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LETTER

Tracking a large-scale and highly toxic Arctic algal bloom: Rapid detection and risk communication

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Scientific Significance Statement

Climate warming is expanding the potential for harmful algal blooms (HABs) to occur in polar waters, raising significant concerns about emerging human and ecosystem health impacts. Recent observations of HAB species and algal toxins in Arctic waters have established a clear need for a better understanding of bloom dynamics coupled with detection and mitigation strategies. During summer 2022, a massive bloom of the toxic dinoflagellate *Alexandrium catenella* was detected as it moved through the Bering Strait region. This bloom was exceptional in scale, density, and toxicity, far exceeding any events reported previously in Arctic waters. This unprecedented risk to the remote coastal communities of the region was communicated in near real time, providing the opportunity for rapid mobilization and establishing a framework for future event response.

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Author Contribution Statement: DMA and RSP conceptualized the field program. Field data collection was conducted by RSP, EF, EM, KH, NNS, MP, JH, KAH, and DAS. All laboratory analyses and data processing related to bloom density and toxicity were performed by EF, KH, NNS, AR, MP, and MB. Hydrographic and velocity analyses were conducted by RSP, PL, LTM, JH, and FB. Nutrient measurements were collected and analyzed by DAS. Bloom communication and response was a collaboration between GS, EP, DMA, KAL, TJF, EM, and EF. Manuscript text was composed by EF with support from all coauthors.

Data Availability Statement: Biological data and metadata associated with the bloom event are available at the NSF Arctic Data Center (ADC) (https://doi.org/10.18739/A2804XM7S). Nutrient data from the NRS2022 cruises are also accessible at the ADC (https://doi.org/10.18739/A2M90249T). All hydrographic CTD data from the NRS2022 cruises are available at the ADC (https://doi.org/10.18739/A2B853K56), and ADCP data are available at the NOAA National Centers for Environmental Information (https://doi.org/10.25921/q8rx-9r22).

Additional Supporting Information may be found in the online version of this article.

Abstract

In recent years, blooms of the neurotoxic dinoflagellate *Alexandrium catenella* have been documented in Pacific Arctic waters, and the paralytic shellfish toxins (PSTs) that this species produces have been detected throughout the food web. These observations have raised significant concerns about the role that harmful algal blooms (HABs) will play in a rapidly changing Arctic. During a research cruise in summer 2022, a massive bloom of *A. catenella* was detected in real time as it was advected through the Bering Strait region. The bloom was exceptional in both spatial scale and density, extending > 600 km latitudinally, reaching concentrations > 174,000 cells L^{-1}, and producing high-potency PST congeners. Throughout the event, coastal stakeholders in the region were engaged and a multi-faceted community response was mobilized. This unprecedented bloom highlighted the urgent need for response capabilities to ensure safe utilization of critical marine resources in a region that has little experience with HABs.

Warming air temperatures (Overland et al. 2019), reduction in seasonal sea ice extent (Stroeve and Notz 2018), and increased northward heat flux through the Bering Strait (Woodgate 2018) are facilitating establishment of temperate and subpolar species in Pacific Arctic waters (Polyakov et al. 2020). This climate change-driven borealization spans trophic levels, from plankton and fish to megafauna (Mueter et al. 2021), with widespread implications for both marine and human communities (Huntington et al. 2020). One emerging organism of significant concern is the harmful algal bloom (HAB) dinoflagellate *Alexandrium catenella*, a globally distributed species that blooms along temperate and subpolar coasts in the spring and summer. Climate change is predicted to expand the spatiotemporal range of this genus in many regions (Gobler et al. 2017; Boivin-Rioux et al. 2021), and particularly in shallow shelf ecosystems with strong seasonal temperature variability (Brosnahan et al. 2020).

A. catenella produces a potent suite of neurotoxins called paralytic shellfish toxins (PSTs), which accumulate in organisms that consume the algae. These toxins are transferred through the food web and cause illness or mortality of marine organisms (Shumway et al. 2003; Starr et al. 2017), as well as paralytic shellfish poisoning (PSP) in humans who eat contaminated seafoods (Etheridge 2010). In recent years, PSTs have been detected widely in the Pacific Arctic, including in many key species of marine birds and mammals (Lefebvre et al. 2016, 2022; Van Hemert et al. 2021). These emerging toxins are a major concern for people in the region, whose culture and lifestyle are underpinned by a strong tradition of marine subsistence harvest, and who also benefit economically from the productive commercial fisheries of the Bering Sea. Unlike other parts of the world where shellfish are considered the primary vector for PSP, people in Alaska and Chukotka utilize a myriad of marine organisms from across the food web (Ballew et al. 2004), many of which are potential vectors for PSTs. Toxin retention in Arctic taxa consumed as seafood is still largely uncharacterized, complicating understanding of this emerging risk.

