

1   **Harmful algal blooms in the Alaskan Arctic: an emerging threat as oceans warm**

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20    1. **Abstract**

21   Harmful algal blooms (HABs) present an emerging threat to human and ecosystem health in the  
22   Alaskan Arctic. Two HAB toxins are of concern in the region - saxitoxins (STXs), a family of  
23   compounds produced by the dinoflagellate *Alexandrium catenella*, and domoic acid (DA),  
24   produced by multiple species in the diatom genus *Pseudo-nitzschia*. These potent neurotoxins

25 cause paralytic and amnesic shellfish poisoning, respectively, in humans, and can accumulate  
26 in marine organisms through food web transfer, causing illness and mortality among a suite of  
27 wildlife species. With pronounced warming in the Arctic, along with enhanced transport of cells  
28 from southern waters, there is significant potential for more frequent and larger HABs of both  
29 types. STXs and DA have been detected in the tissues of a range of marine organisms in the  
30 region, many of which are important food resources for local residents. The unique nature of the  
31 Alaskan Arctic, including difficult logistical access, lack of response infrastructure, and reliance  
32 of coastal populations on the non-commercial acquisition of marine resources for nutritional,  
33 cultural, and economic well-being, poses urgent and significant challenges as this region warms  
34 and the potential for impacts from HABs expands.

35 **Introduction**

36 The waters of the Alaskan Arctic (here defined as the interconnected US sub-regions of the  
37 northern Bering, Chukchi, and Beaufort seas) are undergoing rapid and profound environmental  
38 and ecological changes due to substantial decreases in sea ice quality, extent, and duration, as  
39 a result of atmospheric and ocean warming. Additionally, with a predominantly northward flow of  
40 water through the Bering Strait, alterations in southern and northern Bering Sea marine  
41 ecosystems are now propagating into the Chukchi Sea and beyond (Huntington et al., 2020)  
42 leading to cascading effects on marine ecosystems (Stevenson and Lauth, 2019). Among other  
43 warming-related impacts, harmful algal blooms (HABs) are emerging as a threat to marine-  
44 dependent species in the region, including humans. Although HAB species were first  
45 documented in the Alaskan Arctic as early as the mid-20<sup>th</sup> century (Bursa, 1963), new evidence  
46 suggests that their occurrence and future impacts may be much more widespread and severe  
47 than previously thought (Anderson et al., 2021a).

49 HABs are proliferations of algae that cause harm in a variety of ways, with a key mechanism  
50 being the production of potent toxins responsible for illness and death in humans and wildlife  
51 (Anderson et al., 2012). In the Alaskan Arctic, like elsewhere in the world, toxic algae directly  
52 enter the marine food web through planktivorous filter feeders, such as clams and zooplankton,  
53 and can accumulate to levels that sicken or kill higher trophic level consumers including humans  
54 (Fig. 1). Shellfish have historically been considered the primary source of dietary exposure for  
55 toxins but a significant difference in the Alaskan Arctic is that coastal residents rely on a large  
56 diversity of marine resources for food, adding a new and poorly understood dimension to the  
57 threat from HABs.

58

59 There are two primary HAB toxins of concern in this region: 1) saxitoxin and its congeners  
60 (hereafter, STXs) produced by the dinoflagellate species *Alexandrium catenella* and 2) domoic  
61 acid (DA) produced by some diatom species in the genus *Pseudo-nitzschia*. In many areas of  
62 the world, these toxins cause paralytic and amnesic shellfish poisoning (PSP and ASP  
63 respectively) when shellfish are the toxin vectors, but both can also accumulate in other marine  
64 organisms through food web transfer (Fig. 1). DAP is the term used to describe domoic acid  
65 poisoning among wildlife. Other HAB toxins are likely present within the region as well (e.g.,  
66 diarrhetic shellfish toxins (DSTs) produced by *Dinophysis* spp.) but these are not presently  
67 viewed as significant threats.

