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Gulf of Maine Water Resources

Assessing the Use of NASA Earth Observations for Identifying Harmful Algal
Blooms of *Pseudo-nitzschia* in the Gulf of Maine

DEVELOP Technical Report

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Abstract

The Gulf of Maine has a history of harmful algal blooms (HABs) that have been increasing in frequency and intensity in recent years, raising concerns in the community. Specifically, the *Pseudo-nitzschia* genus possesses harmful toxins that can induce food-borne illnesses and infect humans through ambient water. We observed *in-situ* data from known 2016 and 2020 *Pseudo-nitzschia* blooms as case studies to test the feasibility of using satellite data to track bloom events. In order to map the frequency and distribution of *Pseudo-nitzschia* bloom events, we used satellite data from the Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) and Sentinel-3 Ocean and Land Colour Instrument (OLCI). We utilized Earth observation data to calculate normalized fluorescence line height (nFLH) and absorption by phytoplankton (aph443), which are satellite products that more accurately depict phytoplankton reflectance. We compared these products with *in-situ* observations in order to analyze ocean color differences and distinguish diatomic algal particles from other organic and inorganic particles.

Keywords

harmful algal blooms, remote sensing, *Pseudo-nitzschia*, diatoms, normalized fluorescence line height, absorption by phytoplankton

1. Introduction

Global interest in harmful algal blooms (HABs) has been increasing with intensified monitoring efforts associated with increased aquaculture production (Hallegraeff et al., 2021). HABs are defined as rapid algal growth that produce toxic or harmful effects on humans and marine life. The Gulf of Maine is home to many fisheries and shellfisheries that have recently been shut down due to frequent HAB events, leading to an increase in HAB monitoring in this region. Researchers have predicted that for the Gulf of Maine, HAB events and algal species composition will likely change and intensify (Clark et al., 2019; Clark et al., 2022; Seto, 2018) as the Gulf of Maine has been continuously warming over the last five decades (Seidov, Nishonov, and Parsons, 2021).

One such species of concern is the *Pseudo-nitzschia*. This genus is a diatom that can produce domoic acid, a neurotoxin that can cause Domoic Acid Poisoning (DAP) upon consumption of contaminated shellfish or through exposure to ambient water. Understanding the origin and migration of HABs such as those brought on by *Pseudo-nitzschia* is crucial to proactively organize public health measures and keep communities and coastal habitats safe. Shellfish and fish toxicity through HABs also have a particularly strong impact on coastal New England economies, as shell-fishing and fishing contribute to the primary income of many communities around the Gulf of Maine. Industries such as oyster farming can be impacted by just one HAB event for many years due to the cyclical nature of shellfish production.

Compared to traditional *in-situ* point observations, remote sensing has the potential for large-scale, real-time, and long-term monitoring of HABs (Shen et al., 2012). Remote sensing research specific to the Gulf of Maine has shown promise in tracking and quantifying HABs and the potential to predict such events. For example, Li and He (2014) utilized MODIS sea surface temperature (SST) and chlorophyll-a (Chl-a) data, in combination with *in-situ* data, to characterize mean spatial and temporal patterns of SST and Chl-a in the Gulf of Maine. The two discrete HAB events of *Pseudo-nitzschia* in 2016 and 2020 are optimal case studies to utilize remote sensing imagery and *in-situ* data to test the feasibility of using satellite Earth observations to identify, track, and classify *Pseudo-nitzschia* HABs. The bloom event in 2016 was the first intensely toxic *Pseudo-nitzschia* event in the Gulf of Maine, prompting more thorough monitoring of algal constituents in the region. Algal blooms are visible through ocean color imagery as the high concentration of cells impact the reflectance of bands collected by the Sentinel-3 OLCI and Aqua MODIS sensors. To identify the discrete bloom events, we utilized MODIS data due to past research success with this sensor, in combination with Sentinel-3 data because of its enhanced spatial resolution.