While there is a long history of *A. catenella* blooms and PSTs in the Gulf of Alaska and Russian Pacific coast (Vershinin and Orlova 2008; Lewitus et al. 2012), observations in the Bering Strait and northward are comparatively sparse and largely concentrated in recent years (Bursa 1963; Walsh et al. 2011; Natsuike et al. 2017*a*; Anderson et al. 2022; Einarsson et al. 2022). *A. catenella* overwinters in the benthos as a resting cyst, and accumulations of these cysts (cyst beds) serve as the source for blooms when bottom temperatures are sufficiently warm to induce germination. In recent years a massive *A. catenella* cyst bed (~ 145,000 km^2) has been characterized in the US waters of the Chukchi Shelf (Gu et al. 2013; Natsuike et al. 2013; Anderson et al. 2021). This cyst bed (located in Ledyard Bay, *see* Fig. 1A for place names) represents a significant potential source for polar blooms. Observations of species distribution and regional hydrography indicate that these cysts were likely deposited over time by blooms advected northward through the Bering Strait, although there is still considerable uncertainty as to where in the Bering Sea blooms of *A. catenella* originate.

A HAB-focused research cruise aboard the R/V Norseman II in July–September 2022 aimed to better characterize these regional dynamics. During back-to-back cruise legs, an Imaging FlowCytobot (IFCB) was configured to sample near-surface waters as the ship surveyed the northern Bering, Chukchi, and western Beaufort Sea regions. This instrument collected imagery of the phytoplankton community along the cruise track and enabled real-time detection of a massive and highly toxic bloom of *A. catenella* as it spread into Arctic waters over the course of 6 weeks. Unlike other parts of the contiguous US coastline where state agencies regularly test for HAB species and algal toxins (Shumway et al. 1988), this region of Alaska has no offshore HAB monitoring programs, despite the reliance of many coastal communities (Fig. 1A) on marine resources for subsistence and commercial activities. Shortly after initial bloom detection, risk advisories were distributed to local tribal governments, regional media, and the public. These efforts mobilized a rapid and unprecedented regional