68

69 Recently, STXs and DA have been detected in marine species throughout the Alaskan Arctic at  
70 a variety of trophic levels, including in benthic invertebrates, zooplankton, forage fish, seabirds,  
71 and marine mammals (Lefebvre et al., 2016; Van Hemert et al., 2021a). In most cases,  
72 reported concentrations in marine wildlife have been relatively low, but potential acute and

73 chronic effects on wildlife health require further investigation. Likewise, there are no recent  
74 medical reports of impacts on human health, but the presence of HAB toxins across multiple  
75 trophic levels that serve as human food resources, combined with current and projected impacts  
76 of climate change (Anderson et al., 2021a), suggest a growing risk that warrants additional  
77 research and action.

78

79 Much of the Alaskan Arctic faces unique obstacles in monitoring and responding to HABs due to  
80 its difficult logistical access and lack of response infrastructure. Besides concerns about food  
81 safety due to accumulation of toxins in marine organisms consumed by humans, HABs can  
82 impact food security by affecting fish and wildlife populations directly (i.e., causing illness or  
83 death among animals), further limiting access to these resources. The dearth of current  
84 knowledge about HABs in the Alaska Arctic underscores the need for expanded research,  
85 monitoring, education, and communication to address food security, conservation, and  
86 public/wildlife health concerns. In this review, we summarize the primary HAB threats to the  
87 Alaskan Arctic, identify potential sources of exposure in the marine food web, and discuss  
88 implications for human and ecosystem health along with challenges to HAB monitoring and  
89 management in this dynamic and rapidly changing environment.

90

91 **2. *Alexandrium* and STXs**

92 Currently, the most significant threat to human and ecosystem health from HABs in the  
93 Alaskan Arctic is from *Alexandrium catenella*, a cyst-forming dinoflagellate that produces  
94 STXs. These toxins can accumulate in fish or shellfish to levels sufficient to cause illness  
95 and death in human consumers, as well as mortalities of marine mammals, birds, and fish.  
96 STXs have long been a problem in the Gulf of Alaska, with reports of illness and fatalities in

97 southeastern and south-central Alaska dating back more than 200 years (Lewitus et al., 2012).  
98 In contrast, there are few documented reports in the Alaskan Arctic, though Indigenous oral  
99 history cited by Fair and Ningeulook (1995) describe “a red tide at one time which caused many  
100 deaths” at Ipauraq (located in the US Bering Strait region), though no details were provided on  
101 the food consumed, symptomatology, or when this occurred.

102

103 *Alexandrium catenella* has a unique multi-stage, meroplanktonic life cycle which allows it to  
104 survive unfavorable conditions in seafloor sediments and bloom seasonally in surface waters.  
105 While planktonic blooms and shellfish toxicity are predominantly caused by vegetative  
106 (swimming, photosynthetic) cells, this species also produces a resting cyst that lies inactive in or  
107 near the seafloor and germinates when temperatures and other conditions are favorable. The  
108 distribution and density of resting cysts is used to predict the location and timing of future bloom  
109 occurrence in some regions, such as the Gulf of Maine (Anderson et al., 2014). *Alexandrium*  
110 blooms generally occur in the spring at temperate latitudes, but appear to be present in the late  
111 summer and into early fall in the Arctic (Anderson et al., 2021a).

112

113 In coastal regions north of the Bering Strait, observations of *A. catenella* are limited to a few  
114 sporadic reports over many years, and blooms have historically not been a significant food  
115 safety concern. However, changing environmental conditions driven by warming ocean  
116 temperatures are providing an increasingly hospitable environment for *A. catenella* growth and  
117 persistence.

118

119 Multiple observations by several research groups over the past decade have provided clear  
120 evidence of widespread and dense *Alexandrium* cyst and cell concentrations in the Alaskan