Principle remote sensing techniques for detecting HABs include interpretation of discoloration, spectral analysis, and oceanographic parameters retrieval (Shen et al., 2012). Despite this, one limitation to using remote sensing imagery to detect algal blooms is differentiating between sediment and algal concentrations in the water column and distinguishing unique algal species and genera. The MODIS satellite-based sensor records normalized fluorescence line height (nFLH) and has been advantageous in detecting various blooms in waters rich with colored dissolved organic matter (Hu and Feng, 2016). Even so, false positive bloom interpretations can occur because MODIS nFLH is sensitive to elevated sediment concentrations that can result from winds and shallow waters.

Sentinel-3 OLCI provides satellite-derived Inherent Optical Properties (IOP) products that can characterize constituents in water bodies using algorithms consistent with the OLCI spectral bands. Among the IOP products is absorption coefficient due to phytoplankton at 433 nm (aph433), which can be used in conjunction with nFLH to further validate the presence of a bloom. Assuming that the 2016 and 2020 *Pseudo-nitzschia* blooms in the Gulf of Maine can be retrospectively identified, there is the possibility of distinguishing unique spectral signatures for algal genera (Zhao et al. 2007) and diatoms from other phytoplankton (Sathyendranath et al., 2004).

2. Methods

2.1 Study Area and Period

Our study area was the Gulf of Maine, Buzzard's Bay, and Nantucket Sound. The Gulf of Maine covers 93,000 km² of water and 12,000 km of coastline from Cape Cod, Massachusetts, to the Bay of Fundy, Canada. Buzzard's Bay and the Nantucket Sound are both located directly south of Massachusetts and cover 650 km² and 1920 km², respectively. We selected this region due to the emerging increase of harmful *Pseudo-nitzschia* blooms, rapidly changing oceanic conditions, and the presence of accessible *in-situ* data in this region.



Fig. 1. Study area map created in ArcGIS Pro. Image Basemap Credit: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

We focused on the 2016 and 2020 *Pseudo-nitzschia* bloom events and gathered images from August to December. This study period was chosen because of the large-scale impacts of the blooms, confirmed by ground observations, which are typically present in the late summer and fall. Ground observations, provided by Woods Hole Oceanographic Institution (WHOI), were most complete and accurate in their *Pseudo-nitzschia* concentration recordings throughout the 2016 and 2020 bloom events. According to WHOI and their ground

observations, the 2016 bloom occurred earlier in the year, around August to October, with high concentrations of *Pseudo-nitzschia* at Martha's Vineyard. The 2020 bloom occurred later in the year, around October to December, with high concentrations of *Pseudo-nitzschia* near Harpswell, Maine.

2.2 Data Acquisition

2.2.1 Sentinel-3 OLCI detection

Bands generated by Sentinel-3 from NASA's OceanColor Web have a spatial resolution of 300 meters and cover 1270-kilometer swaths, achieving full Earth coverage every four days. Sentinel-3 imagery was processed through SeaDAS, a NASA-generated software specializing in processing ocean color data. We used georeferenced Level 2 images from August to December of 2016 and 2020.

We acquired both Ocean Color (OC) and IOP files generated by Sentinel-3 from NASA's OceanColor Web. We used the IOP files for their mathematically derived bands that more specifically visualized algal blooms. For our analysis of the OC file, we used the remote sensing reflectance (R_{rs}) bands and interpolated select bands for the nFLH product, which allowed us to improve distinction between reflectance due to algae and reflectance due to other particles in the water (i.e., substrate). For our analysis of the IOP file, we used the absorption coefficient due to phytoplankton at 443 nanometers (aph443), which corrects sensor data to reduce absorption caused by inorganic matter and other non-algal organic matter. This product measures the absorption of pigments within phytoplankton and functioned as a way to observe the presence of algal blooms across multiple images.

2.2.2 Aqua MODIS Detection

The Aqua MODIS sensor generates 36 bands and images the entire surface of the Earth every 1 to 2 days at spatial resolutions of 1000 meters, 500 meters, and 250 meters, depending on the band. We processed Level 2 Aqua MODIS imagery from NASA's OceanColor Web in SeaDAS. We used the OC file generated by MODIS and focused specifically on the nFLH band. Because the Aqua MODIS sensor has a lower resolution than the Sentinel-3 OLCI sensor, MODIS data was not primarily used in further analyses and functioned as a way to preliminarily observe HABs. MODIS was also useful in providing imagery when Sentinel-3 data was unusable due to cloud cover or partial spatial extent, as the Aqua satellite images Earth's surface twice as frequently as Sentinel-3.