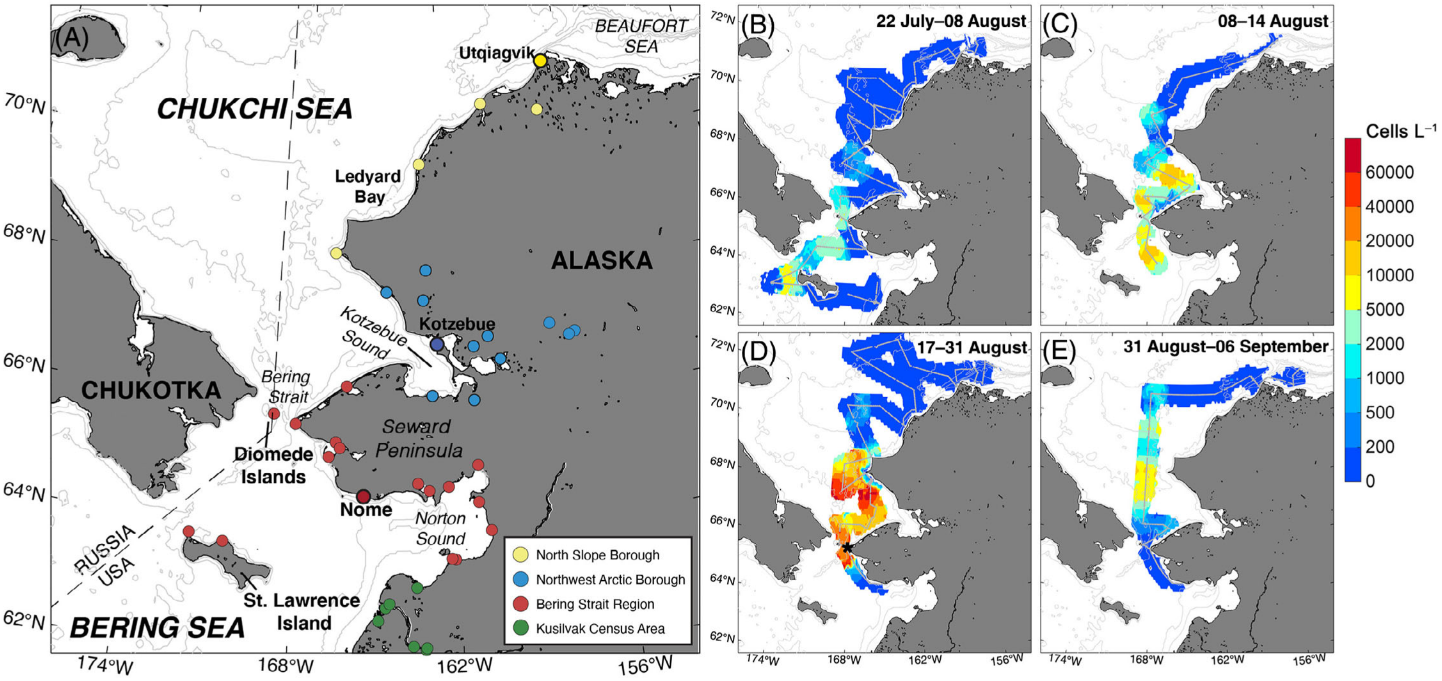

Fig. 1. Regional map and progression of the 2022 *Alexandrium catenella* bloom based on near-surface cell densities. (**A**) Map of the region depicting major water bodies, land masses, and the maritime boundary with Russia. Alaskan communities within designated regional boroughs are indicated by colored points; regional hub communities are labeled in bold. Bloom observations are grouped by the outbound and return transit of each survey, where the gray dots are the shipboard data points; (**B**) 22 July–08 August, (**C**) 08–14 August, (**D**) 17–31 August, (**E**) 31 August–06 September. Graduated color scale indicates *A. catenella* cell density calculated from annotated IFCB imagery; observations are interpolated using a gridding routine that puts more weight along the isobaths (Davis 1998), since the flow on the Chukchi shelf is largely guided by the bathymetry. Locations of the regional hub communities are labeled, and an asterisk is used in (**D**) to indicate location of highest cell density measured in the bloom (174,000 cells L^{-1}).

response in an area with little experience of HABs, much less one of this magnitude.

Methods

Cruise details and hydrographic data

Data collection took place during a two-leg research expedition aboard the R/V *Norseman II* in summer 2022 (NRS2022_01S, 19 July to 15 August; NRS2022_02S, 17 August to 6 September). Each leg departed from and returned to the Bering Strait regional hub community of Nome, Alaska, sampling waters in the Northern Bering Sea, Bering Strait, Chukchi Shelf, and Western Beaufort Sea. Underway velocity profiles were collected with a shipboard acoustic Doppler current profiler (ADCP; TRDI WH300 transducer) (Bahr et al. 2023), and subsequently de-tided using the Oregon State University barotropic tidal model version TPXO (Padman and Erofeeva 2004). Underway temperature and salinity were recorded by an in-line SBE21 thermosalinograph via the ship's underway seawater system (intake at approximately 3 m depth). At discrete stations, a conductivity–temperature–depth (CTD, Sea-Bird 911 plus) system mounted on a rosette with 12 10-liter Niskin bottles was used to profile the water column (McRaven and Pickart 2024). At select stations, discrete samples were collected throughout the water column for *A. catenella* enumeration and nutrient analyses (see Supplementary Methods; Goñi and Stockwell 2024).

Imaging FlowCytobot

An Imaging FlowCytobot (IFCB, McLane Laboratories; Olson and Sosik 2007) was configured to sample from the shipboard underway seawater system. This instrument was programmed to operate continuously, processing ~ 5 mL every 20–30 min with chlorophyll-triggered image acquisition, to provide comprehensive imagery of the phytoplankton community along the cruise track. Images were GPS-stamped and available to view in real-time, allowing rapid identification of harmful algal species. Additionally, all imagery data were processed using a convolutional neural network-based machine classifier that identified *Alexandrium* and 93 other taxonomic groups (most to genus level) (https://github.com/WHOIGit/ifcb_classifier.git). Following the cruise, the output of the machine learning classifier was manually annotated to identify all *A. catenella*, and the resulting human-validated data were used to produce a final estimates of cell concentration (Fachon et al. 2024). This annotated dataset is being used to refine a region-specific classifier for future *Alexandrium* detection.

