Future Projections of Phytoplankton Dynamics and Marine Harmful Algal Bloom Events Due to Climate Change: New Jersey's Changing Coastal Shelf Ecosystem

Authors and Affiliation:

Austin Grubb
Rutgers University, Eagleton Graduate Fellow
Division of Science and Research
&
Nicholas A. Procopio, Ph.D.
Division of Science and Research

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State of New Jersey
Phil Murphy, Governor

Department of Environmental Protection
Shawn M. LaTourette, Commissioner

Division of Science & Research
Nicholas A. Procopio, Ph.D., Director

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Executive Summary

New Jersey's coast, encompassed within the Mid-Atlantic Bight (MAB), is characterized by physical and seasonal dynamics that drive phytoplankton growth, abundance, and composition. Phytoplankton are generally highest in abundance during the fall bloom, when the temperature-induced stratification breaks down stimulating mixing and increasing nutrient concentrations in surface waters. The MAB is one of the fastest warming regions of the ocean, which has coincided with small decreases in primary productivity and shifts in the timing of seasonal transitions. The relative contribution of larger groups (e.g., diatoms) to the phytoplankton community has decreased, whereas the relative contribution of smaller groups (e.g., dinoflagellates, green algae) has increased. These trends, including the variation in growth patterns, are likely to continue as climate change progresses. These variations may result in the increase in the harmful overgrowth of the phytoplankton population, known as a harmful algal bloom (HABs). Harmful algal blooms have occurred in NJ marine waters for decades with the potential to negatively impact New Jersey residents and ecosystems. While there is a lack of short- and intermediate-terms studies investigating the future of HABs in the MAB, future conditions associated with climate change will likely increase the potential for marine HAB events.

Introduction

New Jersey's coast is encompassed within the Mid-Atlantic Bight (MAB), which extends north to south from Cape Cod, Massachusetts to Cape Hatteras, North Carolina and east to west from the U.S. East Coast to the end of the continental shelf. The MAB is a relatively productive continental shelf that provides habitat for a wide variety of fauna and flora, including commercially important species (e.g., sea scallop, black sea bass, and summer flounder), endangered and federally protected whales (e.g., fin, humpback, critically endangered North Atlantic right whales) and sea turtles (e.g., loggerhead, Kemp's ridley, leatherback, hawksbill, and green), and hard and soft corals (NOAA 2025). Like many marine ecosystems, the biodiversity of the MAB's fauna is supported by phytoplankton, which form the base of many marine food webs. However, the phytoplankton can include species that can produce toxins that are harmful to marine, and even human, life.

The MAB has distinct seasonal stratification dynamics that regulate the availability of nutrients and biological production of the region. However, the MAB is rapidly warming due to climate change (Saba et al 2016), which is altering the well-documented seasonal dynamics of the MAB. Warming of the MAB is likely to impact phytoplankton communities and, thus, the rest of the food web and ecosystem in the MAB. Warming is also causing shifts in seasonal and ecosystem dynamics in many oceanic systems (Poloczanska et al. 2016), including the Gulf of Maine (Thomas et al. 2017, Staudinger et al. 2019, Friedland et al. 2020a), the Gulf of Mexico (Li et al. 2022), and the Caribbean Sea (Chollett et al. 2012, Li et al. 2022).

Overall, this review provides a comprehensive overview of the interactions between physical oceanographic processes and phytoplankton communities in the MAB, with a focus on the effects of climate change and the implications for shifting phytoplankton dynamics and potential for increased toxin-rich harmful algal blooms.

Physical Dynamics of the Mid-Atlantic Bight

New Jersey's coast is part of the U.S. Northeast continental Shelf ecosystem (NES), extending from the Gulf of Maine to Cape Hatteras, North Carolina, and specifically the Mid-Atlantic Bight (MAB), which encompasses the southern half of the NES, from Cape Cod, Massachusetts to Cape Hatteras, North Carolina. The MAB has distinct seasonal dynamics that regulate stratification, the availability of nutrients, and the biological production of the region. Stratification in the MAB is predominately temperature-driven, however intense freshwater input (i.e., strong storms, high river runoff) can also contribute to stratification dynamics.

Warming in the spring leads to stratification of shallow waters closest to the coast (i.e., nearshore), separating warmer surface water from deeper colder water. This cold bottom water is isolated from the surface by stratification, freshwater runoff, and reduced wind mixing, forming the "Cold Pool," which extends across the entire MAB (Houghton et al 1982, Lentz et al 2003). On average the Cold Pool represents 30% of the total volume of MAB shelf water (Glenn et al 2004, Houghton et al 1982, Pacheco 1988, Voynova et al 2013), and its cold waters are rich in nutrients needed for phytoplankton growth (Voynova et al 2013). The shelf continues warming throughout spring, leading to the entire shelf—including the deeper waters near and at the shelf break (i.e., offshore region)—becoming strongly stratified by late spring/early summer. Nearshore waters remain more strongly stratified than the offshore region due to freshwater input from the Hudson River (Schofield et al 2008).

The summer is characterized by strong and stable stratification throughout the MAB due to warm surface temperatures and freshwater runoff (Castelao et al 2010). Winds move the Cold Pool across the shelf throughout the summer. Southwesterly winds push warmer surface water offshore, bringing the Cold Pool closer to shore and leading to the upwelling of cold, nutrient rich waters to the surface (Miles et al 2021). Winds from the northeast result in the reverse. Warm surface waters close to shore will be pushed down (i.e., downwelling), pushing the Cold Pool towards the continental shelf break (Miles et al 2021). Summer winds are typically from the northeast or the southwest, pushing the Cold Pool back and forth across the shelf as the upwelling or downwelling conditions alternate (Miles et al 2021).

Stratification and the Cold Pool persist through late summer/early fall, when surface cooling and the increasing frequency of storms lead to the breakdown of stratification and mixing of surface waters with the Cold Pool (Schofield et al 2008, Chen et al 2018, Houghton et al 1982, Lentz 2017). The timing of the breakdown of stratification and the Cold Pool varies significantly each year (mid-September to November; Bigelow 1933, Chen 2018, Lentz 2017, Lentz et al. 2003, Pacheco 1988), as powerful storms (e.g., tropical storms and extra-tropical cyclones) can abruptly break down stratification (Glenn et al 2016, Seroka et al 2016) whereas high discharge from the Hudson River can promote stratification throughout September (Xu et al 2020).

Throughout the winter, surface waters of the MAB remain cold and are well mixed with deeper waters, moving nutrients throughout the water column. Any stratification is typically weak and due to freshwater input from coastal estuaries (Castelao et al 2010). Wind strength and storm frequencies impact how deep mixing occurs. The water column remains well-mixed until spring warming leads to stratification.

Phytoplankton Dynamics

Phytoplankton growth in the MAB is regulated by the seasonal stratification dynamics. At the end of winter, waters throughout the MAB are cool, well mixed, and rich in nutrients (Voynova et al 2013). In nearshore, shallow waters, phytoplankton abundance can remain high since neither nutrients nor light are limiting growth. Deep mixing in the offshore region limits phytoplankton growth by limiting cells' exposure to light. Stratification in the spring may lead to a phytoplankton bloom when phytoplankton abundance is high. Distinct spring blooms are not easily detectable close to shore as it can be difficult to distinguish between blooming conditions and high winter baseline levels of phytoplankton (Friedland et al 2015). Offshore near the shelf break, spring blooms are most common, as the onset of stratification eliminates light limitation in nutrient rich waters (Friedland et al 2015).

Primary productivity declines in the late spring/summer as stratification prevents nutrient rich water from the Cold Pool from replenishing nutrients that were depleted by phytoplankton uptake throughout the spring. Upwelling brings nutrients close to the surface near the coast, leading to periods of high growth and/or blooms in the summer. In late summer/early fall, breakdown of stratification tends to lead to the largest bloom of the year across the MAB, predominately occurring close to the coast (Ryan et al., 1999; Yoder et al., 2002; Xu et al., 2011, Friedland et al 2015). Nearshore fall/winter blooms can be responsible for approximately 63% of annual chlorophyll-*a* production (Ryan et al., 1999; Yoder et al., 2002; Xu et al., 2011). However, fall/winter blooms are not as frequent offshore near the shelf break since breakdown of stratification and deep mixing leads to light limitation (Xu et al 2011, Xu et al. 2013).

