annual mean pattern in turbidity exhibits a decrease from 2005-2009 followed by more uniform mean values over the past decade (Figure 5C). Three years (2006, 2013 and 2015) have exhibited the strongest variability. In 2021 turbidity was slightly lower (clearer water), but more variable.

Irradiance shows increased values since 2017, but the 2021 peak is likely an artifact of missing springtime observations during the early part of the year.

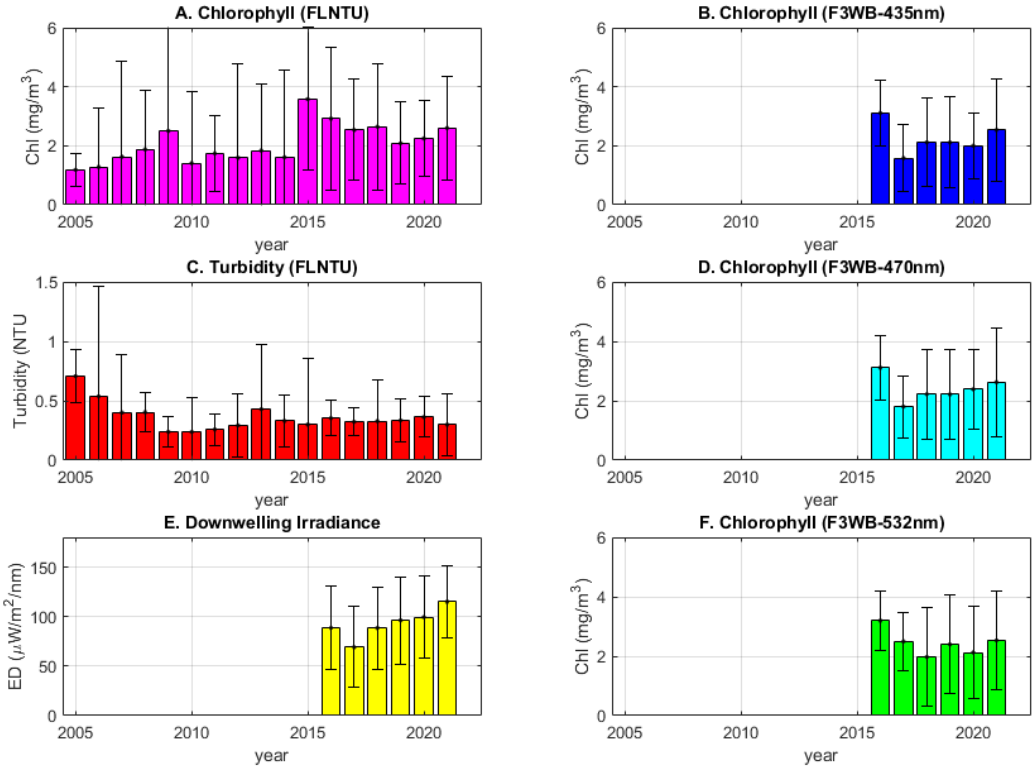


Figure 5. Annual medians of daily values of chlorophyll fluorescence (A, B, D, F), turbidity (C), and solar irradiance (E); error bars indicate standard deviation.

The lack of a significant long-term trend contrasts with a recent study that proposes significant decreases in phytoplankton standing stock across the Gulf of Maine based on an independent ship-based dataset (Balch et al., 2022). Both datasets show clear multiyear, nearly decadal, cycles that cannot yet be statistically resolved with the 15-20 years of available data, particularly when there are sampling gaps.