Toxin analyses: PSTs

At a subset of stations, the plankton community was concentrated for toxin analysis via a net tow (0.5 m, 20 μM mesh) deployed vertically through the top 30 m of the water column. Opportunistically, as bloom concentrations of *A. catenella* (> 1000 cells L^{-1}) were detected in the IFCB imagery, large volumes of underway seawater (20–60 liters) were concentrated using a 15 μM mesh sieve, providing the opportunity to collect toxin data during transit. The concentrated net tow or underway sample was centrifuged ($3000g \times 5$ min) to concentrate biomass, and the resulting pellet was resuspended in 1 mL 0.05 M acetic acid, with triplicate subsamples collected for corresponding *A. catenella* cell counts. Plankton pellets were frozen (-20°C) until further analysis.

To break cells open for complete toxin extraction, samples were subjected to several freeze–thaw cycles, sonified in an ice bath (Branson Sonifier 250D, microtip probe, 1 min at 40-watt output), and centrifuged ($3000g \times 5$ min, 4°C). The supernatant was passed through a Waters Sep-Pak C18 light cartridge and the eluate was centrifuged through an Amicon Ultra 10,000 NMWL molecular weight filter ($14{,}000g \times 15$ min). This purified product was analyzed on a Waters 2695 HPLC coupled to a 2475 fluorescence detector using post-column derivation (Oshima 1995; *see* Supplementary Methods for run specifications) and calibrated with reference standards from the National Research Council Canada (Halifax, Nova Scotia, Canada). Congeners measured included: *N*-sulfocarbamoyl gonyautoxin-2 and -3 (C1 and C2), gonyautoxins-1 through -6 (GTX1, 2, 3, 4, 5, and 6), decarbamoyl gonyautoxin-2 and -3 (dcGTX2 and 3), neosaxitoxin (NEO), decarbamoyl saxitoxin (dcSTX), and saxitoxin (STX). Toxin content of each extract was normalized to cell abundance based on triplicate counts and used to calculate fmol cell^{-1} and relative molar % of each congener. Toxin equivalency factors (TEFs) (Oshima 1995; EFSA 2009) and molecular weights were used to calculate fg saxitoxin equivalents (STX eq) cell^{-1}.

Results

Bloom scale and progression

The summer 2022 *A. catenella* bloom (defined as densities > 1000 cells L^{-1}) was exceptional in density and scale, stretching at least 600 km latitudinally from the northern Bering Sea to the southern Chukchi Sea at its peak extent (Fig. 1B–E). Maximum near-surface concentrations of *A. catenella* were $> 174{,}000$ cells L^{-1}; concentrations in excess of > 1000 cells L^{-1} are considered dangerous (Vandersea et al. 2018). This is extraordinarily dense for an offshore bloom of this species, and far exceeds any other *Alexandrium* blooms previously documented in polar waters (Bursa 1963; Walsh et al. 2011; Natsuike et al. 2017*a*; Anderson et al. 2021). The bloom was first detected west of St. Lawrence Island on 25 July, where near-surface current measurements indicated that the cells entered the study region from western waters and were advected northward through the Bering Strait (Fig. 2). This early stage of the bloom was found on the western US side of the Bering Strait, likely extending into unsampled Russian waters. As the event progressed, Ekman flow, driven by strong southerly winds in early August, mixed the bloom into eastern waters north of the Bering Strait. By mid-August, *A. catenella* made up the majority of surface phytoplankton biomass in large portions of the region, reaching over 70% biomass in the outer waters of Kotzebue Sound (Supplementary Fig. S1C). Subsurface water samples revealed that bloom concentrations persisted through the upper water column and down to 20–30 m at the peak of the event (Supplementary Fig. S2). By early September, the bloom had fully passed through the Bering Strait (Fig. 1E) and was beginning to diminish in intensity, although bloom concentrations were still detectable on the southern Chukchi Shelf.

Nutrient conditions throughout the bloom were variable, with cells present in high densities across a broad range of nutrient concentrations (Supplementary Table S1; Fig. S3). At first bloom detection in late July, nutrients were relatively abundant in near-surface waters (top 20 m), with dissolved inorganic nitrogen (DIN) concentrations of 4.5 ± 4.2 μM, and a mean N : P ratio of approximately 7 : 1. Nitrate was the dominant DIN form but decreased throughout the bloom, while ammonium was enriched at the bloom peak, present at levels of 1.5 ± 1.0 μM or 46% of available DIN. *A. catenella* preferentially uptake ammonium, and these concentrations are within the optimal range for growth (Shankar et al. 2014). Phosphate concentrations remained relatively constant