2.2.3 In-situ Data

We used select datasets from WHOI's Imaging FlowCytobots (IFCBs) for reliable *in-situ* data of the *Pseudo-nitzschia* genus. Data from WHOI's IFCB database was exported as a file with a table of all the samples collected, specified by volume (mL) analyzed, sample time, latitude and longitude coordinates, and a unique process identification (PID) — an identifier for each individual bin of images.



Fig. 2. Stationary IFCB *in-situ* data locations. Image Basemap Credit: Esri, HERE, Garmin, FAO, NOAA, USGS, OpenStreetMap contributors, and the GIS User Community

We processed *in-situ* data for the observed September to December bloom events of 2016 and 2020. As there were gaps in *in-situ* data recordings, along with gaps in usable satellite imagery, we processed *in-situ* data for the time intervals when our datasets aligned. Two stationary coastal monitoring sensors, Martha's Vineyard Coastal Observatory (MVCO), Massachusetts and Harpswell, Maine, were used for the 2016 and 2020 *in-situ* data comparison respectively. MVCO is shown by the purple marker on Fig. 2, and Harpswell by the red marker.

2.3 Data Analysis

2.3.1 Processing Satellite Data

In order to process both Sentinel-3 OLCI and Aqua MODIS data, we cropped viable daily imagery, where our region of interest had roughly greater than 20% coverage, to our study area and reprojected them to the World Geodetic System 1984 (WGS 84) geographic latitude and longitude in SeaDAS using MATLAB. For our analysis of the Sentinel-3 OC file, we conducted a mathematical interpolation in MATLAB to compute nFLH measurements, which reduce the visual representation of reflectance not caused by phytoplankton. In order to calculate nFLH, we used the following equation and Rrs bands directly sensed by Sentinel-3 to interpolate for bands in the equation:

$$nFLH = 47.4890 \times \left(Rrs681 - \left(\left(\frac{28}{44} \right) \times Rrs665 + \left(\frac{16}{44} \right) \times Rrs709 \right) \right)$$

The nFLH calculation uses the empirical value 47.4890, Rrs(681 nanometers), Rrs(665 nanometers), Rrs(709 nanometers), and a spectral interpolation of Rrs(693 nanometers). As Rrs(693 nanometers) was not a direct product in the Sentinel-3 OC files, we interpolated the Rrs value using the closest smaller and larger bands, Rrs(665 nanometers) and Rrs(709 nanometers) respectively. High absorption typically occurs at Rrs(681) when there is a large quantity of organic matter. Using the processed daily NetCDF files, we then utilized the Level-3 binning function in SeaDAS to create weekly and monthly composite imagery aggregated by average aph443 and average nFLH at a spatial resolution of 2 kilometers per pixel. Weekly composite imagery offered more complete images and provided finer temporal representation, which is important as algal blooms have the propensity to change and migrate quickly. All timeseries images were saved as NetCDF files and exported as full scene, full resolution Portable Network Graphics from SeaDAS. For aph443 images, we used the

anomalies2_universal color palette and set the color range from 0 to 0.1. For nFLH images, we used the reversed deep color palette and set the color range from 0 to 0.06. All images used gray land and coastal masks and all missing data, i.e., from cloud coverage and incomplete swath coverage, were classified as the color white.

To confirm that perceived aph433 and nFLH bloom reflectance were caused by diatoms, we used a diatom distinction algorithm provided by Emmanuel Devred, a research scientist with Fisheries and Oceans Canada. The algorithm was generated based on reflectance ratio curves, calculated based on *in-situ* data from MVCO and tested on *in-situ* data from Harpswell. We found it unnecessary to reparametrize the algorithm because, although it was created outside of our project, it was calibrated using the same *in-situ* datasets and in our region of interest. We applied this algorithm to our satellite imagery and produced images that distinguished if reflectance in each pixel was caused by a diatom. The algorithm outputted a 0 if there was no or little diatom-caused reflectance, and a 1 if the reflectance was in large part caused by a diatom.