121 Arctic, indicating the potential for significant bloom development in waters where temperatures  
122 were formerly unfavorable. Gu et al. (2013) were the first to identify *A. catenella* in the US  
123 portion of the Chukchi Sea (hereafter simply termed “Chukchi Sea”) and report the toxicity of  
124 several isolates. Natsuike et al. (2013; 2017) subsequently reported high concentrations of *A.*  
125 *catenella* resting cysts in sediments on the Chukchi shelf, as well as bloom populations in the  
126 water column, and suggested that the cells were transported northward from the northern  
127 Bering Sea. Recently, extremely high concentrations of *Alexandrium* cysts and vegetative cells  
128 were documented over large areas in the Chukchi Sea and adjacent waters, and over multiple  
129 sampling years (Anderson et al., 2021a). These surveys reveal a massive and persistent cyst  
130 accumulation zone (cystbed) on the seafloor of the Chukchi Sea, extending westward to (and  
131 presumably beyond) the maritime border between the U.S. and Russian Federation (Fig. 2).  
132 Maximum cyst concentrations in this cystbed are among the highest reported for this species  
133 globally. Bloom populations of *A. catenella* documented in surface waters of the Bering Strait  
134 and the Chukchi Sea were also notable, with dangerously high cell concentrations covering very  
135 large areas. As with the Chukchi Sea cystbed, these planktonic blooms were certainly more  
136 widespread than was sampled, extending an unknown distance into Russian waters where  
137 sampling was not possible. The *A. catenella* cystbed in the Chukchi Sea is the largest in extent  
138 and overall abundance globally. It is at least 6 times larger in area and 15 times greater in cyst  
139 abundance compared to a similar feature in the Gulf of Maine (Fig. 2 inset) that sustains large-  
140 scale, annually recurrent and dangerous blooms (Anderson et al., 2014). The same now seems  
141 likely in the Alaskan Arctic.

142  
143 The origins and development of these Arctic blooms as well as the formation and persistence of  
144 the regional cystbed can be attributed to two mechanisms (Anderson et al., 2021a). The first  
145 involves northward transport of *A. catenella* populations through Bering Strait into the Chukchi

146 Sea from established blooms in U.S. and Russian waters to the south (Fig. 3A), as originally  
147 proposed by Natsuike et al. (2017). North of Cape Lisburne on the Chukchi Sea shelf, the  
148 poleward flow weakens due to the gentler bottom slope, allowing cysts to settle and accumulate;  
149 a similar mechanism occurs on the Alaskan Beaufort Sea shelf just east of Point Barrow where  
150 another cystbed is located (Anderson et al., 2021a). Over many years, this slowing of the  
151 circulation, coupled with episodic advection of southern blooms with resulting cyst production  
152 and deposition, has created a regional cystbed of unprecedented size and density. Importantly,  
153 historic ocean seafloor temperatures in this cystbed region were likely too cold to support  
154 significant cyst germination, with most cysts cycling repeatedly between dormancy (alive but  
155 unable to germinate) and quiescence (able to germinate but waiting for favorable conditions)  
156 (Fischer et al., 2018). In this scenario, most cysts would remain in the seafloor sediments,  
157 unable to germinate and become active because of cold temperatures, with repeated deposition  
158 events from transported blooms exceeding small germination losses (Fig. 3B). *Alexandrium* can  
159 survive as a cyst for a century or more (Miyazono et al., 2012) until conditions are appropriate  
160 for growth. This imbalance between inputs and losses and the longevity of cysts may explain  
161 the extraordinary size and density of the Alaskan *A. catenella* cyst bed.

162

163 Historically, the main threat to wildlife and human health from STXs was from episodic,  
164 advected blooms in the waters overlying the “sleeping giant” Chukchi Sea cystbed (Fig. 2;  
165 Anderson et al. 2021a). Now, however, rapid warming of the bottom waters of the Chukchi shelf  
166 has exceeded the temperature threshold above which substantial cyst germination and  
167 vegetative cell growth can occur. The warming is due to increased heat flux through the Bering  
168 Strait, which is driven by the greater heat content of northern Bering shelf waters, together with  
169 enhanced northward volume transport. The former is due to stronger atmospheric heating, and  
170 the latter results from a larger sea level height difference between the Pacific and Arctic.

