The Occurrence of *Karenia* species in mid-Atlantic coastal waters: Data from the Delmarva Peninsula, USA

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ABSTRACT

A bloom of *Karenia papilionacea* that occurred along the Delaware coast in late summer of 2007 was the first *Karenia* bloom reported on the Delmarva Peninsula (Delaware, Maryland, and Virginia, USA). Limited spatial and temporal monitoring conducted by state agencies and citizen science groups since 2007 have documented that several *Karenia* species are an annual component of the coastal phytoplankton community along the Delmarva Peninsula, often present at background to low concentrations (100 to 10,000 cells L^{-1}). Blooms of *Karenia* ($> 10^5$ cells L^{-1}) occurred in 2010, 2016, 2018, and 2019 in different areas along the Delmarva Peninsula coast. In late summer and early autumn of 2017, the lower Chesapeake Bay experienced a *K. papilionacea* bloom, the first recorded in Bay waters. Blooms typically occurred summer into autumn but were not monospecific; rather, they were dominated by either *K. mikimotoi* or *K. papilionacea*, with *K. selliformis*, *K. brevis*-like cells, and an undescribed *Karenia* species also present. Cell concentrations during these mid-Atlantic *Karenia* spp. blooms equalled concentrations reported for other *Karenia* blooms. However, the negative impacts to environmental and human health often associated with *Karenia* red tides were not observed. The data compiled here report on the presence of multiple *Karenia* species in coastal waters of the Delmarva Peninsula detected through routine monitoring and opportunistic sampling conducted between 2007 and 2022, as well as findings from research cruises undertaken in 2018 and 2019. These data should be used as a baseline for future phytoplankton community analyses supporting coastal HAB monitoring programs.

1. Introduction

Blooms of the dinoflagellate *Karenia brevis* (Davis) G. Hansen & Moestrup (previously known as *Gymnodinium breve* Davis and *Ptychodiscus brevis* (Davis) Steidinger), or "red tides", are a nearly annual occurrence in the Gulf of Mexico, where they have been documented since Spanish explorers encountered them in the 16th century (Magaña et al., 2003) and continue to be an active area of monitoring and research (Steidinger, 2009; Hu et al., 2022). *Karenia brevis* produces brevetoxin, a neurotoxin which can cause extensive fish and animal mortalities when cell concentrations exceed 10^5 cells L^{-1} (Steidinger,

2009). This toxin can become aerosolized causing acute or chronic respiratory illnesses in individuals exposed to these high concentration blooms (Fleming et al., 2011). Additionally, at cell concentrations above 10^3 cells L^{-1} this toxin can accumulate in shellfish tissues causing neurotoxic shellfish poisoning (NSP) in humans who consume contaminated shellfish, thus presenting a resource management concern for shellfish industries where these blooms occur (Poli et al., 2000; Steidinger, 2009).

Only since the 1970s have environmental and economic impacts from blooms of other *Karenia* species been documented globally. Blooms of *Karenia* spp., that do not include *K. brevis*, have been observed in

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diverse marine environments including Norwegian coastal waters (Dahl and Tangen, 1993); Tokyo Bay, Japan (Takayama and Adachi, 1984); the Gulf of Gabes, Tunisia (Hamza and El Abed, 1994); numerous bays in New Zealand (Chang, 1999; Haywood et al., 2004); Victoria Harbour, Hong Kong (Yang et al., 2000, 2001); Kuwait Bay (Heil et al., 2001); the coastline of South Africa (Botes et al., 2003); the coastline of eastern Tasmania, Australia (de Salas et al., 2004a,b); the Chilean coast (Mardones et al., 2020), and the region between the Kamchatka Peninsula, Russia and Hokkaido Island, Japan (Iwataki et al., 2022; Orlova et al., 2022). Observations suggest that many bloom-forming *Karenia* species can occupy diverse environments and have broader water temperature and salinity tolerances than *K. brevis*. In the United States, until recently, *Karenia* blooms have been restricted to the Gulf of Mexico and Florida's east coast and dominated by *K. brevis,* with other *Karenia* species noted as present or in low concentrations (Steidinger et al., 2008; Steidinger, 2009; Wolny et al., 2015; Harris et al., 2020). However, in the autumn of 2013 a bloom of *Karenia mikimotoi* (Miyake & Kominami ex Oda) G. Hansen & Moestrup was documented by Vandersea et al. (2020) in Kachemek Bay, Alaska, where extensive discolored water was observed, along with localized fish kills. In the late summers and early autumns of 2017 to 2020, blooms of *K. mikimotoi* caused discolored water, hypoxia, and impacts to shellfish resources in the Gulf of Maine (Record et al., 2021; Scully et al., 2022).

Blooms of *Karenia* have rarely been documented in the mid-Atlantic region of the United States. In 2007, a large export event of a Gulf of Mexico *K. brevis* bloom, entrapped in the Loop Current and moved eastward by the Gulf Stream, was documented by Walsh et al. (2009).

This study tracked the parcel of water containing *K. brevis* using satellite remote sensing and simulated surface drifters as it moved through the Florida Straits, up Florida's east coast, and into the mid-Atlantic region. This same year marked the first observed occurrence of multiple *Karenia* species along the Delaware coastline, with blooms dominated by *Karenia papilionacea* Haywood & Steidinger (Bott, 2014). Unlike Florida's rigorous *Karenia brevis* monitoring program (described in Steidinger, 2009 and Hu et al., 2022) there is little harmful algal bloom (HAB) monitoring along the Delaware, Maryland, and Virginia (Delmarva) Atlantic seaboards outside of the region's coastal bays. Despite limited opportunities to make *in situ* observations, data collected by state agencies, universities, and citizen monitoring programs indicate that multiple *Karenia* species are seasonally part of the phytoplankton community along the coast and within the coastal bays of the Delmarva Peninsula. Here we report on the occurrence of multiple *Karenia* species in coastal waters of the Delmarva Peninsula and Chesapeake Bay detected through spatially- and temporally-limited routine monitoring and opportunistic sampling conducted between 2007 and 2022 and focused field campaigns conducted in the coastal waters of the Delmarva Peninsula in 2018 and 2019.