2.3.2 Comparison with *in-situ* data

To calculate a concentration metric for our *in-situ* data, we extracted the PIDs in a dataset and generated files for individual classifier results. The class scores file for each bin is a matrix of normalized class scores for each phytoplankton type. The dominant phytoplankton type of a bin was determined using the class score, if that phytoplankton type had the maximum score and if that score was greater than 0.8, in order to reduce false positive identifications. Using the normalized class score and total image count from the original data set, the concentration was calculated for samples where the dominant phytoplankton genus was *Pseudo-nitzschia*.

We calculated daily average concentrations for all three *in-situ* datasets — MVCO in 2016 and 2020 and Harpswell in 2020. We created time series plots using the calculated average concentrations, focusing on MVCO in 2016 and Harpswell in 2020 because the bloom was at its largest at these distinct locations and times. Then, we matched the *in-situ* data dates with the viable Sentinel-3 imagery. We collected aph443 and nFLH values for the same latitude and longitude coordinates of the two stationary coastal monitoring sensors, using the Sentinel-3 imagery.

3. Results

To visualize trends of the 2016 and 2020 *Pseudo-nitzschia* blooms across the Gulf of Maine, we created timeseries plots of our remote sensing products of interest — aph443 and nFLH. We mainly looked at weekly composite imagery because algal bloom can grow and migrate rapidly. In the 2016 aph443 and nFLH time series (Fig. 3, Fig. 4), a large algal bloom appeared to be present from August to the end of October, beginning in the Bay of Fundy and making landfall in high concentrations around Martha’s Vineyard in late October and the first week of November.

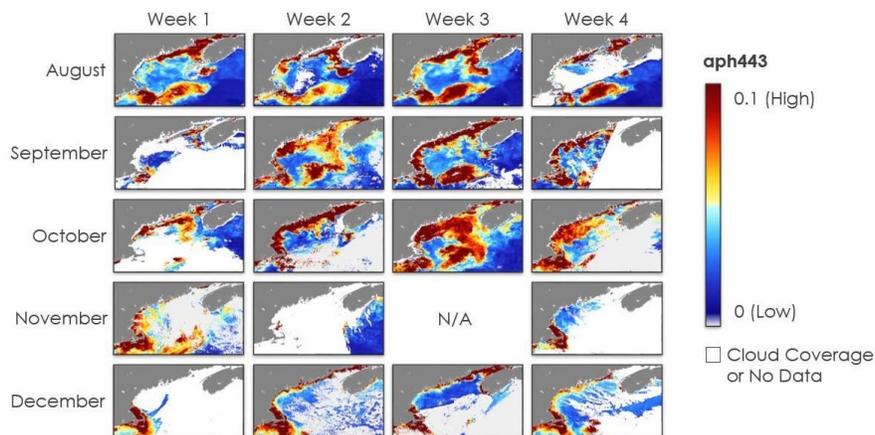


Fig. 3. Weekly aph443 composite time series of the 2016 *Pseudo-nitzschia* bloom from August to December.

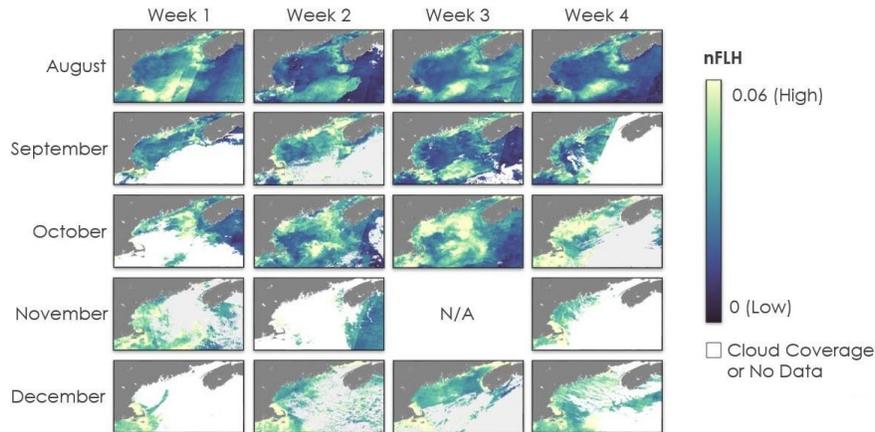


Fig. 4. Weekly nFLH composite time series of the 2016 *Pseudo-nitzschia* bloom from August to December.