171

172 This changing thermal regime favors a second mechanism of bloom development: local bloom  
173 initiation from the Alaskan Arctic cystbed (Fig. 3C). Anderson et al. (2021a) estimate that the  
174 approximately 4 °C increase in bottom water temperatures in the Chukchi Sea over the past two  
175 decades has likely increased cyst germination flux twofold and advanced the timing of cell  
176 inoculation into the euphotic zone by 20 days. Furthermore, warming of surface waters supports  
177 more rapid cell division and bloom development, as well as prolonged bloom duration. Together,  
178 these complementary mechanisms of bloom development in the region, along with continued  
179 warming, dramatically enhance the potential for large-scale, self-initiating and annually recurrent  
180 blooms, with more intense and widespread HAB impacts.

181

### 182 3. ***Pseudo-nitzschia* and DA**

183 In recent decades, DA produced by the pennate diatom genus *Pseudo-nitzschia* has emerged  
184 as a serious threat in coastal waters of North America, causing ASP and DAP events and  
185 fisheries closures on the Atlantic, Pacific, and Gulf of Mexico coasts and across a wide range of  
186 latitudes (Anderson et al., 2021b). While the Alaskan Arctic has not experienced DA events at  
187 the magnitude observed at lower latitudes, the presence of DA in Arctic phytoplankton and  
188 macrofauna points to an emerging threat (Lefebvre et al., 2016; Huntington et al., 2020). With  
189 *Pseudo-nitzschia* blooms and DA production linked in part to anomalously warm ocean  
190 conditions in the northeast Pacific (McKibben et al., 2017), such as warm phases of the Pacific  
191 Decadal Oscillation and the Oceanic Niño Index, more severe DA events could occur due to  
192 Arctic warming.

193

194 With over 50 described *Pseudo-nitzschia* species, this genus occupies a wide range of  
195 temperature and salinity regimes, from estuarine to open-ocean to sea ice (reviewed by (Bates  
196 et al., 2018)). Approximately half these species produce DA, but to varying degrees. Cryptic  
197 morphological diversity among *Pseudo-nitzschia* species further complicates efforts to monitor  
198 and understand the ecological conditions that result in DA production. Data on the diversity and  
199 distribution of *Pseudo-nitzschia* assemblages in the Alaskan Arctic are limited, but at least six  
200 species of predominantly polar, subpolar, or temperate origin have been reported, many of  
201 which occur in sea ice (Fig. 4) (Poulin et al., 2011; Percopo et al., 2016). Several produce DA in  
202 culture, including *P. seriata* and *P. obtusa*, although few Arctic strains have been cultivated and  
203 tested (Bates et al., 2018; Weber et al., 2021)

204

205 For toxic species, biological, chemical, and physical factors such as temperature, light, nutrient  
206 availability, sexual reproduction cycles, and the presence of grazers can influence DA  
207 production (Bates et al., 2018). Arctic isolates of *P. obtusa* and *P. seriata* increased DA  
208 production after exposure to copepods: *P. seriata* increased production by 3300% and toxicity  
209 was induced in *P. obtusa*, previously considered non-toxic (Harðardóttir et al., 2015). This was  
210 most likely a chemically mediated reaction, since DA production in *P. seriata* also increased  
211 following exposure to copepod exudates (Tammilehto et al., 2015). These findings suggest that  
212 co-abundance of *Pseudo-nitzschia* species and zooplankton (which also concentrate DA), in  
213 addition to other factors, should be considered when evaluating DA toxicity in the Alaskan  
214 Arctic.

215

216 The majority of DA observations in the region are associated with marine wildlife rather than  
217 plankton, but recently, toxin production by plankton assemblages has been observed. During

218 the summers of 2017 and 2018, DA was detected in seawater collected from the northern  
219 Bering Sea, Bering Strait, Chukchi Sea, and Beaufort Sea (Huntington et al., 2020; Hubbard,  
220 submitted) suggestive of broad regional distribution of toxic species. Particulate concentrations  
221 of DA measured in the Alaskan Arctic were generally low (<311 ng L<sup>-1</sup>); (Huntington et al.,  
222 2020) compared to the high levels (15,000 ng L<sup>-1</sup>) that can occur in the US Pacific Northwest  
223 (McCabe et al., 2016), a region with recurring DAP events that is connected to the Alaskan  
224 Arctic by major current systems. Duration of blooms in the region is currently unknown (and a  
225 bloom threshold has yet to be operationally defined for the Alaska Arctic), but the persistence of  
226 cells in sea ice and limited observations from seawater samples, as well as DA in biota, suggest  
227 that *Pseudo-nitzschia* is likely present year-round.