2. Methods

2.1. Overview of data collection

The cell abundances of *Karenia* species were measured from water samples collected as part of the Maryland and Virginia state HAB and
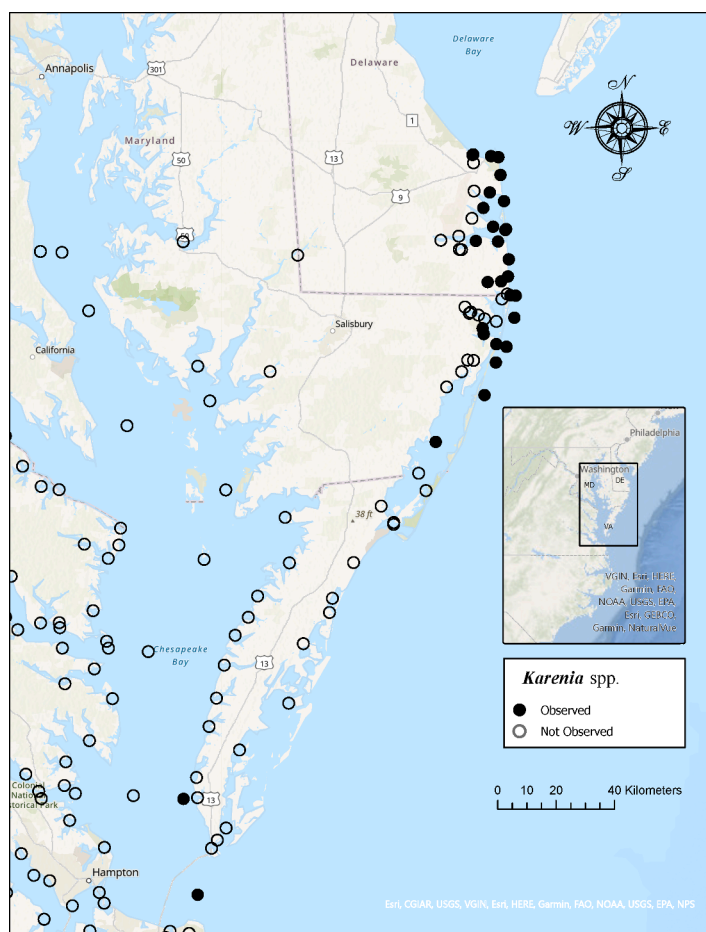

Fig. 1. Map of routine phytoplankton monitoring stations along the Delmarva Peninsula and Chesapeake Bay. For this study, samples were collected between 2007 and 2022 by the UD CMP, MDE, MDNR, VDH, and ODU. Open symbols indicate stations where *Karenia* spp. were not observed. Closed symbols indicate stations where *Karenia* spp. were observed.

shellfish monitoring programs and Chesapeake Bay Program (CBP) water quality monitoring activities (Fig. 1). Water quality monitoring in Delaware was conducted by volunteers participating in the University of Delaware Citizen Monitoring Program (Fig. 1). In 2018 and 2019 a cooperative coastal assessment agreement between the University of Maryland Center for Environmental Science (UMCES) and the Assateague Island National Park Service allowed for the collection of water samples during research cruises along the Delmarva Peninsula coastline (Fig. 2).

State and citizen monitoring programs obtained live or 5 % Lugol's iodine (#LC156725, LabChem Inc., Zelienople, PA, USA) preserved whole water samples from fixed stations or during opportunistic sampling of near surface waters (< 0.5 m) or from the depth of the chlorophyll maximum. Samples collected through the CBP followed the protocols listed in CBP (2017). Briefly, above and below pycnocline composite samples were collected and preserved with 5 % Lugol's iodine. Surface and depth samples preserved with 5 % Lugol's iodine were collected during the 2018 and 2019 Delmarva Peninsula coastal cruises. Environmental data (e.g., temperature and salinity) were collected using Hydrolab Series 5 (Hach Environmental, Loveland, CO, USA) or YSI 85, YSI 6600, Pro2030, or ProSolo (YSI, Inc., Yellow Springs, OH, USA) data sondes concurrently with phytoplankton sample collection.

Using light microscopy, all *Karenia* were identified and enumerated to the species level based on overall cell morphology and nuclear shape and placement as described in Yang et al. (2001), Haywood et al. (2004), de Salas et al. (2004a,b), and Steidinger et al. (2008). When identification to the species level was not possible due to staining, cell distortion, or cell orientation, cells were included in a separate category termed 'Karenia spp.'. An undescribed *Karenia* species, clearly recognizable due to the unique hypocone morphology, resembled "Karenia sp.

#3″, as described by Steidinger et al. (2008); this naming convention was retained for this work. Cell concentration data were plotted using ArcGIS Pro 3.0.3 (Esri, Redlands, CA, USA) and cell concentrations were binned as absent, background ($100 - 1000$ cells L^{-1}), low (>1000 to 10,000 cells L^{-1}), medium (>10,000 to 100,000 cells L^{-1}) and high (>100,000 cells L^{-1}) (see Table 1).

2.2. Delaware

Between May and November 2007 – 2022, live 250-mL phytoplankton samples were collected at least monthly through the University of Delaware's Citizen Monitoring Program (UD CMP) at 26 stations (Fig. 1) located between Broadkill River (38.7904 N, −75.1635 W) and Fenwick Island (38.4519 N, −75.0493 W). Sampling frequency and number of stations sampled increased during HAB events, per the UD CMP guidelines (Whereat et al., 2004). Phytoplankton samples were examined within six hours of collection using American Optical Corporation Series 50 compound microscopes (American Optical Corporation, Buffalo, NY, USA) and enumerated following a modification of the Andersen and Throndsen (2003) droplet method as described in Main et al. (2018). Additional samples were collected at Delaware beaches and inlets by Delaware Department of Natural Resources and Environmental Control (DNREC) staff and preserved with 5 % Lugol's iodine. For these samples, 1 – 3-mL aliquots were settled for a minimum of 30 min in Nunc coverglass-bottom chambers (#155379, Nagle-Nunc, Rochester, NY, USA) and the entire chamber was examined using a Nikon TMS-F inverted microscope (Nikon Instruments Inc., Melville, NY, USA).
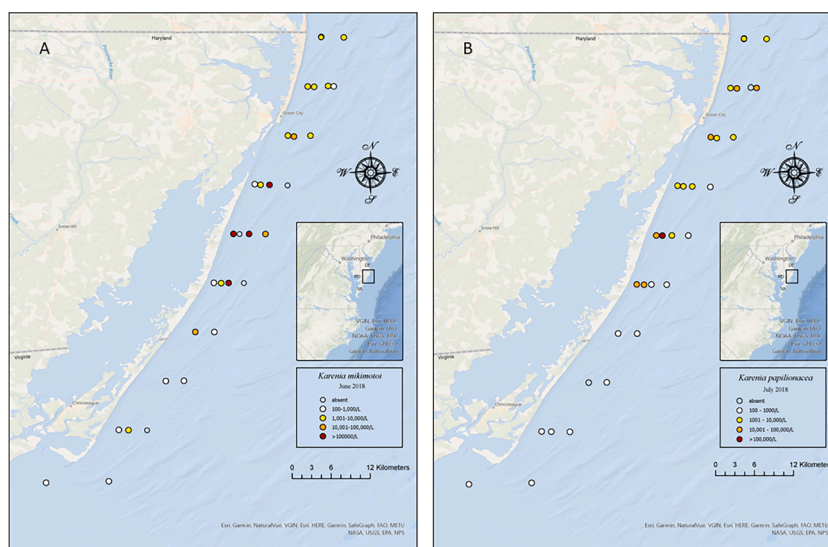

Fig. 2. Maps of the coastal transects sampled during the 2018 and 2019 Delmarva cruises conducted by UMCES. A. Distribution and cell concentrations of the *Karenia mikimotoi* bloom detected in June 2018. B. Distribution and cell concentrations of the *K. papilionacea* bloom detected in July 2018. .

Table 1
Maximum cell L^{-1} concentration and (month) of observation for *Karenia* spp. detected in Delmarva Peninsula and Chesapeake Bay water samples collected between 2007 and 2022. Included are bloom concentrations for each species reported from literature describing more than five years of routine monitoring data.