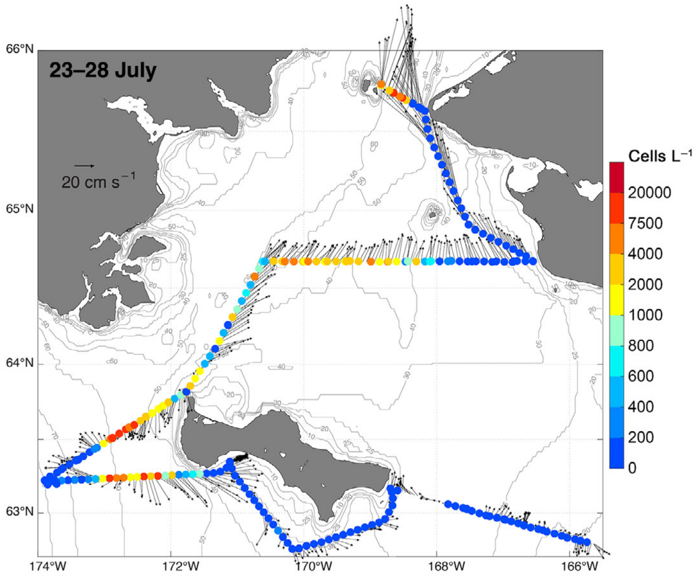

Fig. 2. Surface currents associated with initial bloom detection (23–28 July 2022). *Alexandrium catenella* cell abundance is indicated by colored points and black arrows indicate surface (top 25 m) current velocities measured by the shipboard acoustic Doppler current profiler (ADCP).

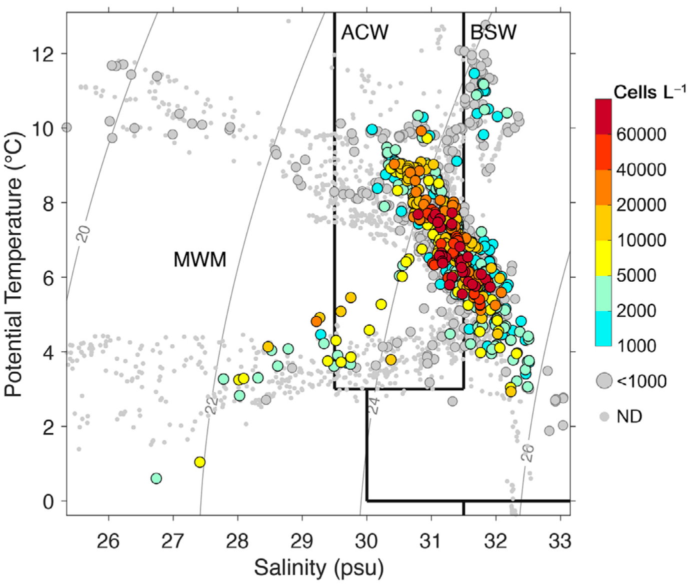

Fig. 3. Water properties of the *Alexandrium catenella* bloom, plotted in potential temperature-salinity (T-S) space. Each point represents a single IFCB sample collected between 22 July and 06 September, where the color indicates *A. catenella* cell density (ND = not detected). Thin gray lines are potential density (kg m^{-3}). Thick black lines delineate the major regional summertime water masses, ACW, Alaskan Coastal Water; BSW, Bering Summer Water; MWM, Melt Water/Meteoric Water (*see* Supplementary Table S2; Pickart et al. 2023).

through the event (0.58 ± 0.22 μM), but by early September DIN was depleted relative to initial concentrations.

At the peak of the bloom, surface waters were predominantly between 5–9°C and 30.5–32 psu (Fig. 3). While cooler than the thermal optimum for this species, these temperature and salinity (T–S) conditions are supportive of *A. catenella* growth (Natsuike et al. 2017*b*). Given this T–S signature and the direction and location of initial bloom detection, it is clear that this bloom originated in Bering Summer Water, which is saltier than Alaskan Coastal Water (Pickart et al. 2023; Supplementary Table S2). However, as the bloom progressed northward it was subsequently mixed into fresher and warmer Alaskan Coastal Waters (e.g., during the southerly wind event). Further study is needed to better understand where in the Bering Sea the cells may have emerged, although this is made challenging by limited access to the Russian EEZ. Observations along the Russian coast indicate a possible source in the Gulf of Anadyr or Kamchatka (Orlova and Morozova 2013); however, cysts have also been documented farther south in the eastern Bering Sea (Natsuike et al. 2013).