Variations in phenology. The continuous observations from A01 clearly demonstrate variations in the timing, or phenology, of the phytoplankton blooms. While the overall concentration of phytoplankton does not exhibit a trend, there is a significant redistribution of *when* phytoplankton bloom. Changing phytoplankton phenology will have significant consequences for organisms that depend upon them as a food source and who time their reproductive cycles based upon bloom timing. Variability in annual median chlorophyll concentrations can be driven by high peak concentrations during blooms, longer blooms or overall higher sustained concentrations. A Hovmöller diagram (Figure 6A) is used to identify which factor may be at play within each year. From 2006 through 2010 a dominant spring bloom occurred in April with a minor secondary bloom in June. In 2011 and 2012 the spring bloom was 2-4 weeks early. From

2013 through 2016, the major spring bloom occurred increasingly later in the spring, to approximately late May by 2016. 2018 and 2020 both exhibited a late February bloom, of much higher magnitude than that observed in 2012. Secondary blooms occurred in April and May. A later spring bloom was observed in 2021. The fall blooms have exhibited a trend from occurring in November, during the early part of the record, to occurring during late August in more recent years (the apparent exception in 2020 is due to missing data from July through September). Clear evidence of the early and extended fall bloom, starting in July, appears in 2021.

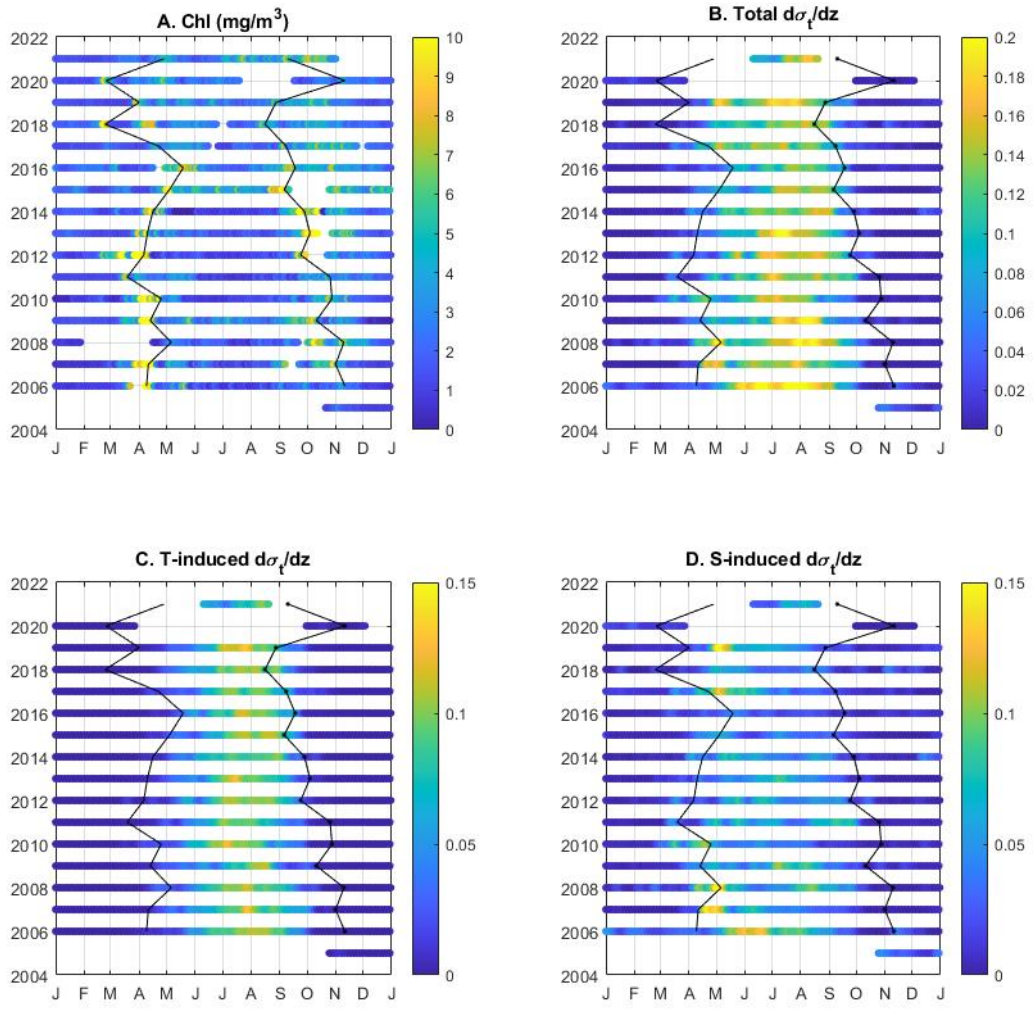


Figure 6. Hovmöller diagrams, over the entire bio-optical times series at Buoy A01, for A. chlorophyll concentration, B. stratification or total vertical density gradient ($^{d\sigma_T}/_{dz}$ from 1 to 20 m, units kg/m^3/m), and the contributions to stratification due to C. temperature and D. salinity (units kg/m3/m for both). Black lines on each figure identify the timing of the peaks of spring and fall blooms.

There are inter-annual variations in stratification in the Gulf of Maine (Thomas et al. 2017). The long-term variations and trends in chlorophyll concentration appear to be linked to regional variations in temperature and salinity stratification. The intensity of stratification in the upper 20 m shows that stratification is maximal in July and August, but the springtime onset of stratification is generally in April and coincides with the spring bloom initiation (Figure 6B). The seasonal decrease in stratification occurs generally in September and October, coinciding with the timing of the fall bloom (Figure 6B). The portion of density stratification due to temperature was computed from the product of the coefficient of thermal expansion and the depth gradient in temperature (Figure 6C). It demonstrates that temperature is the dominant factor determining the intensity and timing of maximal