	Delaware	Maryland	Virginia	Bloom Concentration
K. brevis-like	50,000 (Sep)	14,000 (Aug)	n/a	10^3 (Steidinger, 2009)
K. mikimotoi	10,000 (Apr, Jun, Jul)	42,000 (Aug)	2,800 (June)	10^3 (Li et al., 2019)
K. papilionacea	2,062,000 (Sep)	233,300 (Aug)	5,825,300 (Sep)	10^3 (Yamaguchi et al., 2016)
K. selliformis	n/a	19,900 (Jun)	100 (Oct)	10^5 (Feki-Sahnoun et al., 2017)
Karenia sp. #3	n/a	9,300 (Aug)	n/a	n/a

2.3. Maryland

Monthly monitoring 1.5 km off the Maryland coastline was conducted between April and October from 2014 through 2021 at five stations that are part of the Maryland Department of Environment (MDE) shellfish classification program. Stations were located near the Maryland – Delaware state border (38.4508 N, −75.0326 W) to south of Ocean City (38.2111 N, −75.1286 W). For this program, live 1-L phytoplankton samples were collected from the surface (0.5-1 m) and/or the depth of the chlorophyll maximum (ranging from 1.4-4.9 m). Between 2014 and 2020 year-round, live 1-L surface water phytoplankton samples were collected monthly from 16 stations within the Maryland coastal bays and their major tributaries by the Maryland Department of Natural Resources (MDNR) (Fig. 1).

All samples were examined at MDNR using Nunc coverglass-bottom chambers (#155379, Nagle-Nunc, Rochester, NY, USA) and a Zeiss Axiovert 200 inverted microscope (Carl Zeiss Inc., Thornwood, NY, USA) equipped with an Olympus DP73 digital camera system (Olympus America, Center Valley, PA, USA). Nunc chambers were used to observe live material the day of collection to resolve species identifications. After observations of live material, samples were preserved with 5 % Lugol's iodine and 3-mL aliquots were settled in Nunc chambers for a minimum of 30 min before enumeration. Cells were enumerated using the modified Utermöhl method (Utermöhl, 1958) described by Marshall and Alden (1990).

2.4. Virginia

As part of the CBP monitoring program, on-going from 1985 to present, depth-integrated water samples are collected monthly from above and below the pycnocline at seven stations in the Virginia portion of the Chesapeake Bay mainstem and seven stations in the tidal portions of its tributaries (see CBP (2017) for full sampling methodology) (Fig. 1). Phytoplankton samples (500 mL) were preserved with 5 % Lugol's iodine and returned to the Old Dominion University Phytoplankton Analysis Laboratory (ODU PAL) for analysis. Phytoplankton were concentrated using a series of siphoning and settling steps (Marshall and Alden, 1990; CBP, 2017). Cells were identified and enumerated in 25-mL Utermöhl settling chambers (#435023, Hydro-Bios, Altenholz, Germany) using a Nikon Eclipse TS 100 inverted microscope equipped with a Nikon DS-Fi digital camera system (Nikon Instruments Inc., Melville, NY, USA) following the modified Utermöhl method described by Marshall and Alden (1990).

Between 2007 and 2021, the Virginia Department of Health's Division of Shellfish Safety and Waterborne Hazards (VDH DSSWH) collected 250-mL phytoplankton samples monthly from surface waters (0.5-1 m) at 69 stations located in shellfish growing areas in the Virginia coastal bays and the Chesapeake Bay and its tributaries (Fig. 1). Samples were preserved with 5 % Lugol's iodine solution and returned to the ODU PAL for identification and enumeration of a targeted group of HAB species. For these samples, 4-mL samples were placed in Cellvis 12-well glass bottom plates (#P12–1.5H—N, Cellvis, Mountain View, CA, USA) and screened using an Olympus CK41 inverted microscope equipped with an Olympus SC30 digital camera (Olympus America, Center Valley, PA, USA) following the protocol described in Pease et al. (2023).

2.5. 2018 and 2019 Delmarva Peninsula Coastal cruises

Environmental parameters and samples for phytoplankton community composition analysis were collected during five research cruises in June, July, and October of 2018 and May and July 2019 aboard the *R/V Rachel Carson* or the *R/V Joanne Daiber.* Two to four stations along ten transects, approximately 0.8 to 2.4 km off the Delmarva Peninsula coast, were sampled during these cruises (Fig. 2). The northernmost transects started off the coast of Fenwick Island, Delaware (38.44483 N, −75.0290 W) and the southernmost transects ended south of Assateague

Island, Virginia (37.82906 N, −75.40963 W). Phytoplankton samples, collected at the surface (0.5-1.0 m) and chlorophyll maximum depths (ranging from 2.3 to 14.5 m) using 10-L Niskin bottles on a CTD rosette, were fixed on-site with 5 % Lugol's iodine solution. Samples were examined for phytoplankton community composition and abundance at MDNR using a Zeiss Axiovert 200 inverted microscope and 10-mL Utermöhl settling chambers (#435022, Hydro-Bios, Altenholz, Germany) following the modified Utermöhl method of Marshall and Alden (1990).

3. Results

3.1. Species identification

Five *Karenia* species were routinely identified along the Delmarva Peninsula coastline and in the Chesapeake Bay between 2007 and 2022. Cells identified as *K. brevis*-like (Fig. 3A) resembled *K. brevis* as described by Steidinger et al. (2008), particularly in cell size, nuclear shape and placement (round and located in the left hypotheca), and a slightly excavated hypotheca. However, these cells were only found during blooms of *K. papilionacea*. It is possible they are small-cell forms of *K. papilionacea* as reported by Fowler et al. (2015) or are like the *K. papilionacea* phylotype-I described by Yamaguchi et al. (2016), both of which have a morphological appearance more similar to *K. brevis* than *K. papilionacea* as described by Haywood et al. (2004). Large *K. papilionacea* cells (Fig. 3B) were identified using the overall butterfly-like cell shape, deeply excavated hypotheca, and pointed apical carina as described by Haywood et al. (2004) and Steidinger et al. (2008), whereas small *K. papilionacea* cells were identified by the deeply excavated hypotheca and a slightly pointed apical carina (Fig. 3C).

Both *K. mikimotoi* and *K. selliformis* Haywood Steidinger & MacKenzie cells were identified as described by Steidinger et al. (2008). *Karenia mikimotoi* cells (Fig. 3D) were ovoid in shape with a round to elongate nucleus located along the left side of the cell. *Karenia selliformis* cells (Fig. 3E) were recognized by a wide and deep invagination of the hypotheca and an elongated nucleus located horizontally within the hypotheca. The cells identified as *Karenia* sp. #3 (Fig. 3F) resembled the descriptions given by Steidinger et al. (2008) and de Salas (2004; as "cf. *Karenia* sp. D"). This species is smaller than the other *Karenia* spp., has a deeply invaginated hypotheca with a wide sulcus, a kidney bean shaped nucleus in the epitheca, and few peripherally located chloroplasts.

Light micrographs of living cells were not taken as part of this effort. However, high quality live micrographs of these same species can be reviewed in de Salas et al. (2004b), Haywood et al. (2004), and Steidinger et al. (2008).