The 2020 *Pseudo-nitzschia* bloom had later expansion, around October and November. Based on the 2020 aph443 time series (Fig. 5), the bloom expanded in the second week of October and we expected to see a similar pattern throughout November and December but satellite imagery was sparse. The 2020 nFLH imagery was more complete (Fig. 6), due to the measurement being calculated via interpolation, thus the bloom expansion in October and November is more clearly visualized.

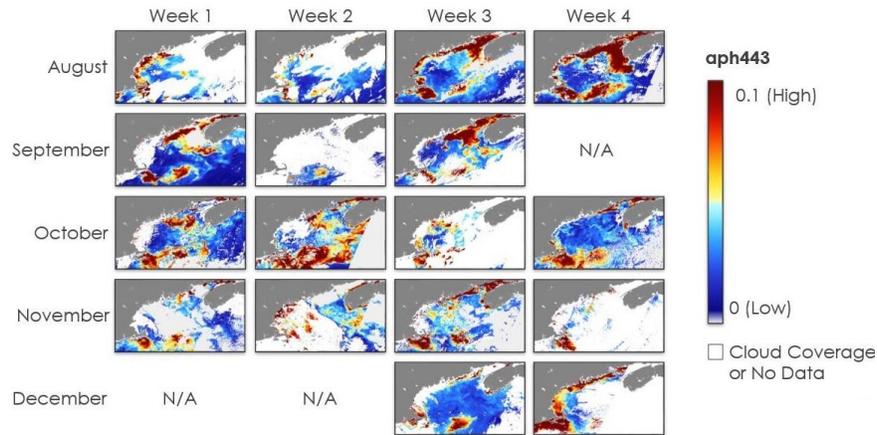


Fig. 5. Weekly aph443 composite time series of the 2020 *Pseudo-nitzschia* bloom from August to December.

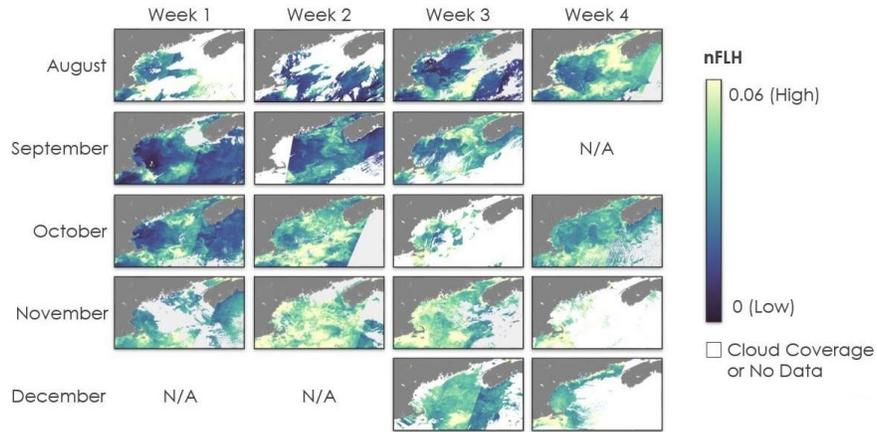


Fig. 6. Weekly aph443 composite time series of the 2020 *Pseudo-nitzschia* bloom from August to December.

To visually compare *in-situ* data with the remote sensing products, we created timeseries plots of calculated concentration for 2016 and 2020. In the 2016 plot (Fig. 7), the concentration peaks in November, and in 2020 (Fig. 8), the concentration peaks in late October and early November. The Harpswell sensor did not collect data during the month of September, which is why Fig. 8 has a different time frame than Fig. 7.