Throughout the surveys, few *A. catenella* cells were observed along the northeast Chukchi Shelf or in the Beaufort Sea. Temperatures on the Chukchi Shelf in summer 2022 were low compared to prior years (Supplementary Fig. S4). In particular, the average near-bottom temperature at stations near the Ledyard Bay cyst bed was 1.8 ± 1.4°C, well below the threshold required for significant germination of *A. catenella* cysts (Anderson et al. 2021). Thermal suppression of the Ledyard Bay cyst bed explains the minimal presence of *A. catenella* in northeastern waters of the study region during this period. After advecting through the Bering Strait, the bloom documented here likely deposited new cysts onto the Chukchi seafloor, reinforcing the reservoir of cysts present to initiate future Arctic blooms.

Toxicity

The poisoning risk from this expansive bloom was compounded by the high toxicity of its cells. The PST congeners produced by *A. catenella* vary in their potency by more than 100-fold (EFSA 2009), and toxin production differs widely across strains and bloom events (Anderson et al. 2012),

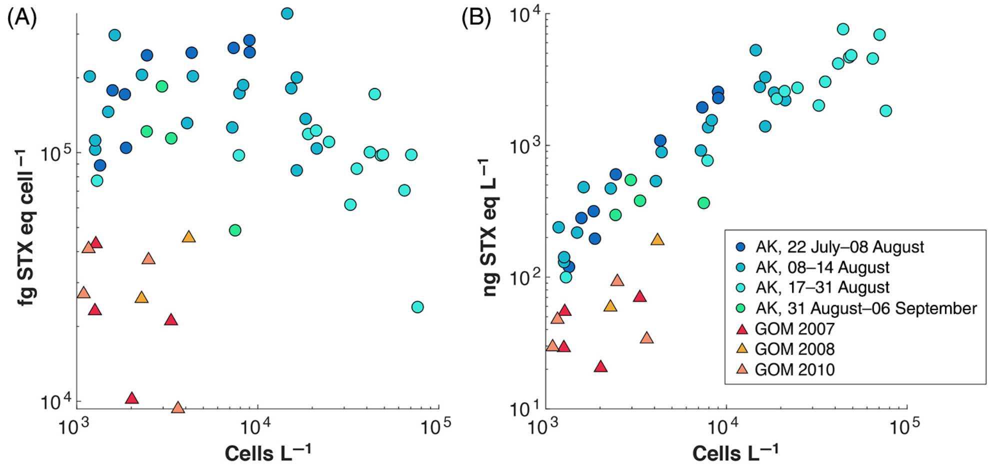

Fig. 4. Bloom toxicity and cell density. (**A**) Cellular toxicity (fg STX eq cell^{-1}) is plotted against cell concentration for all 2022 bloom samples (AK, cool colors, $n = 44$). To place these values into context with another region, cell toxicities and concentrations are also plotted for 3 yr of bloom data from the Gulf of Maine (GOM, warm colors, $n = 10$; sourced from Deeds et al. 2014). (**B**) Cellular density is plotted against toxin content in the water (ng STX eq. L^{-1}, based on cell toxicity × cell density) for both regions.