3.2. Karenia abundance and distribution

3.2.1. Delaware

The first *Karenia* spp. bloom documented in the Delmarva Peninsula region was observed beginning on 30 August 2007 in the Indian River Inlet area of Delaware where medium concentrations of *K. papilionacea* (6.7×10^4 cells L^{-1}) were detected. Monitoring of Delaware coastal and Inland Bay waters continued for one month thereafter even though the bloom appeared to have dissipated from the region after 12 September. The peak *K. papilionacea* concentration during this bloom (2.1×10^6 cells L^{-1}) occurred on 6 September, 1.6 km east of the Indian River Inlet. The bloom was patchy spatially and temporally along the Delaware coastline, but where present, the average *K. papilionacea* cell concentration was 1.3×10^5 cells L^{-1}. Of note, *K. brevis*-like cells were observed during the peak of the *K. papilionacea* bloom (September 5 – 11) at an average concentration of 4.1×10^4 cells L^{-1}, and most commonly occurred in the high salinity (31 – 32) waters offshore of the Indian River Inlet.

Following the 2007 *Karenia* bloom, surface waters (~0.5 m) at 26 stations along the coast and within the Delaware Inland Bays (Fig. 1)
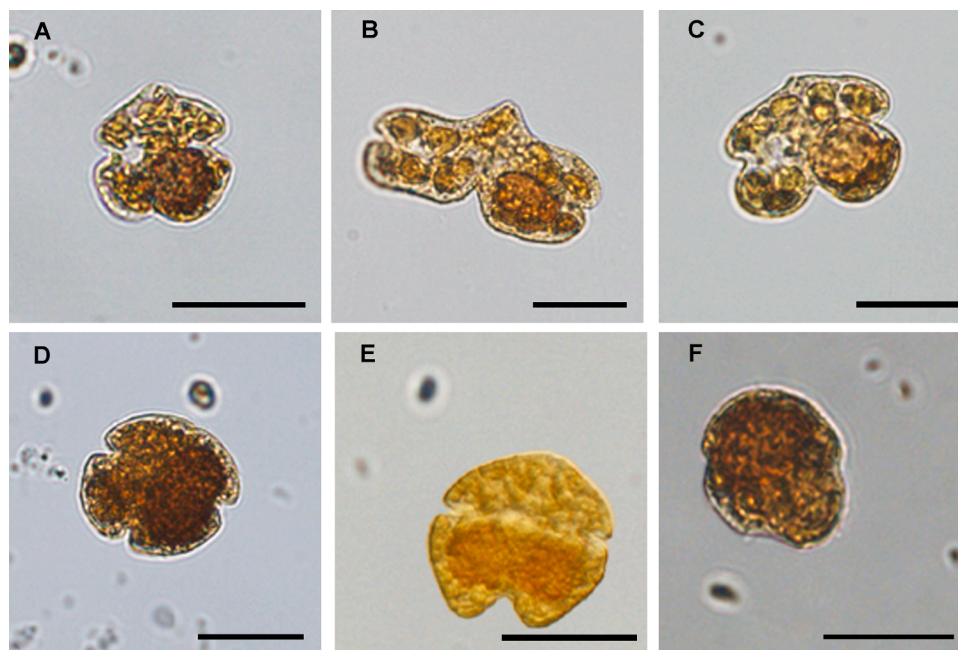
Fig. 3. Light micrographs of *Karenia* species detected in water samples collected in Delmarva Peninsula waters between 2007 and 2022. A. *K. brevis*-like. B. Large cell form of *K. papilionacea*. C. Small cell form of *K. papilionacea*. D. *K. mikimotoi*. E. *K. selliformis*. F. Unidentified *Karenia* species, termed *Karenia* sp. #3, as described by Steidinger et al. (2008) and de Salas (2004).

were routinely monitored for the presence of *Karenia* spp. Between 2008 and 2022, *K. brevis*-like cells were rarely detected, but when observed they were in background to low concentrations ($100 - 10,000$ cells L^{-1}) within a larger *K. papilionacea* population. *Karenia mikimotoi* has been observed in Delaware waters since 2019, but always at low cell concentrations. Neither *K. selliformis* nor *Karenia* sp. #3 have been detected in Delaware waters.

Karenia papilionacea was found in all coastal routine monitoring stations but occurred less frequently within the Delaware Inland Bays. The majority of observations ($n = 163$) made between 2007 and 2022 contained background to low concentrations of this species. Cell concentrations of *K. papilionacea* blooms that occurred in Delaware coastal waters in 2010 and 2016 were on the order of 10^5 cells L^{-1} but no adverse environmental impacts were reported. The *K. papilionacea* blooms documented in all three years (2007, 2010, and 2016) were centred on the region between the Indian River Inlet and Fenwick Island (38.6782 N, -75.0685 W to 38.4519 N, -75.04933 W) between late August and early October (Table 2).

3.2.2. Maryland

Analysis of water samples collected from surface (0.5 to 1.0 m) and/or chlorophyll maximum depths (1.8 to 22.0 m) at five offshore stations indicated the presence of multiple *Karenia* species in at least background concentrations between 2014 and 2022 (Fig. 1). However, nearly monospecific blooms of *K. papilionacea*, with cell concentrations between 10^3 and 10^5 cells L^{-1}, were noted in the late summers of 2016, 2018, and 2019. From April through June, *K. mikimotoi* (average 5.2 ×

10^3 cells L^{-1}) and *K. selliformis* (average 5.0×10^2 cells L^{-1}) were the most commonly occurring *Karenia* species. Between July and October, *K. papilionacea* (average 5.0×10^4 cells L^{-1}) was the most commonly occurring species, but *K. mikimotoi, Karenia* sp. #3, and cells identified as *K. brevis*-like routinely co-occurred within *K. papilionacea* blooms in background concentrations. The maximum cell concentration of *K. papilionacea* (2.3×10^5 cells L^{-1}) recorded from offshore monitoring efforts in Maryland waters occurred on 15 August 2016, within a bloom extending along a broad swath of the coastline north and south of Ocean City, Maryland, from at least 38.3978 N to 38.2898 N latitude (Tables 1 and 2). While concentrations of *K. papilionacea* ranged from 1.1 to 2.3 × 10^5 cells L^{-1} in bloom waters, water samples were negative for the brevetoxin congener PbTx-2 (data not shown) and no adverse environmental impacts were reported.

Within the Maryland coastal bays, *Karenia* species have been documented since 2016 in the surface waters (~0.5 m) at four of the 16 routinely monitored stations. Background concentrations (≤ 1000 cells L^{-1}) of *K. selliformis* have been reported in Chincoteague Bay in the months of April and May. In the Isle of Wight Bay, background (300 cells L^{-1}) to medium (3.1×10^4 cells L^{-1}) cell concentrations of *K. papilionacea, K. mikimotoi*, and *K. selliformis* have been reported between May and October.

3.2.3. Virginia

In 2017, the first observations of *K. papilionacea* on record in the Chesapeake Bay were made in samples collected near the bay mouth in August, September, and October at two CBP long-term monitoring

Table 2

Geographic range, number of occurrences, and salinity and temperature ranges reported for each *Karenia* species detected along the Delmarva Peninsula and within Chesapeake Bay samples collected from 2007 through 2022 via state agency and citizen science monitoring efforts.