Phytoplankton community composition is largely driven by physical conditions (i.e., turbulence, temperature) and nutrient concentrations. Cooler, well-mixed, relatively turbulent, and nutrient-rich environments favor larger phytoplankton communities (e.g., diatoms), whereas warmer, stratified, calmer, and nutrient-depleted environments favor smaller phytoplankton communities (e.g., dinoflagellates, cyanobacteria; Margalef, 1978, Gilbert 2016). Thus, in the MAB, larger phytoplankton (e.g., diatoms) are more abundant and dominant during the spring and fall/winter blooms when mixing increases turbulence and nutrient concentrations near the surface. Smaller phytoplankton (e.g., cyanobacteria, dinoflagellates) dominate the late spring to early fall as the stable stratified water column is depleted in nutrients (Zang et al 2021).

Marine Phytoplankton Monitoring and Data Availability in New Jersey

Monitoring and Observational Data

The Bureau of Marine Water Management (BMWM) monitors phytoplankton in NJ marine waters and maintains a database of phytoplankton occurrence information since 2000 (hereafter BMWM database) and reviewed in 2023. The BMWM sampling plan changed in 2015, increasing the entries from an average of about 89 entries per year from 2000-2014 to an average of about 283 entries per year from 2015-2022 (Fig. 1). The BMWM comprises samples from 47 stations that are part of the phytoplankton sampling network, as well as other stations from other projects or as necessary/requested (Fig. 2a).

Among taxonomic groups, diatoms were reported as the dominant group in approximately 33% of all entries in the BMWM database, though nearly 39% of entries have the dominant taxa documented as 'sparse' (Fig. 3a, Table 1). After accounting for 'sparse' entries, diatoms are often the dominant group every season, however, they were most often reported to be dominant from Dec 1 to April 1 (Fig. 3b). Diatoms were followed by dinoflagellates, which were the dominant taxonomic group in about 13% of entries (Table 1). Dinoflagellates were most often dominant between April 1 and Dec 1 (Fig. 3b), reflecting their preference for warmer conditions. The remaining taxonomic groups were dominant in <5% of all entries in the BMWM database (Fig. 3b, Table 1).

This report also utilizes data for NJ from The Harmful Algal Event Database (HAEDAT), an international meta database of harmful algal bloom events, which contains records dating back to 1985 (Intergovernmental Oceanographic Commission of UNESCO 2023), allowing for the inclusion of data collected prior to 2000 in this review. Events are included as a 'HAEDAT event' when the event meets *at least one* of following the criteria (Intergovernmental Oceanographic Commission of UNESCO 2021):

a) water discoloration, scum or foam causing a socio-economic impact due to the presence of toxin producing or harmful microalgae;
b) precautionary closures of shellfish harvesting areas due to the presence of algal toxins and/or presence of potentially harmful microalgae;
c) biotoxin accumulation in seafood above levels considered safe for human consumption;
d) any event where humans, animals or other organisms are negatively affected by microalgae.

Harmful Algal Blooms

Harmful algal bloom (HAB) species include species of phytoplankton that produce toxins that endanger human health and species that are harmless to humans but can damage marine ecosystems and impact economically important fisheries (Anderson et al 2021). A multitude of environmental factors (i.e., temperature, stratification, acidification, irradiance, and nutrients) impact the formation of marine HAB blooms and make predicting HAB events challenging (Wells et al 2015).

Observations of HABs in NJ marine waters stretch back decades, predating the current BMWM phytoplankton sampling program. Multiple adverse fish and/or shellfish events have been documented since the 1960s. These events can often impact other marine organisms and are recorded in HAEDAT (Intergovernmental Oceanographic Commission of UNESCO 2023; Tables 2, 3a-c). A fish kill in 1968 was caused by a bloom of the dinoflagellate *Prorocentrum micans*. The dinoflagellate *Katodinium rotundatum* caused fish and shellfish kills in 1993 and 2000. A mixed bloom containing dinoflagellates (*K. rotundatum*, *Prorocentrum* spp.), diatoms (*Skeletonema costatum*, *Thalassiosira gravida*, *T. nordenskioldii*, *Cerataulina pelagica*, *Rhizosolenia delicatula*), Euglenids (*Eutreptia lanowii*), and other stramenopiles (*Olisthodiscus luteus*) in Raritan and Sandy Hook bays in 1995 led to fish kills that were attributed to low dissolved oxygen concentrations (Anderson et al 2021). Blooms of the brown tide (harmless to humans, damaging to marine life and ecosystems) alga *Aureococcus anophagefferens* were first documented in Barnegat Bay in 1985, continued to be frequently observed throughout the 1990s and early 2000s (Table 2; Anderson et al 2021), and was last documented as being dominant in NJ coastal waters in August 2010 (BMWM Database 2023). In 2017, a *Chattonella* spp. bloom led to a fish kill in Barnegat Bay (Anderson et al 2021).

A large bloom observed in the summer of 2005 was attributed to a freshwater plume that originated from the Hudson River after a 10-year flood event, driven by enhanced freshwater input from the spring thaw of snow and a series of precipitation events (Frazer et al 2006, Schofield et al 2013). The bloom was largest in the Hudson/Raritan estuary and was dominated by a diverse assemblage of diatoms. Toxic species (*Pseudonitzschia* spp. (diatoms) and *Dinophysis* spp. (dinoflagellates)) were detected in late June, but cell concentrations of these species were too low to be considered a toxic event (Heddendorf 2008). The coastal area near the Hudson/Raritan estuary had similar species composition, but there was a red tide bloom of the algae *Olisthodiscus luteus* in July and an 'extremely large' bloom of the diatom *Cerataulina pelagica* in early June (Table 3a). *Dinophysis* spp. was detected in June but below bloom or toxic concentrations (Heddendorf 2008).

In the summer of 2011, a large phytoplankton bloom occurred off the NJ coast, stretching from Sandy Hook to Cape May and across the continental shelf (Schofield et al 2012, Sha et al 2015). Chl-a concentrations were over an order of magnitude higher than the decadal mean of ocean color data. The bloom—stimulated by freshwater outflow from the Hudson River and wind-driven upwelling of nutrients—resulted in surface waters being supersaturated with oxygen, but the flux of organic matter to bottom waters led to stress-inducing oxygen saturation levels (<60%) for benthic communities. The bloom was largest in late August and was likely disrupted by Hurricane Irene at the end of August (Schofield et al 2012, Sha et al 2015). Closer to shore, diverse communities were documented in the north (offshore of Monmouth County), and green algae species, such as *Nannochloris* sp., were reported along the southern coast (offshore of Ocean and Cape May Counties; BMWM Database 2023). Separate analyses concluded that species of *Gymnodinium*, motile dinoflagellates that can produce toxins (Guiry and Guiry 2023), dominated the bloom farther offshore (Schofield et al 2012).

Notable Toxin-producing HAB Taxa

The BMWM has tracked occurrences of toxin-producing HAB taxa, including taxa that produce toxins that can lead to paralytic shellfish poisoning (PSP), diarrhetic shellfish poisoning (DSP), neurotoxic shellfish poisoning (NSP), and amnesic shellfish poisoning (ASP). *Pseudonitzschia* sp.––a genus of diatoms––were the most widely documented and distributed toxic taxa in NJ, having been observed in all coastal regions (Fig. 4-5). About half of *Pseudonitzschia* species are known to produce domoic acid, the toxin that causes ASP (Bates et al 2018). *Pseudonitzschia* has been reported along a wide range of water temperatures, throughout the year, but less so during the summer (June to Sepember; Fig. 6a, 7). *Pseudonitzschia* was also documented over a wide range of cell concentrations (Fig. 8). However, *P. brasiliana* and *P. delicatissima* were observed with higher median temperatures (21.10 and 13.59°C, respectively) and cell concentrations (1800 and 80 cells ml^{-1}, respectively) than *Pseudonitzschia* sp. (7.80°C and 40 cells ml^{-1}, respectively; Fig. 7-8).