228

229 In other regions, *Pseudo-nitzschia* species composition, abundance, and DA concentration are  
230 known to change rapidly over time and space due to ocean currents and changing ecological  
231 conditions. This is the case in the Alaskan Arctic as well, where varied water masses and  
232 dynamic circulation are important determinants in the distribution of *Pseudo-nitzschia* spp. and  
233 zooplankton grazers over short and long time scales. Indeed, a diversity of species occur across  
234 the region and over seasons, including in sea ice (Poulin et al., 2011; Bates et al., 2018). Given  
235 the warming temperatures of Pacific-origin water entering the Arctic through the Bering Strait  
236 together with the increased flux of this water, there is the potential for northward expansion of  
237 more temperate and subpolar *Pseudo-nitzschia* species (Fig. 4). Predicted changes in  
238 hydrographic regimes and sea ice extent/duration, coupled with complex and environmentally  
239 dependent mechanisms underlying growth and DA production, suggest that multiple factors are  
240 likely to be important for toxicity over varying time scales.

241

242 Although there is still much to be learned about the potential risk to human communities and  
243 wildlife populations in the Alaskan Arctic from this important HAB group, the presence of toxic  
244 *Pseudo-nitzschia* species indicates potential for trophic transfer through Alaskan food webs.  
245 Fortunately, DA levels detected thus far in water, and wildlife (see below), have been low, but  
246 certainly warrant continued research and monitoring. The potential effect of DA on Arctic  
247 ecosystems is a major concern, though not enough is known of lethal doses and toxin transfer  
248 pathways to be definitive at this time. Likewise, predicting what projected ocean warming will do  
249 to distribution and abundance of toxigenic *Pseudo-nitzschia* species is challenging.

250

251 **4. Human and wildlife health implications of STXs and DA**

252 During toxic HAB events, STXs and DA accumulate in filter-feeding marine organisms such as  
253 zooplankton, clams, worms, and fish. These accumulated toxins can be passed to upper trophic  
254 levels, where they can cause severe illness and death of humans and wildlife (Fig. 1);  
255 (Landsberg et al., 2014). Although both STXs and DA are detected throughout food webs in  
256 many parts of the world, their known impacts vary by taxa and geographic region. Globally,  
257 STXs have been responsible for mortality in fish, invertebrates, sea turtles, seabirds, and  
258 marine mammals (Landsberg et al., 2014). In contrast, reports of DA-associated wildlife  
259 mortality have been limited to marine mammals and seabirds, mostly along the west coast of  
260 the contiguous U.S. (Landsberg et al., 2014). Both STX- and DA-producing HABs are present in  
261 Alaskan Arctic ecosystems and have the potential to impact a wide variety of wildlife species, as  
262 well as humans. Although no confirmed cases of STXs- or DA-associated poisonings have been  
263 reported in wildlife or humans in the Alaskan Arctic, however, these toxins have been  
264 documented in zooplankton, clams, worms, planktivorous fish, marine mammals and seabirds,  
265 providing evidence of exposure to HAB toxins across multiple trophic levels (Lefebvre et al.,  
266 2016; Van Hemert et al., 2021a; Lefebvre, in review); (Fig. 5).

267 Typically, STXs and DA are found at highest concentrations in gastrointestinal tract, liver, and  
268 kidney of marine organisms, a pattern that has also been observed among Arctic seabirds and  
269 marine mammals (Lefebvre et al. 2016, Van Hemert et al. 2021). Planktivorous fish have also  
270 been shown to depurate toxins quickly and have the highest concentrations (> 90%) in viscera  
271 (Lefebvre et al. 2001). However, some species of clams like the razor clam (*Siliqua patula*) have  
272 been shown to contain DA in edible tissues at levels above regulatory limits and to remain toxic  
273 for over a year (Wekell 1994). More species-specific information on uptake and depuration is  
274 needed to determine which tissues could harbor potentially harmful levels of toxin and whether  
275 human risk reduction is possible through specific harvesting or food preparation measures.