Species	Geographic Range (north to south)	Number and (Timing) of Occurrences	Salinity (ppt)	Temperature (°C)
K. brevis-like	38.79 N, -75.16 W to 38.32 N, -75.061W	17 (Aug – Nov)	27.4 – 32.9	16.5 – 26.0
K. mikimotoi	38.79 N, -75.16 W to 38.28 N, -75.09W	25 (May – Dec)	19.0 – 30.9	7.0 – 26.7
K. papilionacea	38.79 N, -75.16 W to 36.99 N, -76.01 W	239 (Jun – Nov)	23.7 – 33.5	8.9 – 26.5
K. selliformis	38.45 N, -75.03 W to 38.09 N, -75.28W	14 (Apr – Jul)	24.6 – 29.4	15.5 – 20.8
Karenia sp. #3	38.37 N, -75.13 W to 38.21 N to -75.12W	7 (Jun – Oct)	19.7 – 30.9	16.4 – 28.3

stations (Fig. 1). At station CB 7.4 (36.9933 N, −76.0106 W), *K. papilionacea* was found in samples collected above the pycnocline in August (2.1×10^5 cells L^{-1}) and October (3.0×10^4 cells L^{-1}). In October, *K. papilionacea* was also observed below the pycnocline, but at lower concentrations (8.9×10^3 cells L^{-1}). The highest concentration of *K. papilionacea* recorded in Virginia waters, 5.8×10^6 cells L^{-1} (Table 1), was observed in a sample collected above the pycnocline at station CB 7.3E (37.2286 N, −76.0542 W) in September. Despite the elevated *K. papilionacea* cell concentrations, no environmental impacts were reported. Other *Karenia* species were not observed in these samples and no *Karenia* were observed in surface water samples collected by VDH as part of the shellfish monitoring program during that same year. Despite the bloom observed off the Delmarva coast in 2018, no *Karenia* were observed in samples collected at CBP stations or samples collected within the Virginia coastal bays by VDH. The other *Karenia* species observed in Maryland and Delaware waters have not been detected in Virginia's coastal bays or within the Chesapeake Bay since routine monitoring was started in 2007. However, *K. mikimotoi* was recorded in Virginia coastal waters at background concentrations off the southern end of Assateague Island during the 2018 and 2019 cruises.

3.2.4. 2018 and 2019 Delmarva Peninsula coastal cruises

In the summer and autumn of 2018, *Karenia* spp. were observed in Delmarva Peninsula coastal waters in both surface samples and samples collected at the depth of the chlorophyll maxima (Table 3; Fig. 2). In June, the bloom was dominated by *K. mikimotoi* (maximum concentration of 1.9×10^5 cells L^{-1}). *Karenia mikimotoi* comprised 98 % of the *Karenia* population and *K. papilionacea* and *K. selliformis* contributed the other 2 %. The *K. mikimotoi* bloom was concentrated along the Maryland coastline off of Assateague Island (Fig. 2A). In July, the bloom was dominated by *K. papilionacea* (maximum concentration of 1.6×10^5 cells L^{-1}), which comprised 96 % of the *Karenia* population. *Karenia brevis*-like cells, *K. mikimotoi, K. selliformis*, and *Karenia* sp. #3 were all documented in samples collected during this bloom. The *K. papilionacea* bloom extended over much of the Maryland coastline (Fig. 2B). Severe weather prevented sampling of coastal waters in August and September. When sampling resumed in October, *Karenia* populations had decreased to background concentrations. All previously reported species were present, except cells identified as *K. brevis*-like, and more than 50 % of the *Karenia* population was composed of *Karenia* sp. #3.

Additional cruises were conducted along the same transects in May and July of 2019 but only background concentrations of *K. mikimotoi* and *Karenia* sp. #3 were detected (data not shown). During these cruises, 70 % of *Karenia* observations were from samples collected from the depth of the chlorophyll maximum or bottom of the water column (3.4 to 11.9 m).

4. Discussion

Phytoplankton communities along the eastern seaboard of the United States have been sporadically documented during research cruises since the early 20th century (Cleve, 1900; Bigelow 1915; Cowles, 1930). Marshall and colleagues conducted extensive *in situ* sampling of the phytoplankton communities in the coastal waters off the Delmarva Peninsula between the 1960s and 1980s (Marshall, 1969a, 1969b, 1976, 1978, 1982, 1984, 1985, 1986, 1988, 1991; Marshall and Cohn, 1983, 1987; Marshall and Ranasinghe, 1989; Marshall and Shomers, 1990; Marshall et al., 1981; Matta and Marshall, 1984; Wagoner and Marshall, 1991). These studies observed a phytoplankton community dominated year-round by diatoms and cryptophytes with distinct winter and summer dinoflagellate populations, the latter of which increased in abundance offshore during summer blooms. However, there has been limited *in situ* phytoplankton surveillance at the species level in the past three decades. More recent observations of phytoplankton communities have been conducted using Chemtax applications (2004 – 2009; Pan et al., 2011) and satellite remote sensing (2002 – 2016; Moisan et al., 2017). A bi-weekly to monthly microscopy-based phytoplankton community analysis was conducted by Makinen and Moisan (2012) at stations 9.6 km and 40.7 km off of Assateague Island between June 2005 and December 2007. Collectively, these works indicate, that at a functional group level, the phytoplankton community structure observed between 2002 and 2016 was similar to that described between the 1960s and 1980s by Marshall and colleagues.

Marshall (1982) made the first report of *Karenia* (as *Gymnodinium breve*) from coastal waters in the mid-Atlantic region in June 1980 from samples collected between the mouth of Chesapeake Bay, Virginia and Oregon Inlet, North Carolina. In November 1987, a *K. brevis* bloom was transported to the North Carolina coast via the Gulf Stream where it persisted for approximately four months (Tester et al., 1991). This *K. brevis* bloom, reported as *G. breve*, contained other *Gymnodinium* species (West et al., 1996), which may represent organisms now identified as other *Karenia* species (Daugbjerg et al., 2000; de Salas, 2004; Haywood et al., 2004). Two decades later a red tide, expatriated from Florida and traveling within the Gulf Stream, was transported to Delaware's coastal waters where it was observed in the late summer of 2007 (Walsh et al., 2009) and determined to be dominated by *K. papilionacea* with the presence of *K. brevis*-like cells (Bott, 2014). Portions of this same exported bloom persisted from September 2007 through January 2008 in the coastal bays on Florida's east coast (Walsh et al., 2009) and contained multiple *Karenia* species, including *K. brevis, K. mikimotoi, K. papilionacea, K. selliformis*, and the undescribed *Karenia* sp. #3 (Wolny et al., 2015).

Following this 2007 bloom, water quality and HAB monitoring programs in the Delaware and Maryland portion of the Delmarva Peninsula have routinely detected these same five *Karenia* species in summer and autumn offshore and coastal bay phytoplankton populations ranging from background (100-1000 cells L^{-1}) to bloom level (>100,000 cells L^{-1}) concentrations. However, the origins of these populations are unknown. Using a genetic analysis, Coyne et al. (2015) detected the presence of a *K. papilionacea* strain, unique from Gulf of Mexico and New Zealand strains, in the shelf waters off Delaware in June 2015 and then along the coast in July 2015, indicating a potential regional offshore source for coastal blooms. Liu et al. (2020; 2021) showed that cyst production and sequestering in sediments is a possible source of the *K. mikimotoi* blooms in the coastal waters of China, but cysts have not been documented in other *Karenia* species (Persson et al., 2013; Feki-Sahnoun et al., 2017) and were not detected in Delaware coastal sediments (Coyne et al., 2015). Ballast water could also be an

Table 3

Abundance, location, timing, and the salinity and temperature ranges reported for each *Karenia* species detected offshore the Delmarva Peninsula during the 2018 coastal cruises.