Dinophysis sp.––a genus of dinoflagellates––were the second most documented toxin producing taxa and have been reported in most regions in NJ (Fig. 4-5). Both *Pseudonitzschia* sp. and *Dinophysis* sp. have been documented regularly since the start of the BMWM phytoplankton sampling program in 2000, but *Dinophysis* sp. has only been reported during warmer months (May to September; Fig. 6a) and has occurred at a higher median temperature (17.40°C) than *Pseudonitzschia* sp. (Fig. 7). The remaining toxic taxa—all dinoflagellates—have been documented less often (Fig. 4-5). *Alexandrium* sp. and *Prorocentrum lima* have only been reported in one and two instances, respectively, and only during the summer months when temperatures were >20°C (Fig. 6a, 7). However, other species of *Prorocentrum* were reported at a number of instances throughout the 1990s.

The genus *Karenia*—previously classified as *Gymnodinium*—consists of dinoflagellate species that are very toxic and lethal to marine life, with some producing brevetoxins that can lead to NSP in humans (Brand et al 2012). *Karenia brevis*—perhaps the most infamous species—is often responsible for toxic red tides in coastal Florida. *K. brevis* is widespread throughout the Gulf of Mexico, but blooms mostly occur in coastal Florida and Texas. However, they can spread to Florida's Atlantic coast, where they have the potential to be transported farther north by the Gulf Stream (Anderson et al 2021). The first report of *K. brevis* north of Cape Hatteras, North Carolina, occurred in Delaware in the late summer of 2007 (DNREC 2020). To date, only *K. mikimotoi* and *K. papilionacea* have been documented in NJ bays and coastal waters (Anderson et al 2021, Li et al 2019, BMWM Database 2023, Intergovernmental Oceanographic Commission of UNESCO 2023).

While the population of *K. mikimotoi* is thought to be cosmopolitan, blooms have been documented primarily in Europe and Asia, and none have been reported in North America as of 2018 (Brand et al 2012, Li et al 2019). However, *K. mikimotoi* in Europe was previously classified as *Gymnodinium aureolum*, which had recorded blooms in NJ and Long Island throughout the 1970s-1980s (Li et al 2019). Hansen et al (2003) reclassified *Gymnodinium aureolum* from Europe as *K. mikimotoi*, but the *G. aureolum* isolate from coastal waters of the eastern US was not reclassified so it is uncertain if the 1970-1980s blooms were *K. mikimotoi* (Li et al 2019). *K. mikimotoi* was most recently documented in NJ in mid-December 2017 in Raritan Bay, but at a low cell abundance (5 cells ml^{-1}; Fig. 6a, 8). Questions remain about how *K. mikimotoi* spreads, but it appears to be spread by near-shore currents instead of open ocean circulation (Li et al 2019). *K. mikimotoi* is adapted to survive at a wide range of light levels and temperatures (4-30°C), with blooms tending to occur over a narrower temperature range (13-22°C; Li et al 2019). Though it does not produce brevetoxins, PSP or DSP, *K. mikimotoi* produces other toxins that are very lethal to most fish and are also lethal to other organisms including some shellfish (Li et al 2019).

K. papilionacea also has a wide distribution in the Gulf of Mexico and along the Atlantic coast of the U.S. and has been found in as far north as Delaware and NJ (Brand et al 2012, Coyne et al 2015, Fowler et al 2015; BMWM Database 2023). Like *K. brevis*, *K. papilionacea* produces brevetoxins that can lead to NSP (Fowler et al 2015). A low observed cell abundance of *K. papilionacea* (20 cells ml^{-1}; Fig. 8) was reported in NJ in October 2016 at water temperatures of 16.7°C (Fig. 7). In late August to early September 2022, a larger bloom dominated by *K. papilionacea* occurred along the Atlantic coast, with documented temperatures and cell abundances ranging from 21.1-23.9°C and 40-440 cells ml^{-1}, respectively (Fig. 4, 6a, 7, 8).

In a recent study that evaluated the temporal and spatial changes of microalgae, with a focus on harmful algae blooms and algal/bacterial toxins in salt marsh ponds on the Sheepshead Meadow peninsula in Tuckerton, New Jersey, low concentrations of brevetoxin were detected between July and August 2023 (Ren et al 2025). Brevetoxin concentrations found in the mix of water and sediment from the ponds ranged from 0.43 to 2.03 µg/L. Toxin production was attributed to *Chattonella subsalsa* and *Heterosigma akashiwo.* Both HAB species are raphidophytes which are associated with brown or red tide blooms and brevetoxin production (Zhang et al. 2006).

Climate Change and the Physical Environment

Ocean warming

The Northeast continental shelf ecosystem—including the NJ MAB—is one of the fastest warming ecosystems in the world (Saba et al 2016). Between 1982 to 2014, sea surface temperatures (SST) in the MAB warmed approximately 0.3°C (0.54°F) per decade (Thomas et al 2017). From 1998 to 2019, the northern and southern regions (divided at the mouth of the Hudson River to the Hudson Canyon at the continental shelf break) of the MAB experienced 0.5°C (0.9°F) and 0.28°C (0.50°F) of warming per decade, respectively (Friedland et al 2020a). The MAB experienced the warmest year on record in 2012 (Friedland et al 2020a) and 2017 was marked by a marine heatwave (Gawarkiewicz et al 2019). Warming of NJ coastal shelf waters is not restricted to the surface layer but extends throughout the water column to bottom waters (Forsyth et al 2015, Kavanaugh et al 2017, Friedland et al 2020b), with recent work demonstrating that the Cold Pool is warming and shrinking (Friedland et al 2022).

As ocean warming progresses, the NES is projected to continue warming faster than the global average (Saba et al 2016, Patel et al 2021), which will continue to impact stratification, the Cold Pool, and biological productivity in the region. Warming of the NES is expected to remain faster than the mean global ocean average rate of warming in the long term, with projected warming ranging from 2ºC to 3.2ºC (3.6ºF to 5.8ºF) by 2080 depending on emissions scenario (Saba et al 2016, Jewett and Romanou 2017). The degree of the impacts on the Cold Pool and stratification is an active area of research and long-term climate-based projections are needed to better assess the potential impacts on the marine ecosystem (Friedland et al 2022).

Acidification

Ocean acidification occurs due to the surface ocean taking up atmospheric carbon dioxide, which drives changes to oceanic carbonate chemistry that reduces seawater pH (Orr et al 2005, Doney et al 2009, Gledhill et al 2015). Globally, the pH of the open ocean has decreased by 0.017–0.027 pH units per decade since the late 1980s (Zeebe 2012, Gledhill et al 2015, Sutton et al 2016, IPCC 2019). By the end of the century (2081-2100), surface ocean pH is projected to decline by up to 0.3 pH units relative to 2006-2015 under a high emissions scenario (RCP8.5; IPCC 2019).

Coastal regions like the MAB are even more susceptible to pH decreases due to processes like coastal upwelling, low-alkalinity freshwater runoff, and biological processes (Kwiatkowski and Orr 2018, Cai et al 2020, Wright-Fairbanks et al 2020). Further, eutrophication from nutrient runoff can lead to phytoplankton blooms that can ultimately lead to reductions in pH as the organic matter sinks and is broken down by microbial activity (Cai et al 2011). Due to these factors and relatively low resolution of data from fixed monitoring stations and ship-based monitoring campaigns, assessing pH changes on the MAB has been difficult. This is changing, as recently an autonomous Slocum glider was fitted with sensors to monitor pH and carbonate chemistry seasonal dynamics throughout the water column (Wright-Fairbanks et al 2020). Continued monitoring of carbonate chemistry dynamics will allow for better predictions of how stark pH reductions will be on the MAB.