276 Based on available food web data from the Alaskan Arctic, STXs appear to be a more urgent  
277 threat to wildlife and human health than DA. Across multiple taxa, STXs have been detected  
278 more frequently and at higher relative concentrations than DA (Lefebvre et al., 2016; Van  
279 Hemert et al., 2021a). DA levels measured in zooplankton, clams, worms, fish, and marine  
280 mammals from the Chukchi Sea and Alaskan Beaufort Sea regions were well below the seafood  
281 safety regulatory limit (20 µg DA/g tissue; Lefebvre, unpublished data). In contrast,  
282 concentrations of STXs at or near the seafood safety regulatory limit (80 µg STX eq./100 g  
283 tissue) were measured in Alaskan Arctic clams, zooplankton, and Pacific walruses (Lefebvre, in  
284 review).

285 The higher levels of STXs found in clams make them the most toxic vectors identified in the  
286 Alaskan Arctic region to date, suggesting that they present a distinct risk to marine mammals  
287 and humans. This finding agrees with previous studies showing higher prevalence and  
288 concentrations of STXs in clam-feeding walruses and bearded seals compared to other marine  
289 wildlife that feed on fish or zooplankton, such as spotted seals, bowhead whales, and seabirds  
290 (Lefebvre et al., 2016; Hendrix et al., 2021; Van Hemert et al., 2021a; Lefebvre, in review).

291 In addition to known shellfish vectors, other potential sources of STXs and DA in Arctic food  
292 webs warrant consideration. Forage fish are known to accumulate STXs in regions where *A.*  
293 *catenella* blooms are common, including the Gulf of Alaska (Van Hemert, 2021b). In a 2019  
294 survey of Arctic forage fish, STXs were detected at low to moderate concentrations in fish  
295 collected from the northern Bering Sea and Bering Strait region, but not in fish collected from  
296 the northern Chukchi and Alaska Beaufort Seas (Lefebvre, in review). More samples are clearly  
297 needed to determine the role of fish as potential vectors in the Alaskan Arctic.

298 Nontraditional vectors (Deeds et al., 2008) include zooplankton and other marine invertebrates  
299 that are important food sources for many wildlife species in the Arctic. The high energetic  
300 demands of northern seabirds, whales, and other cold-adapted taxa may result in the  
301 consumption of harmful quantities of toxin during HAB events, even when prey toxin  
302 concentrations are relatively low (Van Hemert, 2021b). It is also important to note that toxic  
303 doses and susceptibility among marine mammals and seabirds have not yet been determined,  
304 and impacts on wildlife health cannot be inferred from human seafood safety guidelines  
305 (Lefebvre et al., 2016; Van Hemert et al., 2021a). As knowledge of HABs in the Alaskan Arctic  
306 expands, additional sampling as well as targeted experimental studies are needed to determine  
307 species' sensitivity to better understand risks to piscivorous seabirds and other marine wildlife.

308 Although many questions remain about the ecosystem-level impacts of HABs in the Alaskan  
309 Arctic, growing evidence indicates the possibility of an emerging wildlife health issue. Recent  
310 reports demonstrated increasing prevalence of DA in marine mammals (Hendrix et al., 2021),  
311 along with possibly harmful concentrations of STXs in seabirds associated with known mortality  
312 events (Van Hemert et al., 2021a). These findings, combined with projections of more frequent  
313 and intense STX-producing HABs due to warming ocean conditions in the Arctic (Anderson et  
314 al., 2021a), suggest that marine wildlife (and the people that harvest and consume them) may  
315 face growing exposure risks.