Species	Maximum cell L^{-1}	Offshore Area of Occurrence	Timing	Salinity	Temperature(°C)
K. brevis-like	1.10×10^3	DE, MD	July	29.2 – 30.3	24.0 – 26.4
K. mikimotoi	1.91×10^5	DE, MD, VA	June, July, October	28.1 – 33.4	19.4 – 25.1
K. papilionacea	1.59×10^5	DE, MD, VA	June, July, October	28.3 – 33.4	21.8 – 26.4
K. selliformis	1.99×10^4	DE, MD, VA	June, July, October	28.5 – 33.3	21.3 – 25.4
Karenia sp. #3	1.50×10^3	DE, MD	July, October	30.0 – 32.9	23.4 – 24.3

introduction mechanism of *Karenia* spp. to the Delmarva Peninsula region. Thousands of commercial vessels visit ports in both Chesapeake Bay (Carney et al., 2017) and Delaware Bay (Altiok et al., 2012) annually. Carney et al. (2017) reported that ballast water discharges to the Chesapeake Bay increased by 374 % between 2005 and 2013 and an earlier study by Drake et al. (2005) indicated that 15 % of commercial vessel traffic to this region came from Florida ports. However, Garrett et al. (2011) did not find *Karenia* spp. cells or cysts in ballast water or sediment samples collected from commercial vessels docked in Tampa Bay ports during a 3-year study conducted to determine the possibility of HAB species, including *Karenia* spp., being moved into or out of Florida waters from ballast exchange operations. Finally, Tester and Steidinger (1997), Walsh et al. (2009), and Weisberg et al. (2019) demonstrated that *K. brevis* blooms (and other *Karenia* species contained therein; Wolny et al., 2015) can be exported out of the Gulf of Mexico via the Loop Current and transported along the United States east coast via the Gulf Stream. While this latter mechanism is the most likely source of the Delmarva Peninsula *Karenia* blooms, the lack of routine monitoring of coastal and shelf waters precludes a broader understanding of the origins of *Karenia* populations in the mid-Atlantic region and spatially- and temporally-rigorous sampling should be considered in future monitoring and research programs to answer this question.

The different environmental conditions wherein each *Karenia* species have been observed suggests that each species may have its own environmental niche in the mid-Atlantic region (Tables 2 and 3). In the Gulf of Mexico, *K. brevis* is the most successful of the *Karenia* species based on its numerical and spatial dominance across a range of elevated temperatures (20 – 28 °C) and salinities (31 – 37) observed there (Steidinger, 2009). Based on data collected during the 2018 and 2019 Delmarva Peninsula coastal cruises and regional monitoring programs, *K. mikimotoi* occupies the broadest temperature and salinity niche space (7.0 – 26.7 °C and 19.7 – 30.9 salinity) of the *Karenia* species. However, routine monitoring data suggest that *K. papilionacea* is the most frequently detected and abundant *Karenia* species in the mid-Atlantic region of the United States (n = 239 observations, maximum concentration = 5.8×10^6 cells L^{-1}). Targeted monitoring of coastal waters and kinetic studies using cultured isolates from contrasting environments would help shed light on the optimal niche space for each *Karenia* species as other mid-Atlantic HAB species (e.g., *Chattonella* spp., *Heterosigma akashiwo*, *Margalefidinium polykrikoides*) are known to occupy different niche spaces than their global counterparts (Handy et al., 2005; Zhang et al., 2006; Mulholland et al., 2009).

Both the historical work in the mid-Atlantic region conducted by Marshall and Cohn (1983, 1987) and Wagoner and Marshall (1991) and the more recent studies by Pan et al. (2011) and Moisan et al. (2017) indicate that summer dinoflagellate populations, and their fractional contribution to the total chlorophyll, increase from the coastline towards the shelf, with the greatest concentrations at the mid-shelf region (Moisan et al., 2017) and to the south of the Chesapeake Bay mouth (Wagoner and Marshall, 1991). This area has largely been devoid of systematic, high frequency *in situ* monitoring of phytoplankton populations. Satellite imagery processed by Moisan et al. (2017) shows seasonally high concentrations of the carotenoids 19′-hexanoyloxy-yfucoxanthin and 19′-butanoyloxyfucoxanthin, pigments often used as a proxy measurement for haptophytes (Latasa, 2007), but these are also the principal accessory pigment of species within the Kareniaceae (Steidinger et al., 2008), whose presence on the shelf has not been regularly investigated. The intrusion of *Karenia* populations to the mid-Atlantic region has vast implications for resource management. The impacts of these blooms depend upon the relative concentrations of each *Karenia* species, the relative rates of toxin production, and the differential toxicity to aquatic communities. Currently, resource management strategies, such as the National Shellfish Sanitation Program (NSSP) guidelines, are based on the cell abundance and brevetoxin concentrations associated with *K. brevis*, which has not yet been observed in actionable concentrations ($\geq$ 5000 cells L^{-1}; NSSP, 2017) in the

Delmarva Peninsula's shellfish harvesting areas. Using LC-MS, Fowler et al. (2015) reported that *K. papilionacea* strains established from a Delaware population produce PbTx-2, though at a significantly lower concentration per cell compared to *K. brevis*. *Karenia papilionacea* is suspected to be toxigenic in other parts of the world (Haywood et al., 2004; Amzil et al., 2021) however, whole water samples collected during nearly monospecific *K. papilionacea* blooms on the Maryland coast, with cell concentrations (1.1 to 2.3×10^5 cells L^{-1}) at or greater than those reported as toxic by Fowler et al. (2015; 1.0×10^5 cells L^{-1}), were negative for brevetoxin.

The toxicity of local *K. mikimotoi* blooms has not been assessed, although hemolytic activity has been reported in cells cultured from Texas blooms (Neely and Campbell, 2006) and *K. mikimotoi* blooms from other regions have caused significant fish kills and economic losses (Li et al., 2019; Sakamoto et al., 2021). Since the 1990s, *K. selliformis* has caused significant fish kills and shellfish toxicity events in Mediterranean waters due to the presence of gymnodimines (Feki et al., 2013). More recently, massive marine life mortality events have been associated with *K. selliformis* blooms in Chilean coastal waters, around Hokkaido Island, Japan, and the Kamchatka, Russia coastline but the mode of toxicity has not been elucidated (Mardones et al., 2020; Iwataki et al., 2022; Orlova et al., 2022). The toxin profile of *K. selliformis* populations found in US waters has not been explored. Culturing and characterizing these species, along with the commonly occurring, yet unidentified *Karenia* sp. #3, is necessary to better relate toxin production by species to environmental variables and to establish a risk management strategy.