Precipitation and Changes to Freshwater Inputs

Freshwater input to the NJ coastal shelf––which can increase stratification and is dominated by outflow from the Hudson River (Castelao et al 2010)––will be impacted by changes in precipitation levels and events. Annual precipitation levels have increased in the Northeast US, with much of the region experiencing a >15% increase in precipitation during the fall seasons [comparison period 1901-1960 vs 1986-2015] (Easterling et al 2017). The decadal average precipitation in NJ has increased roughly 3-5 inches (about 7%) since the early 1900s (NJDEP 2020). Extreme precipitation events in the Northeast U.S. are becoming more frequent and intense (Davenport et al 2021, Easterling et al 2017, Papalexiou and Montanari 2019), including the frequency of extreme events in NJ (DeGaetano and Tran 2021). A change in the normal decadal ocean variability is linked to increases in extreme precipitation events over the last few decades (Hoerling et al 2016).

Annual precipitation in the New Jersey region is expected to increase by 6% to 9% by 2100, under moderate (SSP2-4.5) and high emissions projections (SSP5-8.5), respectively (AdaptWest, 2022). Extreme precipitation events, such as the 100-year storm, are projected to increase in intensity throughout the Northeast US and NJ (Easterling et al 2017, DeGaetano 2021). However, the drivers for the regional increases are unclear; proximity to the coast, shifting currents in the Atlantic Ocean, and natural variability are likely factors (Dupigny-Giroux et al 2018, Karmalkar and Horton 2021).

Climate Change and Phytoplankton Shifts

Observed Changes

The changing thermal dynamics of the NES has the potential to impact phytoplankton communities. It is difficult to assess whether climate change has driven changes in primary production and phytoplankton communities over the last few decades are due to intermittent sampling and differences in analysis techniques. Remote sensing via satellites provides decades of observation data, helping to address this problem[1]. Phytoplankton blooms appear to be increasing in frequency across the wider NES as SST increases (Dai et al 2023), and chlorophyll-*a* (Chl-a) concentrations have decreased since 2012 (Friedland et al 2020a).

The MAB has experienced long-term changes in phytoplankton communities. Schofield et al (2008) found that Chl-a concentrations declined 43% and 29% in the fall and winter seasons, respectively, when comparing satellite data gathered between 1978-1986 and 1998-2006 on the MAB. Despite small increases in Chl-a in spring and summer (8% and 14%, respectively), the annual net change in MAB Chl-a biomass concentration was a reduction of 14%, highlighting the dominance of the fall and winter blooms (Schofield et al 2008). The declines in Chl-a coincided with a shift from cold phase (mid-1960s to mid-1990s) to warm phase (mid-1990s to present/2008) of the Atlantic Multidecadal Oscillation (an index for differences in SST across the Atlantic Ocean), highlighting the

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[1] Other challenges arise when comparing data obtained from different satellites, which have used different sensors to detect phytoplankton and estimate primary production (CZCS 1978-1986, SeaWiFS 1998-2006, MODIS on Aqua 2002-Present, VIIRS 2011-Present). However, these data can still provide useful insights for understanding general trends in chlorophyll across under-sampled marine ecosystems.

role of temperature in regulating stratification and phytoplankton dynamics on the MAB (Schofield et al 2008).

Warming on the MAB has shifted seasonal temperature transitions (i.e., thermal transitions from winter to spring temperatures or from summer to fall temperatures), but this shift has not led to a noticeable shift in bloom timing. For instance, the spring thermal transition is occurring <10 to about 12 days earlier compared to late 1990s/mid 2000s, with no correlation with differences in the relatively infrequent spring blooms (Friedland et al 2015, Friedland et al 2023). The fall thermal transition has experienced a greater shift, a delay of 2 weeks, but similarly has not been correlated with shifts in fall bloom starts or changes in bloom duration (Friedland et al 2023).

Recent analyses for the MAB similarly suggest that primary production has shifted as ocean warming has progressed. Small reductions in mean annual Chl-a concentrations have been observed for the southern half of the MAB (encompassing most of the NJ coast), with values decreasing from approximately 1.65 mg m^{-3} (1998-2012 mean) to approximately 1.2 mg m^{-3} by 2019 (Friedland et al 2020a). This decrease in mean annual Chl-a values coincided with shifts in phytoplankton community composition. Smaller phytoplankton (pico- and nanoplankton) increased their relative contribution to the total phytoplankton community whereas the larger microplankton decreased (Friedland et al 2020a). Decreases in the proportion of diatoms likely drove the decrease in microplankton. Alternatively, dinoflagellates, green algae, prymnesiophytes, and prokaryotes increased their relative contributions to the total phytoplankton community over the same period (Friedland et al 2020a).

Future changes to expect

Climate change will continue to impact global marine phytoplankton abundances and distributions throughout the century. Globally, increases in stratification––due to ocean warming and increased freshwater inputs will likely decrease nutrient concentrations and net primary productivity and favor smaller phytoplankton (Fu et al 2016, Henson et al 2021).

Continued rapid warming in the North Atlantic Ocean (encompassing the MAB) will lead to longer and stronger thermal stratification that will favor small phytoplankton (Thomas et al 2017, Zang et al 2021). In the North Atlantic, models predict that many diatoms and dinoflagellates will shift northward (Barton et al 2016). Less stratified, nutrient-rich, turbulent cooler waters generally favor larger diatoms whereas smaller groups (i.e., dinoflagellates, cyanobacteria) typically predominate in warmer, more stratified waters that are calmer and low in nutrients (Gilbert 2016). As such, dinoflagellates are expected to expand northward in the North Atlantic as climate change progresses and creates more favorable conditions (i.e., warmer, more stratified waters that are low in nutrients and turbulence; Barton et al 2016). Notably, shifts in seasonal community composition are predicted to be larger than the predicted basin-scale median changes. This is driven by predictions that climate change will have significant impacts on the characteristic spring bloom and seasonal phytoplankton community succession in the North Atlantic Ocean (Barton et al 2016).

Future Projections and Implications

Climate change is predicted to increase HAB events globally due to a number of factors. Predicted levels of ocean warming will lead to higher ocean temperatures that generally favor smaller cells like cyanobacteria and dinoflagellates that include HAB species. HAB species tend to grow faster under higher temperatures, which may also contribute to higher toxicity in many species (summarized by Gilbert 2020, Ralston and Moore 2020). Increases in stratification strength and duration due to ocean warming will likely benefit HAB species by maintaining higher light and nutrient limited conditions favorable to HAB species (Gilbert 2020, Ralston and Moore 2020). These factors will likely contribute to expanded ranges for HAB species (Paerl and Huisman 2008, Fu et al 2012, Gilbert et al 2014, Wells et al 2015, Golber et al 2017). This may be mitigated, to some degree, by warming that exceeds the thermal range for some HAB species. For instance, *A. anophagefferens* blooms may be restricted as waters where blooms used to regularly occur frequently reach temperatures outside their thermal range––upper limit at 25°C, with 15-20°C considered optimal bloom conditions (Nuzzi and Waters 2004, Gobler and Sunda 2012, Anderson et al 2021).

Heavy precipitation events will contribute to increases in stratification and HAB blooms. The rapid influx of massive freshwater riverine runoff—often full of nutrient pollution—can quickly create a freshwater cap that is resistant to mixing. Nutrient pollution from heavy precipitation events/heavy freshwater input is thought to have contributed to a large phytoplankton bloom in the Chesapeake Bay in 2003 (Miller et al 2005). Heavy precipitation from hurricanes likely contributed to the very large and intense cyanobacterial and dinoflagellate blooms in Florida (Mettler 2016, Gilbert 2020). The cyanobacteria *Microcystis* bloomed in the summers of 2016-2018 on Florida's east coast (Mettler 2016, Gilbert 2020), and blooms of *Karenia brevis* (a dinoflagellate) occurred in 2005-2006 and in 2017-2018 following intense freshwater input from hurricanes (Gilbert 2020).

Due to the challenges and complexities in modeling HABs, there are few documented projections for how HABs in the MAB will respond to climate change in the short- to intermediate-term. However, given the climate trends summarized above, general patterns can be inferred. As HAB species tend to favor warmer waters, projected ocean warming in the MAB will likely benefit toxin-producing species. The potential range of subtropical phytoplankton HAB species may expand north into NJ coastal waters and the length of the seasonal window when HABs are likely to occur will likely increase. Projected increases in annual precipitation and extreme precipitation events in NJ will likely increase the frequency of freshwater nutrient runoff events that create HAB-favorable conditions. Increased temperatures and freshwater runoff during the summer and early fall months will likely strengthen stratification, which will also benefit HAB species. While ocean currents may ultimately be responsible for transporting subtropical phytoplankton HAB species northward towards the MAB, climate change will likely result in conditions that are more and more favorable to HAB growth and blooms in NJ coastal waters.