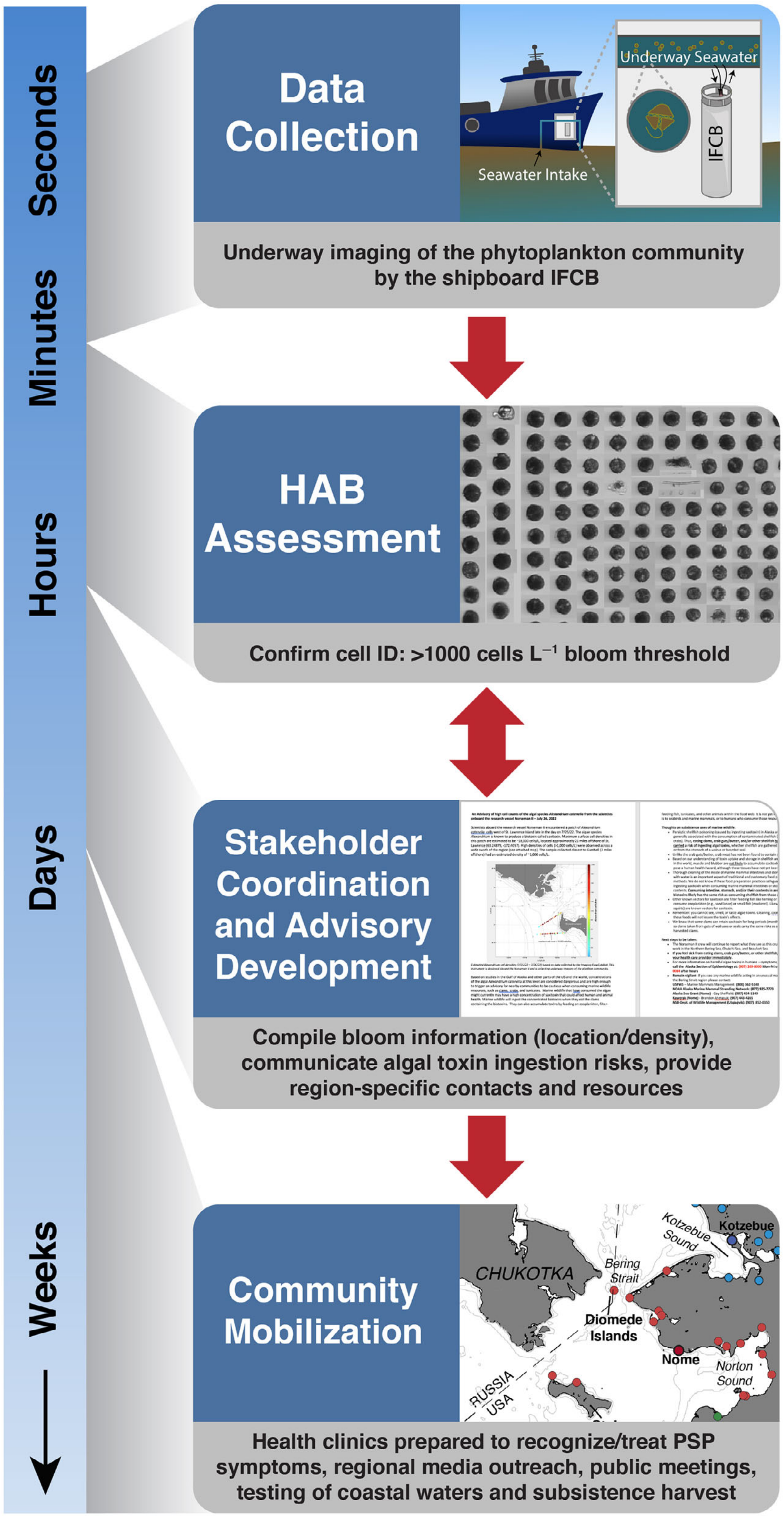

Fig. 5. Timeline and structure of information flow from the shipboard IFCB to the regional coastal response. Steps in this process included: Data Collection (seconds to minutes), HAB Assessment (minutes to hours), Stakeholder Coordination and Advisory Development (24–48 h, *see* Supplementary Materials for advisory text), and Community Mobilization (days, weeks, continuing).

making the specific toxin profile an important component in assessing the risk presented by a bloom. The bloom described here produced high-potency congeners: 49% ± 11% gonyautoxin-4 (GTX4), 21% ± 10% neosaxitoxin (NEO), 12% ± 4% gonyautoxin-3 (GTX3), and 9% ± 4% saxitoxin (STX), with minor contributions from other congeners (Supplementary Table S3).

The amount of toxin within cells was also high (525 ± 252 fmol cell^{-1}), or 150,000 fg STX eq cell^{-1} after normalizing all congeners for potency relative to saxitoxin, and estimated volumetric toxin concentrations ranged from 100 to 7600 ng STX eq. L^{-1} (Fig. 4). These levels far exceed any bloom toxicity that has been recorded in the Gulf of Maine (GOM) across many years of mapping and observation (Stock et al. 2007; He et al. 2008; Deeds et al. 2014); the GOM is used here as a comparison because it is a well-studied shelf ecosystem with comparable *A. catenella* ecology where seasonal blooms regularly cause widespread fishery closures (Bean et al. 2005; Anderson et al. 2014). In general, the toxin content of cells in this Alaskan bloom appears to be higher than that measured for GOM populations (Poulton et al. 2005; Deeds et al. 2014). One possible reason for this is that *A. catenella* cells accumulate more toxins under low-temperature growth conditions (Anderson et al. 1990; Navarro et al. 2006).

The high toxicity of the 2022 Alaskan *A. catenella* bloom begs the question: what is the fate of these PSTs in the environment? While the primary concern during blooms is that toxins will enter the food web through *A. catenella* consumption, the hydrophilic nature of PSTs allows them to persist extracellularly at significant levels (Lefebvre et al. 2008) with unknown ecological implications. PSTs are also degraded over time (Donovan et al. 2008), or preserved in the cysts of *A. catenella* after the bloom terminates (Oshima et al. 1992). The relative prevalence of each of these pathways in the Arctic remains an important area for future study. Although no large-scale die-offs have been directly linked with this bloom, a mortality of 25 adult walruses and 2 gray whales was recorded on 21 August along the northern Seward Peninsula. The walrus carcasses were in moderate to advanced states of decay indicating that they had died prior to observation, likely south of the Bering Strait, and been subsequently washed ashore. No PSTs were detected in samples collected from two walruses, making it impossible to confirm the role of toxins in the cause of death. However, given the compromised state of the carcasses, PST exposure cannot be ruled out.