stratification at mooring A as well as the timing of the fall onset of destratification. This destratification will inject nutrients into the euphotic zone and stimulate the fall bloom. The portion of density stratification due to salinity was computed from the coefficient of haline contraction and the depth gradient in salinity (Figure 6D). It demonstrates that the onset of the spring bloom is determined by the timing of the springtime freshening of the surface layer. Unfortunately, the 1m sensor that measures temperature and salinity malfunctioned April – October 2020, Dec 2020 – June 2021, and after August 2021 so stratification cannot be computed during those intervals.

Temporal patterns in phytoplankton community composition. The FL3-WB three-excitation single emission chlorophyll fluorometer, yields time series of the intensity of the chlorophyll fluorescence in response to each excitation wavelength (color of the instrument LED flash that stimulates fluorescence). The fluorescence response to these flashes is proportional to the amount of light absorbed at that wavelength, and therefore the relative concentrations of specific pigments in the phytoplankton. Pigmentation is generally taxonomically distinct. Thus, variations in the fluorescence response to different colors provides qualitative indices for phytoplankton community composition. Fluorescence ratios, once corrected for non-photochemical quenching as carried out during data processing (step 5), are comparable to pigment absorption ratios. The power of the ratios analysis is that it removes the impact of biomass and represents solely pigmentation differences. Raw fluorescence for each channel is calibrated to the diatom *Thalassiosira pseudonana*, thus ratio values of 1.0 indicate diatom domination. Variations from 1.0 indicate variations in pigment composition relative to the diatom signal (Proctor and Roesler, 2010; Thibodeau et al. 2014).

The evolution of phytoplankton groups since 2016 suggests that when there is a bloom (high values in Figure 7A and spring and fall months in Figure 7B), the ratios are both close to 1, indicating diatom dominance. The non-bloom values include distinct clusters of points associated with different phytoplankton groups (circles in Figure 7 and values in Table 2). The seasonal evolution between these groups exhibits uniformity from year to year with the progression from spring and fall Diatom blooms to Dinoflagellates to Chlorophytes (green alga) and Haptophytes (including Coccolithophores). Early winter has Cyanobacteria (blue-green algae such as Synechococcus) and Cryptophytes. The community structure for 2021, was different from that observed in previous years, with a lack of chlorophytes and cyanobacteria,

but presence of diatoms, dinoflagellates, cryptophytes and haptophytes. The higher-than-typical summer bloom in July and August appears to be dominated by diatoms.