The cell concentrations of mid-Atlantic *Karenia* populations (10^5 cells L^{-1}) are less than those of catastrophic *Karenia* blooms reported globally ($10^6 – 10^7$ cells L^{-1}; Steidinger 2009; Vandersea et al., 2020; Hu et al., 2022; Iwataki et al., 2022; Orlova et al., 2022), but are of equal concentrations to the *K. mikimotoi* blooms that impacted shellfish resources in the Gulf of Maine (10^5 cells L^{-1}; Scully et al., 2022). Despite the occurrence of elevated concentrations of *Karenia* spp. on the Delmarva Peninsula coast at temperature and salinity ranges in which other
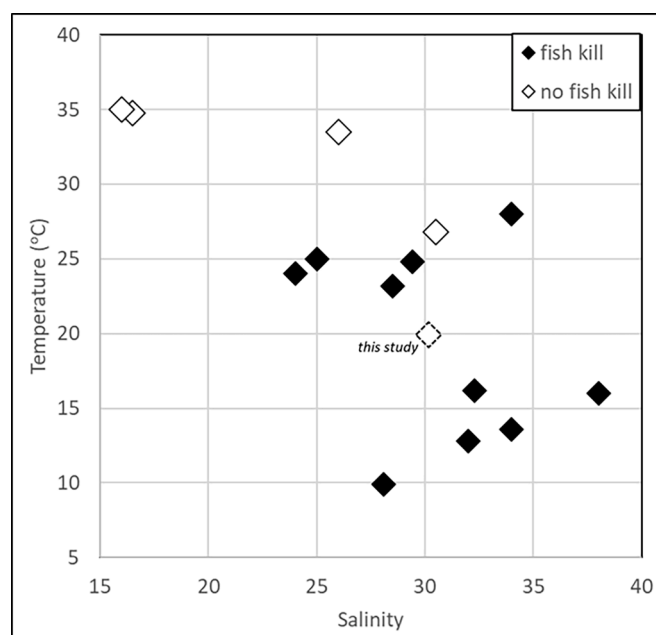

Fig.4. Scatterplot of average temperature and salinity data reported in the literature for fishery impacting (black diamonds) and fishery non-impacting (white diamonds) *Karenia mikimotoi* blooms. Data from this study are represented in the dashed line white diamond. The data presented here were collected from this study, the references listed in Table 4, and Matsuyama (2006), Robin et al. (2013), PIRSA (2014), O'Boyle et al. (2016), Shimada et al. (2016), Aoki et al. (2017), Vandersea et al. (2020), Baohong et al. (2021), (Onitsuka et al. (2021), and Iwataki et al. (2022).

Karenia blooms have caused fish kills (see example for *K. mikimotoi* in Fig. 4), no adverse environmental or human health problems have been reported to date. This is not unlike other toxic, bloom-forming species found in the Delmarva Peninsula region. For reasons unknown, species of *Dinophysis* and *Pseudo-nitzschia* are seasonally present at cell concentrations of concern but have not been associated with negative environmental impacts due to reduced toxin production compared to their global counterparts (Thessen and Stoecker, 2008; Wolny et al., 2020a; Ayache et al., 2023). From a limited number of reports, it appears that not all *Karenia* blooms have been associated with harmful environmental impacts (Table 4). Similarly, not all cultured *Karenia* strains maintain the ability to produce toxins (Sunda et al., 2013), which Lekan and Tomas (2010) linked to inherent genetic differences between cultured strains, indicating toxicity variation within natural populations is possible. The genetic assessment conducted by Coyne et al. (2015) demonstrated that the Delaware *K. papilionacea* population was distinct from the Gulf of Mexico and New Zealand populations, which coupled with different environmental conditions, may explain the lack of or reduced toxin production by the population found here (Fowler et al., 2015) compared to *K. papilionacea* populations reported to be toxic by Haywood et al. (2004) and Amzil et al. (2021). The long-term shifting of environmental conditions may play a role in the toxicity of numerous HAB species (Griffith and Gobler, 2020; Wells et al., 2020; Anderson et al., 2021). Specifically, for *Karenia*, climate change is being correlated to changes in the toxicity of *K. brevis* and *K. selliformis* (Brandenburg et al., 2019) and *K. mikimotoi* and *K. papilionacea* (Kwok et al., 2016) blooms.

Until local representatives of each *Karenia* species are isolated and cultured and controls on their growth and production of bioactive compounds assessed, their potential significance as a toxin source in the current and predicted conditions for the Chesapeake Bay, Delmarva Peninsula, and mid-Atlantic shelf waters cannot be determined. Further, until we better surveil mid-Atlantic waters for the presence of *Karenia* spp., their potential impacts to aquatic and coastal communities cannot be addressed. At present, phytoplankton collections along Delaware's coast are limited to a volunteer-based HAB monitoring program and no routine offshore monitoring is being conducted. Maryland conducts temporally- and spatially-limited phytoplankton monitoring offshore and within its coastal bays. Virginia phytoplankton monitoring is confined primarily within Chesapeake Bay, with limited sampling occurring in the Virginia coastal bays, and no routine offshore monitoring. The data compiled and presented here are from limited *in situ* monitoring activities along the Delmarva Peninsula coast. These data suggest there has been a routine occurrence of several *Karenia* spp. for the past 15 years, although no adverse environmental impacts have been reported. Because data are sporadic, it is difficult to assess whether *Karenia* spp. blooms are of emerging concern in this region. Spatially and temporally robust HAB monitoring programs in this region would help fill data gaps and allow resource managers to assess the potential for a *Karenia* population to impact fishery and recreational resources in the mid-Atlantic region. Climate change is altering mid-Atlantic niche environments and oceanographic patterns (Saba et al., 2016), and could alter the relative distribution, success, and toxicity of *Karenia* in the mid-Atlantic region as it has for other regional harmful algal species (Vidyarathna et al., 2020).

The ultimate causes of the spatial and temporal patterns of *Karenia* spp. observed during the 2018 Delmarva cruises are unknown, but likely reflect differences in each *Karenia* species' environmental preferences, as well as differing physical and environmental forces acting on each species. In a recent study by Kim et al. (2023) in Korean waters, co-occurring *K. mikimotoi* and *K. papilionacea* blooms were documented in the months of March through July, similar to the observations made along the Delmarva Peninsula in 2018. Studies conducted on these species, both in the Korean Strait and the East China Sea, indicate optimal growth occurs between 20 – 24 °C, but that the growth rate of *K. papilionacea* is greater than that of *K. mikimotoi* (Baohong et al., 2021; Kim et al., 2023). Both Vandersea et al. (2020) and Scully et al. (2022) showed that the blooms of *K. mikimotoi* observed in Kachemak Bay, Alaska, and Cape Cod Bay, Massachusetts, respectively, coincided with these regions' maximum water column stratification period. Both studies also noted sufficient nutrient pools at depth, which were exploited by *K. mikimotoi* as the populations underwent diel vertical migration. Similar dynamics have been described for *K. papilionacea* blooms in Japanese coastal waters by Yamaguchi et al. (2016). Bottom phytoplankton populations were not evaluated as part of the 2018 cruises, however, bloom concentrations of both *K. mikimotoi* and *K. papilionacea* were noted from samples collected at the depth of the chlorophyll maximum in June (5.3-11.5 m) and July (6-7.7 m), respectively. In 2019, cruises conducted in May and July failed to find a surface population of *Karenia* but did detect background concentrations of *K. mikimotoi* and *Karenia* sp. #3 in at-depth waters (3.4-11.9 m). Of note, *K. papilionacea* was detected in elevated concentrations at the pycnocline (5 m) in the lower Chesapeake Bay in the late summer and early autumn of 2017, indicating that perhaps a larger, undetected population was advecting into the Bay from offshore, deep waters or that the bloom was concentrated at depth to take advantage of a nutrient pool. Physical forcings, such as those proposed for the 2018 Gulf of Mexico *K. brevis* bloom by Weisberg et al. (2019), in which an overwintering population was reseeded with a new bloom population or nutrient regeneration from N_2 fixation, decaying fish, and other processes (Mulholland et al., 2004; 2006; 2014; Walsh et al., 2009; Bronk et al., 2014; Heil et al., 2014), may play a role in the species diversity and cell concentrations seen here as in other areas where *Karenia* blooms are known to persist.