316 The potential impacts of HABs on the food web of the Alaskan Arctic are far-reaching, as marine  
317 wildlife of the northern Bering, Chukchi, and Beaufort seas are essential to the nutritional,  
318 cultural, and economic well-being of coastal communities. HAB toxins present two major  
319 hazards to coastal communities: 1) illness or mortality via direct consumption of potentially toxic  
320 seafoods; and 2) compromised food security via both avoidance of foods due to fear of toxicity  
321 and the loss (through mortality) of essential marine resources used for food. Of note are recent  
322 studies demonstrating that repetitive, low-level exposure, especially in subsistence populations  
323 and high fish/shellfish consumers, can have negative outcomes (e.g. problems with everyday  
324 memory; e.g., Grattan et al. 2018).

325 It is essential to recognize not only the acute toxicity risks posed by HABs but also the  
326 multifaceted impacts on traditional food sources and culture. The low-level presence of STXs  
327 and DA is not new to northern and western Alaskan waters (Lefebvre et al., 2016), but local  
328 concerns now reflect both a rapid increase in knowledge about HABs as well as the associated  
329 shift in perceptions of food safety and availability.

330

### 331 **5. Challenges and approaches to monitoring and management**

332 The Alaskan Arctic faces multiple challenges in monitoring and responding to HABs, some of  
333 which are unique to the region. A detailed analysis is beyond the scope of this review; here we  
334 summarize the main challenges and suggest possible approaches.

335

336 Efforts to monitor and manage HABs in the region are hindered by a lack of information, limited  
337 infrastructure, and unique spatial challenges inherent to the Alaskan land- and seascapes (Fig.  
338 6). Foremost among the challenges is the need to provide coverage across large stretches of  
339 sparsely populated coastline. Transportation and communication infrastructure is limited and

340 often impacted by harsh weather. As a first step towards enhanced communication, the Alaska  
341 Harmful Algal Bloom Network (AHAB: <https://aoos.org/alaska-hab-network/>) has been  
342 established to share information among a diverse group of scientists and interested  
343 stakeholders throughout Alaska (Anderson et al., 2019). This is, however, a stakeholder-  
344 initiated effort currently funded by federal appropriations that are subject to funding  
345 uncertainties, and thus a more stable state-supported communications strategy and network  
346 might be needed to enhance and sustain HAB response.

347

348 Scientists, managers, and agencies concerned with HAB events are primarily urban-based in  
349 Alaska, far from the northern and western coasts, so they are largely reliant on coastal  
350 communities for awareness of a HAB event or human medical emergency. The lack of a robust  
351 infrastructure contributes to a high-risk situation, as recently demonstrated in 2020 with the first  
352 human HAB/PSP fatality since 2010 in Alaska, and the first reported fatality in western Alaska  
353 (<https://content.govdelivery.com/accounts/AKDHSS/bulletins/295e317>).

354

355 An additional complication is that resource managers, community leaders, and regulatory  
356 officials must deal with multiple HAB toxins and algal species that occur in different seasons and  
357 locations, with blooms that are highly episodic and as yet, unpredictable. HAB toxins can also  
358 accumulate in, and affect, a diverse suite of marine species that are food sources for local  
359 communities. The State of Alaska tests all commercial shellfish harvest, but there is no state-run  
360 testing program for recreational and subsistence harvest. With no federally-authorized  
361 commercial harvest of seafood in the Chukchi and Beaufort Seas, all seafood is harvested on a  
362 non-commercial basis and thus is not included in state-funded HAB monitoring.

363

364 Given the geographic and logistical constraints of monitoring HABs in the Alaskan Arctic and the  
365 lack of a state-funded toxin testing program for non-commercial harvest, the marine ecosystem  
366 of the Alaskan Arctic, and the people that rely on it, are at risk. A monitoring approach to be  
367 considered would be the establishment of a local or regional monitoring program, perhaps  
368 modeled after the program run by the Sitka Tribe of Alaska. This effort is focused on the Gulf of  
369 Alaska and is limited to shellfish, but staff and facilities for HAB toxin analysis are in place to  
370 serve community concerns about HABs through shellfish toxin testing, paid for by the users.  
371 Currently there is no community-based HAB testing in the Alaskan Arctic, and if one is  
372 established, it is important to recognize that shellfish are only a minor and occasional  
373 component of diets in the region. Regional monitoring programs will thus need to develop  
374 protocols and capabilities to test seabirds, fish, and marine mammals as well. Ongoing research  
375 by university, agency, and other partners can provide information about the presence of HAB  
376 toxins in fish and wildlife but current sampling efforts are limited and many diagnostic tools used  
377 are not directly applicable to food safety assessments.