Tables and Figures

Table 1. Dominant taxonomic groups documented in BMWM database. The number of entries that taxonomic groups were reported as dominant. Entries without a dominant taxa were documented as ‘sparse’ or left blank (shown as NA).

Taxonomic group	**Entries as dominant group**	**Percent of all entries**
chlorophytes	79	2.20%
cryptophytes	4	0.11%
cyanobacteria	1	0.03%
diatoms	1171	32.58%
dinoflagellates	477	13.27%
euglenids	32	0.89%
mixed phytoplankton	150	4.17%
mixed picoplankton	170	4.73%
microzooplankton	1	0.03%
other heterokonts	4	0.11%
raphidophytes	8	0.22%
sparse	1386	38.56%
NA	111	3.09%
Total entries	**3594**	**100.0%**

Table 2. HAB events recorded in Barnegat Bay, retrieved from HAEDAT. * = recorded as dominant species

Location	Year	Start/Detection Date	Approximate Duration	Impacts	Toxin detected	Causative Species	Additional Species
Barnegat Bay (possible)	1987	July	8 days	Water discoloration, mortality of juvenile and larval scallops, and eelgrass mortality. No human illnesses.		*Aureococcus anophagefferens*	
Barnegat Bay	1989	Mid-June	4 months	Water discoloration		*Nannochloris atomus**	
Barnegat Bay	1990	15-Jun	3 months	Water discoloration		*Nannochloris atomus*	
Barnegat Bay	1991	Early June	4 months	Water discoloration and possible ecological damage (eelgrass mortality)		*Nannochloris atomus*	
Barnegat Bay	1994	July	3 months	Water discoloration and benthic affected (possible eelgrass die-off)		*Nannochloris atomus*	
Barnegat Bay	1998	15-May	20 days	Water discoloration		*Prorocentrum minimum*	
Barnegat Bay	1999	4-May	1 month	Water discoloration, high phytoplankton, Juvenile clams in culture resumed growth after bloom crashed.	Yes	*Aureococcus anophagefferens*	
Barnegat Bay	2000	May		Water discoloration, high phytoplankton, planktonic, benthic, shellfish affected		*Aureococcus anophagefferens*	
Barnegat Bay	2001			Water discoloration, shellfish affected		*Aureococcus anophagefferens*	
Barnegat Bay	2005	27-Jul		high phytoplankton			*Nitzschia sp.*
Barnegat Bay	2017	4-Aug		natural' fish, birds, aquatic mammals affected; Possible botulism caused by Low oxygen in the lagoon area	Unexplained toxicity	*Chattonella spp.*	

Table 3a. HAB events recorded offshore and in Raritan – Sandy Hook Bay, retrieved from HAEDAT. * = recorded as dominant species

Location	Year	Start/Detection Date	Approximate Duration	Impacts	Toxin detected	Causative Species	Additional Species
Offshore (5 mi off LBI)	1989	26-Oct	4 days	Water discoloration		*Katodinium rotundatum**, *Gyrodinium estuariale**, *Eutreptia lanowii**, *Chroomonas amphioxieia**	*Gyrodinium pellucidum,* *Chrysochromulina sp.,* *Tetraselmis sp.*
Offshore (5 mi off LBI)	2005	5-Jul		Water discoloration, high phytoplankton		*Olisthodiscus luteus*	
Offshore (Atlantic Ocean)	2005	8-Jun		Water discoloration, high phytoplankton			*Cerataulina pelagica*
Raritan - Sandy Hook Bay	1988	24-May				*Eutreptia lanowii**, *Katodinium rotundatum**, *Olisthodiscus luteus**	*Prorocentrum triestinum,* *Prorocentrum minimum*
Raritan - Sandy Hook Bay	1989	Mid-July	2 months	Water discoloration		*Skeletonema costatum**, *Cylindrotheca closterium**, *Thalassiosira spp.,* *Hemiaulus sinensis*	
Raritan - Sandy Hook Bay	1990	13-Jun	6 days	Water discoloration		*Olisthodiscus luteus,* *Cyclotella sp.,* *Katodinium rotundatum,* *Euglena/Eutrepia sp.*	
Raritan - Sandy Hook Bay	1995	Late May	2 months	Dead fish found along the south shore, 19-24 July, just west and east of Keyport Harbor at Cliffwood Beach and Union Beach., high phytoplankton		*Skeletonema costatum,* *Thalassiosira gravida,* *Thalassiosira nordenskioldii,* *Cerataulina pelagica*	
Raritan - Sandy Hook Bay	1995	Late May	2 months	Dead fish found along the south shore, 19-24 July, just west and east of Keyport Harbor at Cliffwood Beach and Union Beach.		*Skeletonema costatum,* *Thalassiosira gravida,* *Thalassiosira nordenskioldii,* *Cerataulina pelagica*	
Raritan - Sandy Hook Bay	1998	19-May	2 months	Water discoloration		*Rhizosolenia spp.,* *Skeletonema costatum,* *Thalassiosira spp.,* *Asterionella glacialis*	

Table 3b. HAB events recorded offshore and in Raritan – Sandy Hook Bay, retrieved from HAEDAT. * = recorded as dominant species

Location	Year	Start/Detection Date	Approximate Duration	Impacts	Toxin detected	Causative Species	Additional Species
Raritan - Sandy Hook Bay	2000	28-Jun	3 months	Water discoloration; 'natural' fish, benthic, shellfish affected, high phytoplankton		*Katodinium rotundatum*	
Raritan - Sandy Hook Bay	2017			high phytoplankton		*Pseudo-nitzschia spp.*	
Raritan - Hudson estuary	1991	20-May	10 days	Water discoloration		*Prorocentrum minimum*	
Raritan Bay	1993	20-Jul	4 days	Roughly 15,000 dead finfish and shellfish were observed over a total stretch of about 2000 yards at Cliffwood Beach; several more dead fish and crabs were seen in Keyport Harbor about the same time (7/21-22). Kill of marine fauna in vicinity of Cliffwood		*Katodinium rotundatum**	*Olisthodiscus luteus, Euglena sp., Chroomonas spp.*
Raritan Bay	1994	June	4 months	Water discoloration		*Euglena sp., Chaetoceros spp., Thalassiosira sp., Skeletonema costatum*	
Raritan Bay - Offshore (entire coast)	1988	24-May				*Cerataulina pelagica*	*Skeletonema costatum*
Raritan Bay - Offshore (South)	1989	20-Jun	11 days	Water discoloration and fish affected		*Katodinium rotundatum, Eutreptia lanowii, Cryptomonas sp., Gymnodinium sp.*	

Table 3c. HAB events recorded offshore and in Raritan – Sandy Hook Bay and other regions, retrieved from HAEDAT. * = recorded as dominant species

Location	Year	Start/Detection Date	Approximate Duration	Impacts	Toxin detected	Causative Species	Additional Species
Sandy Hook Bay	1990	25-Jun	5 days	Water discoloration		*Katodinium rotundatum**	
Sandy Hook Bay	1990	16-Jul	1 day	Water discoloration		*Katodinium rotundatum*,* *Euglena sp.,* *Protoperidinium trochoideum*	
Sandy Hook Bay	1990	2-Aug	1 day	Water discoloration		*Skeletonema costatum,* *Thalassiosira nordenskioldii*,* *Chaetoceros sp.,* *Cyclotella sp.*	
Sandy Hook Bay	1991	20-Jul	20 days	Water discoloration and flocculent deposits		*Thalassiosira nordenskioldii,* *Chaetoceros socialis,* *Leptocylindrus minimus,* *Cyclotella sp.*	
Sandy Hook Bay	1994	3-Aug	4 months	Water discoloration and fish affected		*Navicula sp.,* *Chaetoceros spp.,* *Prorocentrum minimum*,* *Prorocentrum redfieldii*	
Sandy Hook Bay and Shrewsbury River	1990	18-Jun	1 day	Water discoloration		*Cyclotella sp.*,* *Phaeodactylum tricornutum,* *Katodinium rotundatum**	
Shark River	1991	25-Jul	6 days	Water discoloration		*Prorocentrum redfieldii,* *Prorocentrum minimum,* *Gyrodinium sp.,* *Euglena sp.*	
*Not indicated	1997			Water discoloration and moderate levels of brown tides		*Aureococcus anophagefferens*	