Rapid regional response

Traditional methods of HAB detection involve laboratory microscopy or toxin analyses (Sellner et al. 2003), leading to delays between data collection and dissemination of results. During this field program, data produced by the shipboard IFCB allowed for real-time HAB identification and response. Within hours of initial bloom detection, the research team contacted healthcare and research partners based in the Bering Strait region to report findings (Fig. 5). As the event progressed and the bloom moved northward, these teams collaborated to draft and release multiple advisories that informed communities of the evolving bloom and risks associated with ingesting algal toxins.

Despite the fact that no HAB of this magnitude had been recorded in the region previously, the community response was rapid, comprehensive, and effective: healthcare clinics mobilized to recognize and treat symptoms of PSP, local media was notified, shore-based HAB sampling efforts were bolstered, and public meetings were held to educate community members about the event. As a result of this information, many coastal residents elected to forgo subsistence harvesting of organisms that were identified as potential toxin vectors (e.g., clams, crabs, forage fish, tunicates, etc.). While these precautions may have prevented illness they were not without significant cost, placing a burden on community members for alternative sourcing of nutrition. Additionally, some seafoods were diverted from household meals for toxin testing, and in one instance a clam submitted by a local family was found to be > 5× the regulatory limit for PSTs. Unfortunately, samples had to be shipped large distances (> 1800 km) to the nearest testing facility, greatly limiting toxin testing in the timely manner required to make well-informed consumption decisions. Overall, the response to this event highlighted the community's ability to collaboratively and quickly respond to an emerging food security and human health threat; this was perhaps best exemplified by the fact that no cases of PSP were reported during or after the bloom. At the same time, it also underlined the need for regionally-based resources such as HAB analytical laboratories and monitoring infrastructure.

Conclusions

The massive spatial scale, high cell density, long duration, and potent toxicity of this HAB event posed an unprecedented risk to human and ecosystem health as well as harvest activities in the Bering Strait region and beyond. While populations of *A. catenella* have been well documented in the Pacific Arctic as well as the north Atlantic (Baggesen et al. 2012; Burrell et al. 2013), the 2022 event was, to our knowledge, the largest *Alexandrium* bloom ever documented in polar waters (Ho et al. 2003; Anderson et al. 2022; Klemm et al. 2022). It represented a striking example of northward bloom advection from subpolar waters, as well as eastward penetration into Alaskan Coastal waters due to local wind forcing; this mixing of nutrient-rich western Bering Sea water with the warm coastal current likely created favorable temperature and nutrient conditions for *A. catenella* growth and accumulation.

Given the absence of any regional offshore HAB monitoring program, a bloom of this size may have escaped detection until cases of PSP had already occurred. However, the underway shipboard characterization of this massive HAB, combined with the real-time communication of *A. catenella* concentrations and PST risks to coastal stakeholders, provided the situational awareness needed for rapid implementation of public health precautions. These outcomes underscore the importance of proactive coordination between research teams and community-based organizations, who can activate existing communication networks to reach remote areas. The results also demonstrate the utility of new technologies, such as the IFCB, for shipboard cell identification and enumeration in remote regions where wide-scale offshore sampling presents logistical or operational challenges.

HAB monitoring and research in western and northern Alaska is subject to unique considerations not shared by the contiguous United States. These include vast amounts of uninhabited coastline between coastal communities accessible only by ship or aircraft, an international border with limited transboundary communication, lack of a regionally based toxin testing infrastructure, and centrality of marine resources to life, culture, and economic well-being. Access to these critical resources is already being impacted in many ways by climate change. For example, eroding coastline and loss of sea ice are altering access to fishing and hunting grounds (Hauser et al. 2021; Gleason et al. 2023); traditionally harvested species are shifting in distribution or behavior (Gadamus et al. 2015); and newly accessible waterways in the Arctic are leading to increased industrial ship traffic, with additional potential to disrupt marine life (Huntington et al. 2015). Amidst this shifting seascape, HABs are yet another emerging regional food security, food safety, and human health threat. As continued warming shifts the Pacific Arctic toward more favorable conditions for *A. catenella* blooms, comprehensive monitoring and response resources will be essential in mitigating the impacts of future bloom events.

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