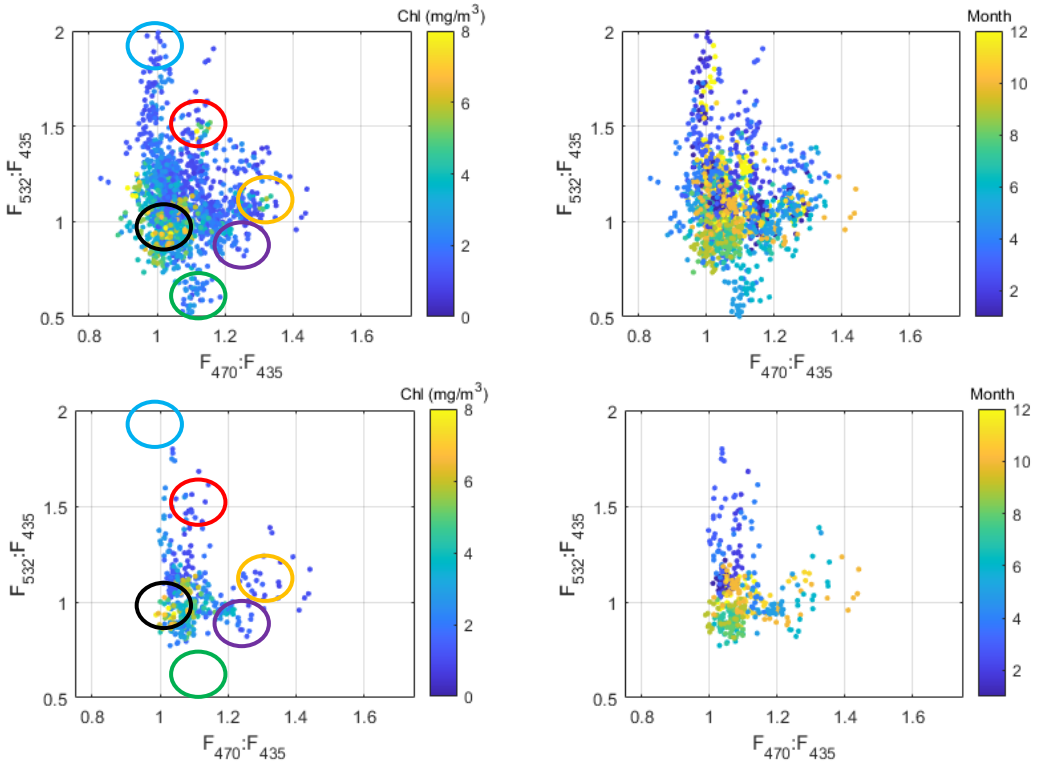


Figure 7. Fluorescence ratio-ratio display of the entire time series (top panel) and for 2020-21 sampling (deployments A0143 and A0144; bottom panel) of daily median values of fluorescence measured at mooring A with the WETLabs FL3-WB multichannel fluorometer. Data points are color-coded by chlorophyll concentration (left panel) and month (right panel). Circles indicate observed clusters associated with specific phytoplankton classes, values of which are presented in Table 2: Chlorophytes (green), Haptophytes (purple), Diatoms (black), Dinoflagellates (orange), Cryptophytes (red), Cyanobacteria (cyan).

Using these results to interpret the ratio-ratio space inhabited by the observations yields a repeatable sequence over the entire time series but also the opportunity to observe inter-annual variations in community structure. The optical evidence is intriguing but would certainly benefit from validation with either high performance liquid chromatography (HPLC) pigment analysis such as that performed by Kramer and Siegel (2019) on global data sets (including Harpswell Sound in eastern Casco Bay, Maine), or by imaging-in-flow cytometry (Kalmback et al. 2017). Both of these analyses could be provided by the Bowdoin research team, as part of a future augmentation of the program, if samples from the monthly surveys were provided.

Table 2. Fluorescence ratio clusters observed in the timeseries of FL3-WB multichannel fluorometer.