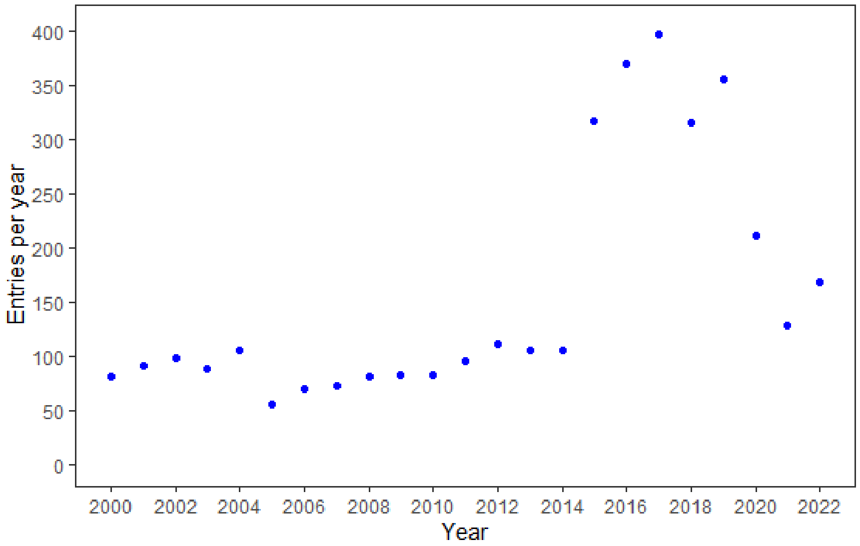

Figure 1. Phytoplankton monitoring by the Bureau of Marine Water Monitoring (BMWM). Number of entries per year to the BMWM phytoplankton database, 2000-2022. The number of entries in the database per year increased significantly in 2015 due to a change in the phytoplankton sampling plan, which increased the entries from an average of ~88.5 entries per year from 2000-2014 to an average of 283.3 entries per year from 2015-2022.

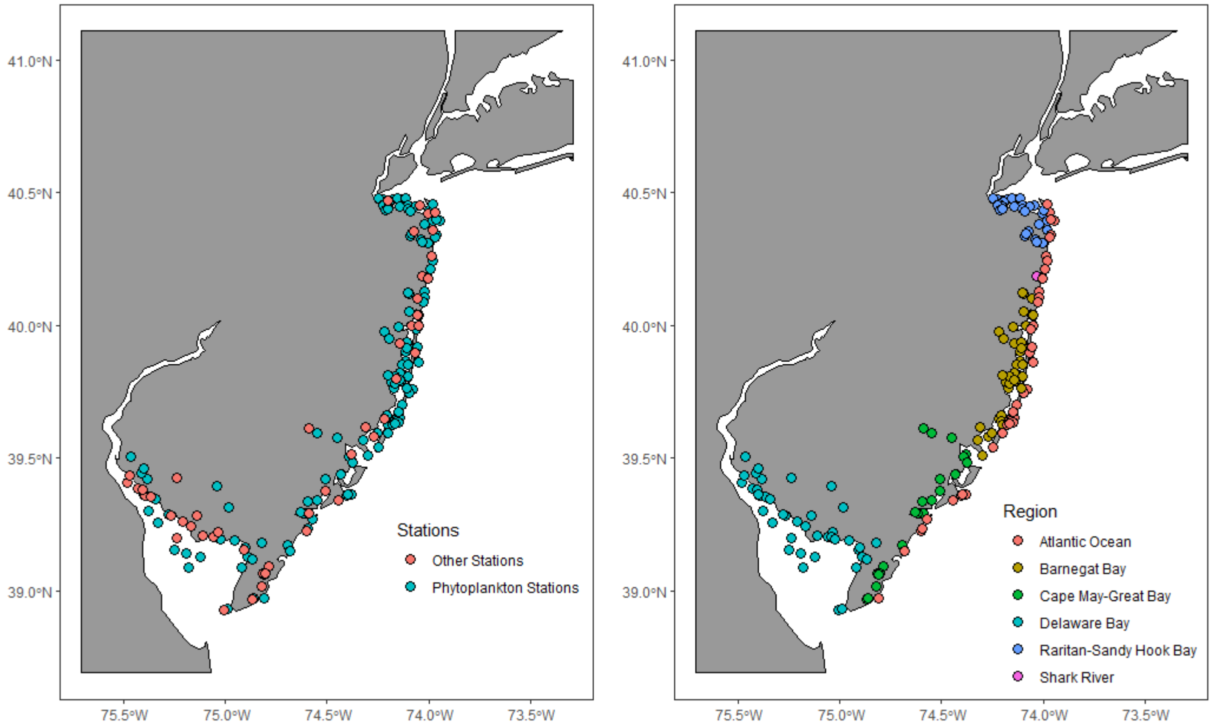

Figure 2. BMWM Stations sampling phytoplankton across New Jersey. (*Left*) Phytoplankton stations (cyan) are the 47 stations that make up the regular phytoplankton sampling network. Other stations (coral) are part of other projects that also collect phytoplankton samples if necessary or areas of concern that are sampled. (*Right*) Stations by regions; Atlantic Ocean (coral), Barnegat Bay (tan), Cape May to Great Bay (green), Delaware Bay (cyan), Raritan Bay and Sandy Hook Bay (blue), and Shark River (pink). Atlantic Ocean stations are coastal stations outside of bays. Inland stations are placed in region where they drain. Shark River drains directly into the Atlantic Ocean.

Figure 3. Dominant phytoplankton taxonomic groups observed in NJ in BMWM database overtime. (a) All entries documenting dominant taxonomic groups (by color) throughout the year from 2000-2022. (b) Entries documenting dominant taxonomic groups (by color) throughout the year after removing "sparse" and "NA" from data (b).