Dating back to 2007 in Delaware (Bott, 2014) and 2012 in Maryland (J. O'Neil and J. Wolny, unpublished data), multiple *Karenia* species have been annually reported at background to low cell concentrations (100 to < 10,000 cells L^{-1}) in summer to early autumn samples collected as part of each state's coastal HAB monitoring and offshore research programs. Based on a limited number of samples, *Karenia* appear to

Table 4
Published reports of non-harmful *Karenia* blooms.

Species	Maximum cell L^{-1}	Area of Occurrence	Timing	Average Salinity	Average Temperature (°C)	Reference
K. longicanalis	1.8×10^5	Victoria Harbour, Hong Kong	May	30	n/a	Yang et al., 2001
K. mikimotoi	10^4	English Channel	August	34.75	16.5	Zevenboom et al., 1991*
	3.9×10^4	Hoketsu Bay, Japan	August	33.5	26	Koizumi et al., 1996**
	1.5×10^7	Cochin Estuary, India	October	26.8	30.5	Madhu et al., 2011
	1.4×10^6	English Channel	July	35	16	Hartman et al., 2014
	1.9×10^5	Delmarva Coast	June	27.9	19.6	this study
K. papilionacea	1.8×10^4	Arabian Gulf	January	41.6	14.0	Al-Yamani et al., 2012
	6.1×10^3	Kochi Prefecture, Japan	May, June	33.4	29.2	Yamaguchi et al., 2016
	3.2×10^7	Kuwait Bay	April	41.6	23.8	Polikarpov et al., 2020
	2.1×10^6	Delmarva Coast	July	25.5	20.9	this study
	5.8×10^6	Chesapeake Bay	September	26.3	23.2	this study

*Data published using *Gyrodinium aureolum* as species name. **Data published using *Gymnodinium mikimotoi* as species name.

occur less frequently in Virginia coastal waters. However, *Karenia* blooms do occur in mid-Atlantic waters as evidenced by high concentrations of *K. papilionacea* found in the Chesapeake Bay, from samples collected near the Bay mouth and Virginia's eastern shore, and blooms of both *K. mikimotoi* and *K. papilionacea* found along the Delaware and Maryland coasts in 2010, 2016, 2018, and 2019. The *K. papilionacea* bloom documented in 2016 occurred along both Delaware and Maryland coastlines but was not reported in Virginia waters. In 2017, when *K. papilionacea* was reported in the Chesapeake Bay for the first time, concentrations were equal to bloom concentrations of *K. brevis* in the Gulf of Mexico (10^6 cells L^{-1}; Steidinger, 2009), but no blooms were reported in either Delaware or Maryland waters. In the summer of 2018, when bloom concentrations of *Karenia* were reported in Maryland's coastal waters, cells were in low abundance in Delaware coastal waters (1000 cells L^{-1} in June and $\leq$ 7000 cells L^{-1} in July) and absent in the lower Chesapeake Bay and the Virginia coastal bays. The data presented here indicate that along the Delmarva Peninsula *Karenia* blooms are patchy and likely subject to estuarine outflows, prevailing wind patterns, and/or ocean currents. The inclusion of more *in situ* sampling coupled with remote sensing technologies (e.g., regionally tuned satellite algorithms, autonomous monitoring platforms, imaging flow cytobot arrays) and interagency cooperation are needed to detect and track HAB occurrences. Satellite remote sensing is proving useful for detecting and tracking non-*Karenia* HABs in this region (Wolny et al., 2020b; Xiong et al., 2023). Unfortunately, not enough data exist to determine how successful these remote sensing processes are at detecting and tracking *Karenia* blooms along the Delmarva Peninsula even though satellite remote sensing has been used successfully to monitor *Karenia* blooms in other global locations (Jordan et al., 2021; Hu et al., 2022; Iwataki et al., 2022).

5. Conclusions

Karenia populations are routinely present in the mid-Atlantic region, raising concerns that there are now resident offshore populations or populations being introduced seasonally via the Gulf Stream more frequently than historic phytoplankton surveys have shown. Coastal HAB monitoring occurring on the Delmarva Peninsula is spatially- and temporally-limited raising the possibility that the full extent of these blooms are not being detected with current *in situ* sampling efforts. Similar shifts in HAB events have been noted for other locations on the United States eastern seaboard during the same time period of this study. These emerging HABs (i.e., *Pseudo-nitzschia australis* in the Gulf of Maine (Clark et al., 2022), *Dinophysis acuminata* in Long Island Sound (Hattenrath-Lehmann et al., 2013) and Chesapeake Bay and the Delmarva Peninsula's coastal bays (Wolny et al., 2020a; Ayache et al., 2023), and *Aureoumbra lagunensis* in Florida's Indian River Lagoon (Phlips et al., 2021)) have been tied to warming water masses, ocean current variations, and changes in circulation patterns within smaller embayments that impact water residence times. The role that climatic variability (e.g., shifts in the Gulf Stream), environmental niche changes (e.g., warming water temperature), and outflow variations from the Chesapeake Bay and Delaware Bay plumes (Filippino et al., 2009; Saba et al., 2016; Jiang and Xia, 2016; Xu et al., 2020) play in establishing and concentrating *Karenia* blooms in this region of the mid-Atlantic coast are unknown. A toxin risk assessment should be conducted in Maryland and Delaware waters to safeguard aquatic resources even though no adverse events due to *Karenia* blooms have been reported to date. A toxin assessment conducted in the Virginia portion of the Chesapeake Bay in 2019 and 2020 did not find brevetoxin in whole water or shellfish tissues (Pease et al., 2023), but this study excluded Virginia's coastal bays and offshore sites, where *Karenia* would most likely occur. Investigating these questions, alongside evaluating risks to the Delmarva Peninsula's growing aquaculture and coastal fishery industries (Froehlich et al., 2022), will require focused research efforts and *in situ* water quality and HAB monitoring programs with greater spatial and temporal extent than

current capacities.

CRediT authorship contribution statement

Jennifer L. Wolny: Conceptualization, Data curation, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing, Visualization. **Edward B. Whereat:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Todd A. Egerton:** Data curation, Formal analysis, Resources, Visualization, Writing – original draft, Writing – review & editing. **Leah A. Gibala-Smith:** Data curation, Investigation, Writing – review & editing. **John R. McKay:** Investigation, Resources, Writing – review & editing. **Judith M. O'Neil:** Funding acquisition, Investigation, Resources, Writing – review & editing. **Catherine E. Wazniak:** Funding acquisition. **Margaret R. Mulholland:** Conceptualization, Project administration, Resources, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

www.citizen-monitoring.udel.edu, www.eyesonthebay.dnr.maryland.gov, and https://datahub.chesapeakebay.net.

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