Phytoplankton group	**F532:F440**	**F470:F440**
Chlorophytes	0.5	1.1
Haptophytes	0.8	1.3
Diatoms	1.0	1.0
Dinoflagellates	1.1	1.3
Cryptophytes	1.5	1.1
Cyanobacteria	2.0	1.0

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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	2005-2020	
2	Month	1-12	
3	Day	0-31	
4	Hour	0-25	
5	Minute	0-60	
6	Second	0-60	
7	Date.Time	732607 – 738462	MATLAB® format, decimal local standard time (EST)
8	Raw Fchl	-3.42 – 230.91	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	-1.58 - 45.19	Values corrected (Carberry et al. 2019)
16	Flag_SVO	0, 1	Single value outlier
17	Fchl_corr_SVO	NaN	Values removed
18	Flag_MDL1	0, 1	< - Method detection level (MDL)
19	Flag_MDL2	0, 1	-MDL to 0
20	Flag_MDL3	0, 1	0 to +MDL
21	Fchl_corr	-0.04 to 29.47 /NaN	Cumulative removal/correction
22	Deployment	15 – 44	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	2005-2021	
2	Month	1-12	
3	Day	0-31	
4	Hour	0-25	
5	Minute	0-60	
6	Second	0-60	
7	Date.Time	732607 - 738462	MATLAB® format, decimal local standard time (EST)
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_MDL1	0, 1	< - Method detection level (MDL)
17	Flag_MDL2	0, 1	-MDL to 0
18	Flag_MDL3	0, 1	0 to +MDL
19	Turb_corr	-0.05 to 9.81 /NaN	Cumulative removal/correction
20	Deployment	15 - 44	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	2005-2021	
2	Month	1-12	
3	Day	0-31	
4	Hour	0-25	
5	Minute	0-60	
6	Second	0-60	
7	Date.Time	732607 - 738462	MATLAB® format, decimal local standard time (EST)
8-14	Raw Ed(7)	-33.32 - 240.31	
15	Flag_Offset	0, 1	
16-22	Ed(7)_corr_offset		Corrected for spectral and intersensor 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_MDL1	0, 1	< - Method detection level (MDL)
33	Flag_MDL2	0, 1	-MDL to 0
34	Flag_MDL3	0, 1	0 to +MDL
35	Flag Cal	0, 1	Indicates multiplicative scaling
36-42	Ed(7)_final	-0.05 – 229.45/NaN	Cumulative removal/correction
43	Deployment	15 – 44	Deployment number
44	OCI_507_SN	001-9999	OCI 507 sensor serial number

Table A4. List of submitted data arrays (.mat files) for chlorophyll fluorescence (from FLNTU sensor and each of the three channels of the F3WB sensor), turbidity, spectral irradiance, and central wavelengths of irradiance sensor.

Array Name	**Description**	**Units**	**Array size (row x columns)**	**Format**
H_Chl H_Chl_43 H_Chl_44	hourly chlorophyll fluorescence, FLNTU for full time series and each deployment	mg/m3	6085x23 3322x23	Table A1
H_NTU_43 H_NTU_44	hourly turbidity from FLNTU for full time series and each deployment	NTU	6085x21 3322x21	Table A2
H_F1 H_F1_43 H_F1_44	Hourly chlorophyll fluorescence response from 435 nm excitation (F3WB) for full time series and each deployment	mg/m3	6085x23 3322x23	Table A1
H_F2 H_F2_43 H_F2_44	Hourly chlorophyll fluorescence response from 470 nm excitation (F3WB) for full time series and each deployment	mg/m3	6085x23 3322x23	Table A1
H_F3 H_F3_43 H_F3_44	Hourly chlorophyll fluorescence response from 532 nm excitation (F3WB) for full time series and each deployment	mg/m3	6085x23 3322x23	Table A1
H_ED H_ED_43 H_ED_44	Hourly spectral irradiance, 7 channels for full time series and each deployment	μW/cm2/nm	6085x44 3322x44	Table A3
H_ED_43_wave H_ED_44_wave	Irradiance central wavelength	nm	7x1 7x1	n/a

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