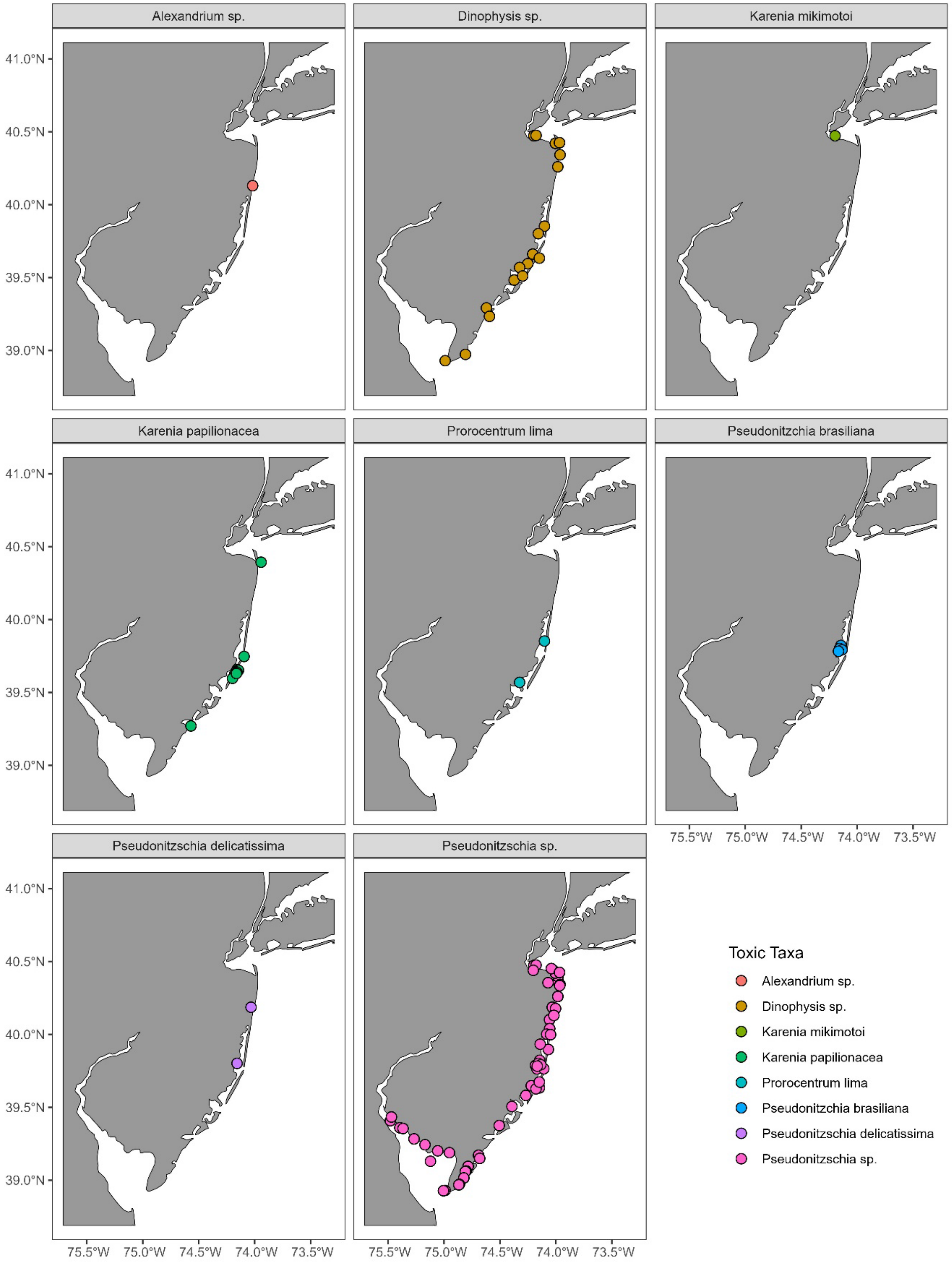

Figure 4. Distribution of documented toxic phytoplankton taxa in NJ in BMWM database. Data of phytoplankton locations are divided into panels by toxic taxa (and indicated by point color) from 2000-2022.

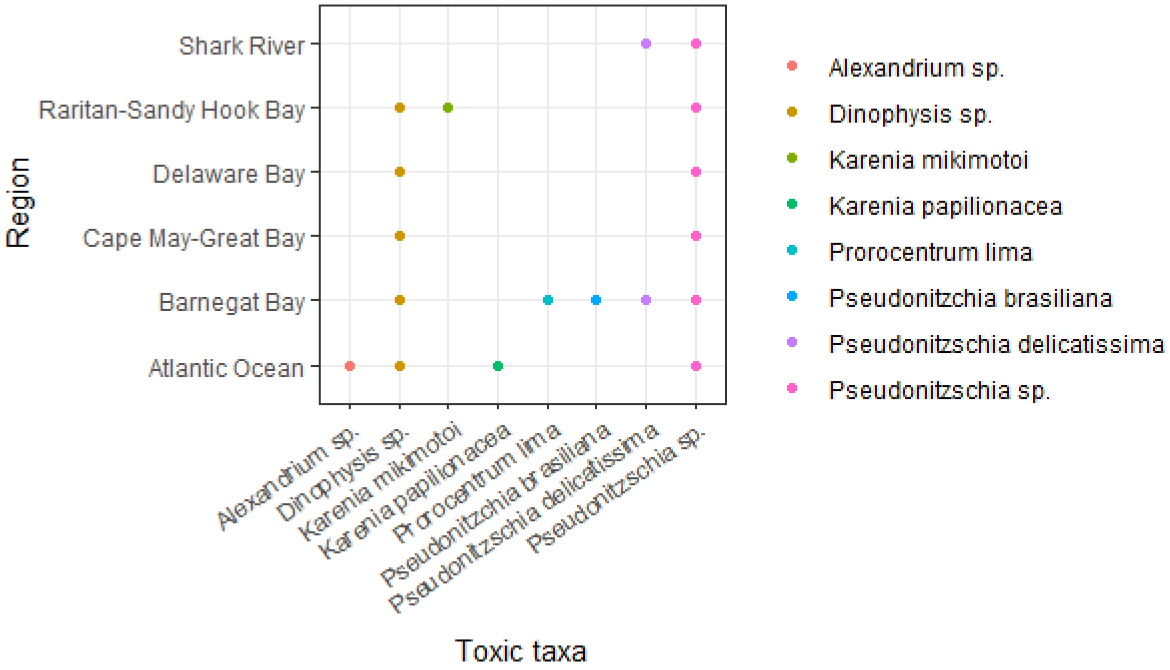

Figure 5. Toxic taxa by region. Regions where toxic taxa has been documented in the BMWM database, 2000-2022.

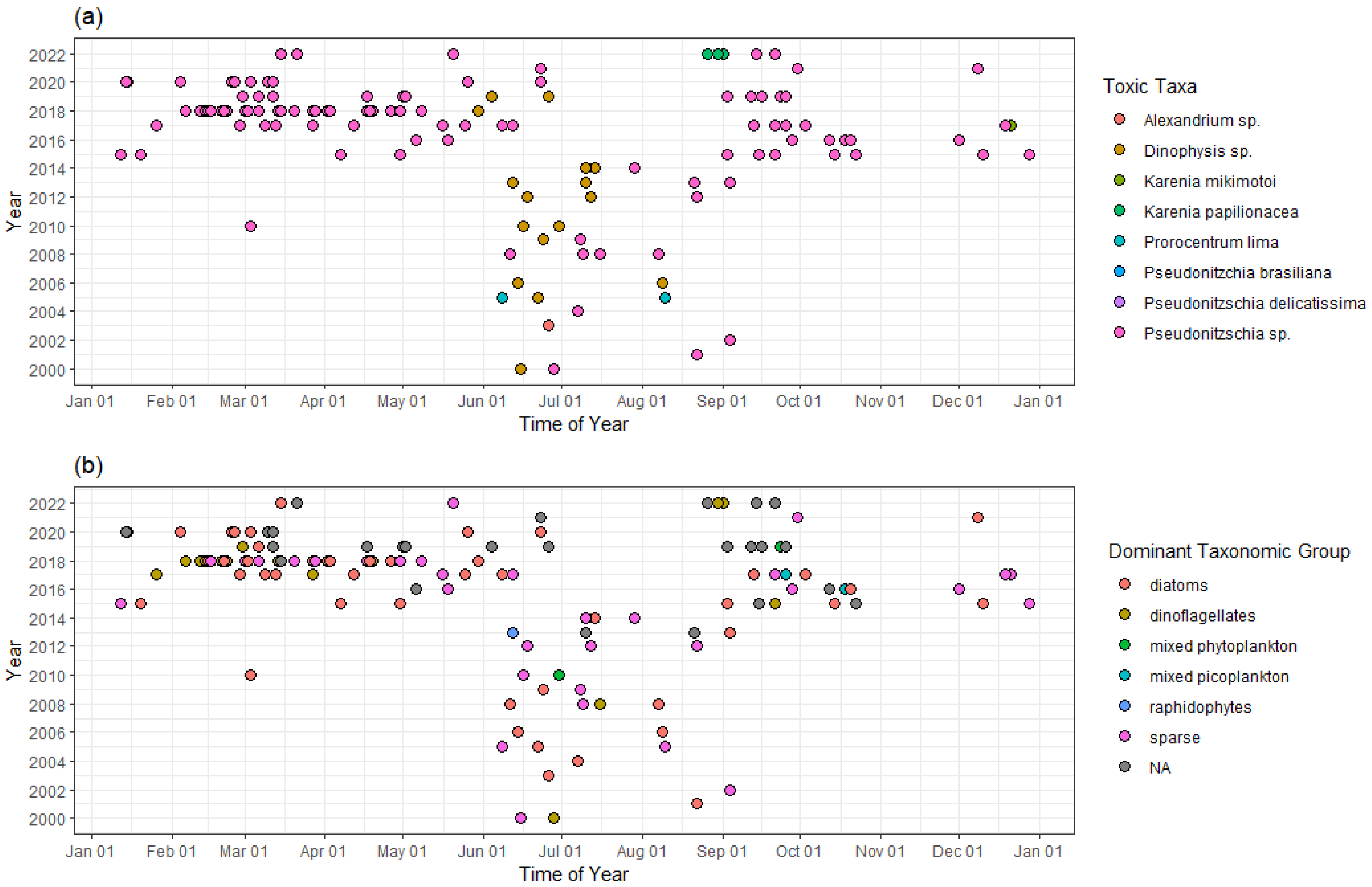

Figure 6. Phytoplankton documented when toxic taxa were observed in NJ in BMWM database overtime. (a) All toxic taxa (by color) documented throughout the year from 2000-2022. (b) Dominant taxonomic groups (by color) when toxic taxa were documented throughout the year.