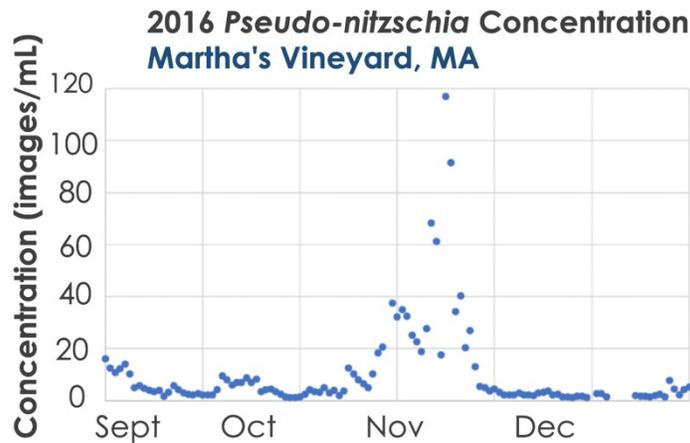


Fig. 7. Timeseries of *Pseudo-nitzschia* Concentration in 2016 at Martha's Vineyard, MA.

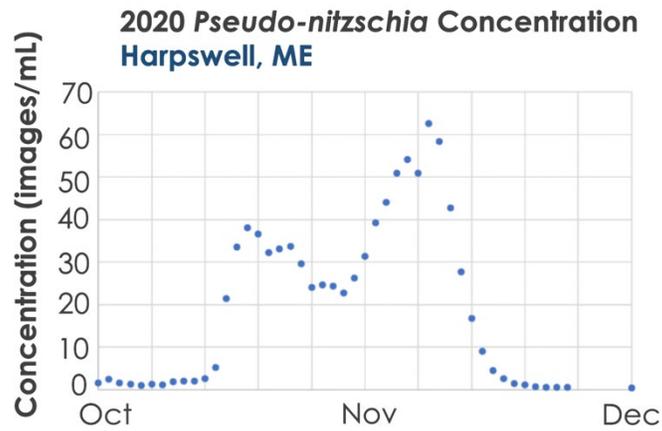


Fig. 8. Timeseries of *Pseudo-nitzschia* Concentration in 2020 at Harpswell, ME.

Diatom calculations for 2016 and 2020 had mixed agreement with the aph443 and nFLH imagery. In both years, the number of diatom-dominated pixels increased as time progressed, which aligned with the aph443 and nFLH imagery. In some cases, the diatoms appeared to be located in different places than areas of high aph443 and nFLH reflectance.