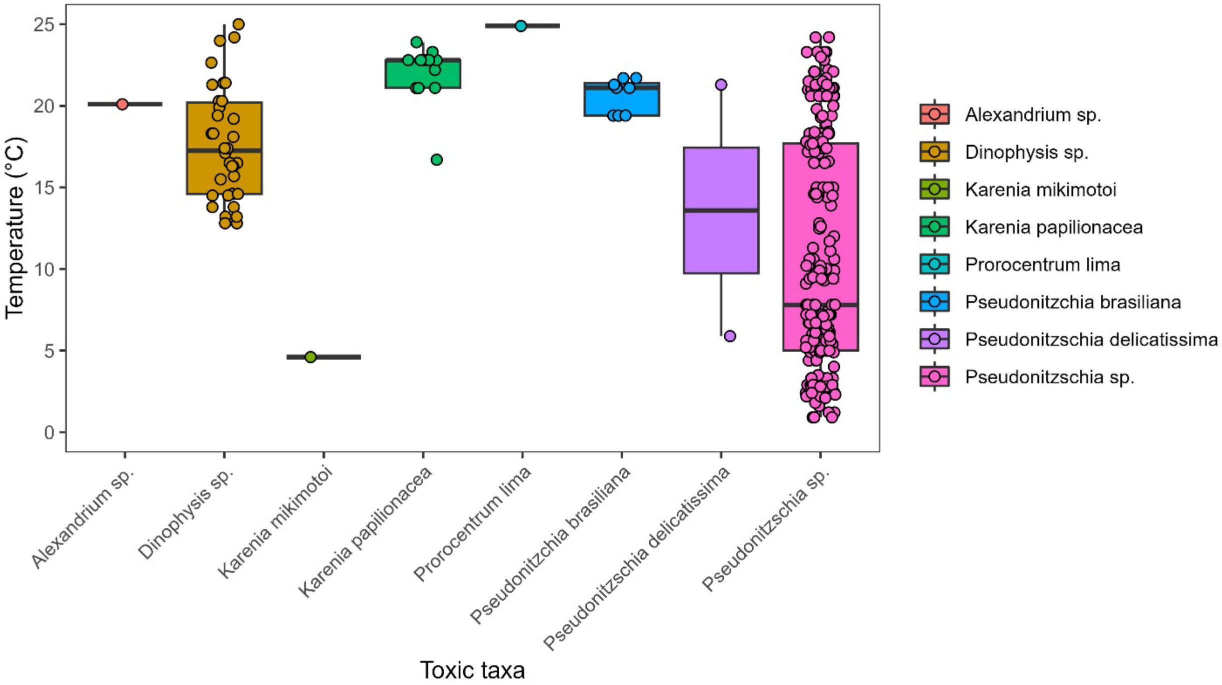

Figure 7. Recorded temperatures for toxic phytoplankton taxa observations in BMWM database. Water temperatures (°C) when toxic phytoplankton taxa, *Alexandrium* sp. (n=1), *Dinophysis* sp. (n=35), *Karenia mikimotoi* (n=1), *Karenia papilionecea* (n=13), *Prorocentrum lima* (n=2), *Pseudonitzchia brasiliana* (n=8), *Pseudonitzschia delicatissima* (n=2), and *Pseudonitzschia* sp. (n=218), were observed. Observations of toxic phytoplankton taxa without a reported temperature (n=11) are excluded. Upper and lower bounds of each box plot represent the 25th and 75th percentiles around the median, with whiskers representing data that are ≤1.5 times the interquartile range. Data beyond this range are outliers.

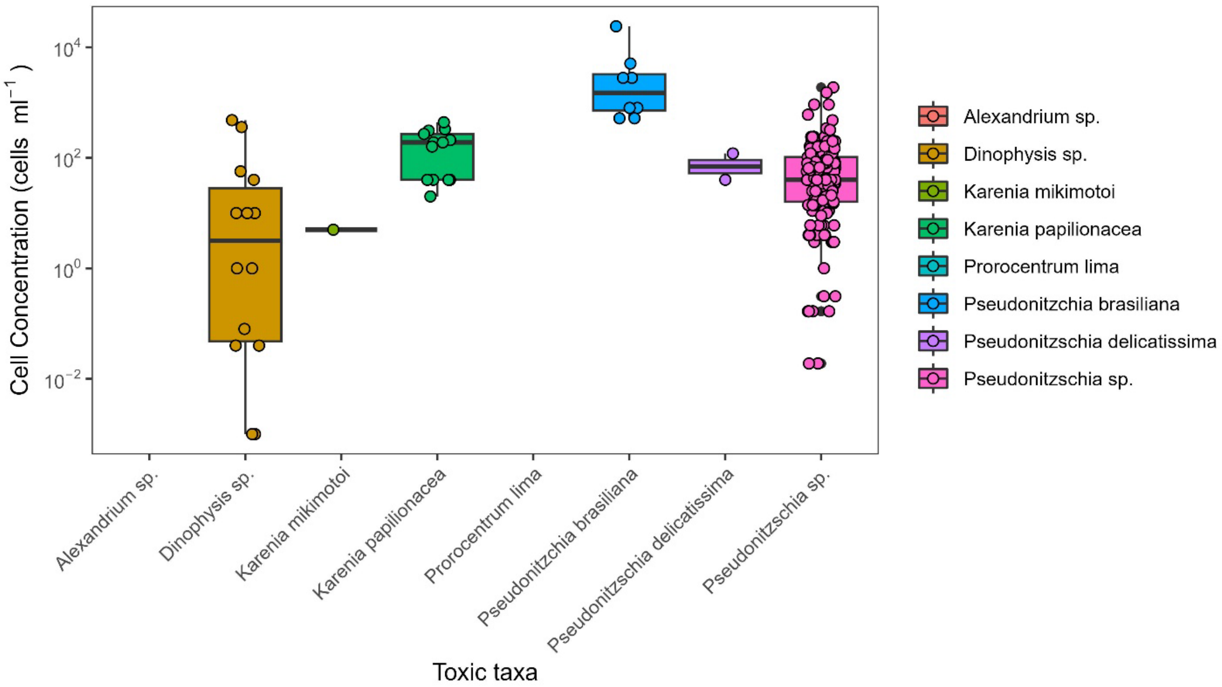

Figure 8. Cell concentrations for toxic phytoplankton taxa observations in BMWM database. Cell concentrations (cells ml^{-1}) of toxic phytoplankton taxa, *Alexandrium* sp. (n=0), *Dinophysis* sp. (n=14), *Karenia mikimotoi* (n=1), *Karenia papilionecea* (n=13), *Prorocentrum lima* (n=0), *Pseudonitzchia brasiliana* (n=8), *Pseudonitzschia delicatissima* (n=2), and *Pseudonitzschia* sp. (n=188), observed in NJ waters. Observations of toxic phytoplankton taxa without a reported cell concentration (n=62) are excluded. Upper and lower bounds of each box plot represent the 25th and 75th percentiles around the median, with whiskers representing data that are ≤1.5 times the interquartile range. Data beyond this range are outliers.

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