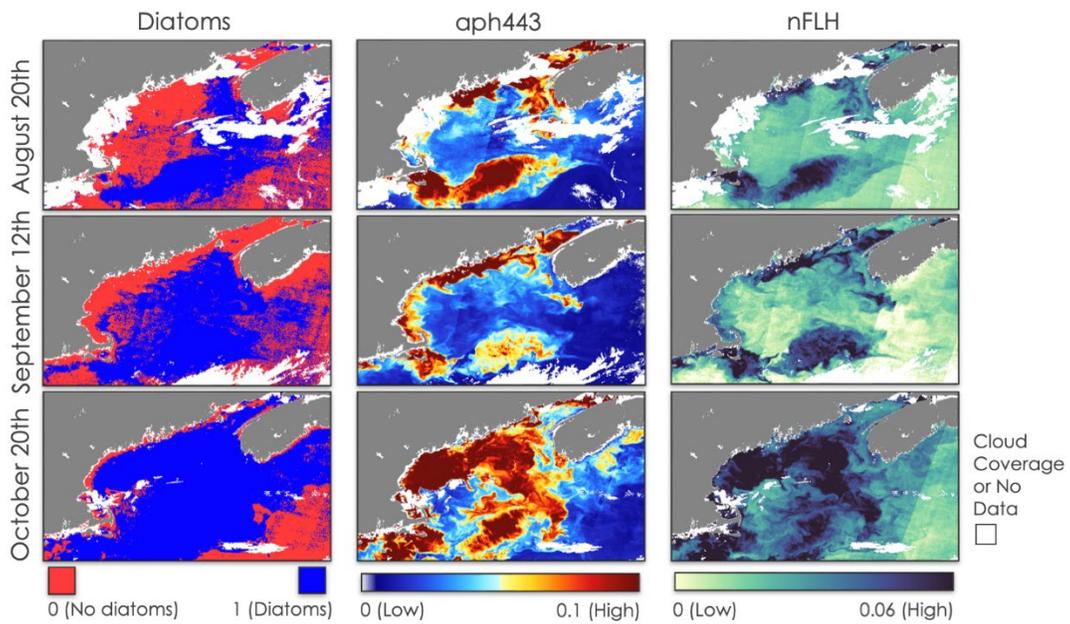


Fig. 9. Selected daily diatom, aph443, and nFLH comparison for 2016.

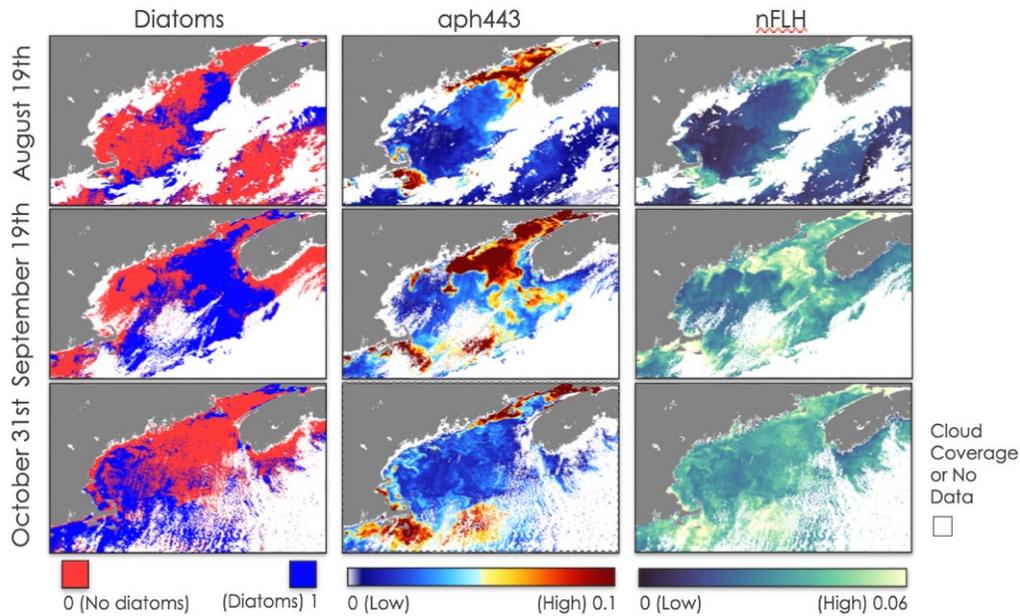


Fig. 10. Selected daily diatom, aph443 and nFLH comparison for 2020.

4. Discussion

4.1 Analysis of Results

In regard to validating our satellite imagery, we found that the remotely-sensed data appeared to align with the *in-situ* data, indicating that Earth observations could be used to track *Pseudo-nitzschia* bloom events in the Gulf of Maine. However, our aph433 and nFLH satellite measurements visualized broader reflectance due to phytoplankton, thus our analyses required further specification of reflectance due to *Pseudo-nitzschia*. For our statistical visualizations, concentration peaked in November 2016 and peaked in late October and early November of 2020, confirming the general *Pseudo-nitzschia* trends we observed in our satellite imagery.

The outputted diatom images, produced by the algorithm, had varied success. There was greater agreement in open water regions, compared to coastal areas, possibly due to higher interference from increased sediments and other colored dissolved organic matter near the shore. In Fig. 9, for example, the aph443 and nFLH imagery indicated a large bloom in the Bay of Fundy, but the diatom algorithm did not indicate diatoms. In September and October (Fig. 10), the three products are in better agreement as the bloom migrated into deeper, clearer waters. As Martha's Vineyard and Harpswell are on the coast, we could not directly cross-reference the *in-situ* data with our diatom products.

4.2 Limitations

While our study presented an important investigation into the use of remote sensing to track algal blooms in the Gulf of Maine, we encountered some limitations in the process. Using satellite imagery limited the number of viable days within our time frame for data analysis, as neither of the satellites we used imaged the entire Gulf of Maine daily. This frequently resulted in partial images or days when the Gulf of Maine was not imaged at all. Additionally, satellites were not able to measure reflectance through cloud cover, which meant that days with heavy cloud cover were also not able to be analyzed. For days with viable data, we were limited in our analysis when specifying reflectance due to algae, as MODIS and OLCI were unable to completely distinguish between reflectance caused by phytoplankton from other organic cells and oceanic detritus. While we used multiple algorithms and equations to attempt to isolate diatom reflectance, there was inherent uncertainty introduced by interpolating Rrs bands for determining the cause of reflectance in a given image. We used the *in-situ* data as a way to confirm our remote sensing results, but our satellite images covered a much broader spatial extent than the *in-situ* data. Finally, because increased monitoring of algae in the Gulf of Maine started in response to the toxic 2016 *Pseudo-nitzschia* bloom, we were limited by the available *in-situ* data.

4.3 Future Work

While our project specifically focused on the 2016 and 2020 *Pseudo-nitzschia* bloom events, our results are promising for future use of satellite imagery in tracking other HABs in the Gulf of Maine. Ergo, many avenues for future research and the implementation of Earth observations are possible. A future goal of our work is to be integrated into WHOI's open-source algal bloom platform, the HABHub, so that remotely sensed imagery depicting blooms can be configured as a layer. Additionally, expanding the time range and genus or species of focus is a worthwhile continuation of our work. Because we were largely testing the feasibility of using satellite imagery to confirm a known *Pseudo-nitzschia* bloom, our processes could be replicated to retrospectively confirm bloom development and migration in other years in the Gulf of Maine. It would also be beneficial to expand the region of interest as currents from the Scotian Shelf have the capacity to transport algal species into the Gulf of Maine, which is particularly important within the context of warming waters as algal composition and sea surface temperatures potentially change. NASA's Plankton, Aerosol, Cloud and ocean Ecosystems (PACE) satellite mission is scheduled to launch in 2024, which will advance satellite observations of global ocean color and biogeochemistry, providing us much more robust ocean color products that can be used for detailed tracking of future harmful algal blooms. In the future, we hope to explore potential sources of the misalignment in our diatom images. One possible method would be to produce 8-day composite diatom images and determine if greater agreement exists when comparing diatom presence and aph433 and nFLH satellite products.

5. Conclusion

We validated that Sentinel-3 products are a viable method of tracking *Pseudo-nitzschia* blooms in the Gulf of Maine by comparing remote sensing products with *in-situ* data and corroborating the presence of diatoms in satellite imagery. Generally, the diatom distinction algorithm had high agreement in offshore, open water regions and is worth further exploration. This study can support organizations focused on managing water resources in the Gulf of Maine, such as with their monitoring of *Pseudo-nitzschia* bloom events, and support communities that economically rely on the region.

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Glossary

Earth observations – Satellites and sensors that collect information about the Earth's physical, chemical, and biological systems over space and time

ESA – European Space Agency

HAB – Harmful algal bloom

HABHub – WHOI *in-situ* open-source data portal for regional integration and historic real time sharing of phytoplankton monitoring, shellfish toxicity and closures, and sensor data collected by IFCBs

IFCBs – Imaging FlowCytobots, deployed by WHOI to take regular measurements and microscopic photographs of algae in the Gulf of Maine

MODIS – Moderate Resolution Imaging Spectroradiometer. Hyperspectral satellite-based sensor with 36 bands

NOAA – National Oceanic and Atmospheric Administration

Rrs – Remote sensing reflectance

SeaDAS – Software produced by NASA for the processing, display, analysis, and quality control of ocean color data

Sentinel-3 – European Space Agency Earth observation satellite dedicated to oceanography

WHOI – Woods Hole Oceanographic Institution

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