378

379 Experience in other regions of the world suggests that a plankton screening program to detect  
380 HAB cells in coastal waters could also be a useful element in local or regional monitoring  
381 programs. Local monitoring using plankton nets and inexpensive microscopes is common in  
382 many areas subject to HABs (Trainer et al., 2014), and training and funding to establish this  
383 capability should be a high priority activity in the Alaskan Arctic going forward. Given the many  
384 existing and growing challenges to coastal communities, however, citizen or volunteer plankton  
385 monitoring programs may not be feasible in this region. The direct testing of seafood harvest  
386 should therefore be considered, though the manner in which this could be accomplished is  
387 unclear given limited transportation infrastructure and analytical capabilities.

388

389 With respect to ecosystem health and food security, potential impacts from STXs and DA to  
390 most marine wildlife in the Alaskan Arctic are unknown and thus there is no firm guidance to  
391 provide for the safety of coastal communities. Ongoing grant-funded research programs will  
392 soon provide data of this type, and it will be critical to include effective communication and  
393 outreach plans to provide coastal communities the data and implications as they become  
394 available.

395

396 Yet another concern is that the marine ecosystems of the Alaskan Arctic are shared with the  
397 Russian Federation, and transboundary communications can be logically and bureaucratically  
398 challenging. Efforts are needed to promote collaborations in research, monitoring, and  
399 communications to protect shared wildlife resources and public health.

400

401 Recent technological advances in HAB monitoring may also provide important monitoring tools  
402 for the region. Given frequent cloud cover and the lack of HABs of sufficient density to be  
403 visible from space, traditional satellite remote sensing has limited utility in the Arctic. Of more  
404 value are new sensors capable of detecting and quantifying HAB cells and toxins in situ  
405 (Doucette and Kudela, 2017). A promising development in this regard is the advent of ocean  
406 observing systems (OOSs) - arrays of moored and mobile instruments that can collect and  
407 transmit data continuously from remote locations to shore-based scientists and managers.  
408 Instruments capable of measuring HAB cells and/or toxins already exist, such as the Imaging  
409 Flow Cytobot (IFCB), a high-speed, submersible microscope that can autonomously operate  
410 24/7 and take hundreds of thousands of images of phytoplankton daily (Olson and Sosik, 2007).  
411 Machine-learning algorithms then identify and enumerate algal species such as the major HAB  
412 taxa described here, providing near-real time data on HAB threats (Brosnahan et al., 2015).

413 These instruments can be deployed on docks or piers, or placed on fishing or research vessels  
414 for analysis of underway samples (Fig. 7). It should also soon be possible to deploy them  
415 seasonally on autonomous surface vehicles (ASVs) equipped with solar power and  
416 communications hardware. Given the demonstrated northward transport of *Alexandrium* blooms  
417 through the Bering Strait and into the Chukchi Sea, an IFCB-equipped ASV located near  
418 Kotzebue Sound could provide valuable data on incoming HABs, for example.

419

420 These are some of the approaches that could be taken to begin to monitor for and respond to  
421 HAB events in the Alaskan Arctic. Many other regions of the world face recurrent HABs that  
422 contaminate seafood products and affect ecosystem health, yet it has proven possible to protect  
423 human health and sustain fisheries and other ecosystem services through informed  
424 management actions. The unique nature of the Alaskan Arctic, the lack of scientific  
425 understanding of HAB impacts on marine wildlife, and the reliance of coastal populations on  
426 non-commercial harvesting for nutritional, cultural, and economic well-being poses new and  
427 significant challenges that need to be immediately addressed as this region continues to warm  
428 and the potential impacts from HABs expand.

429

## 430 7. Acknowledgements.

431 The authors acknowledge that the Alaskan Arctic as described here includes the lands and  
432 waters of the Inupiaq, Saint Lawrence Island Yupik, and Central Yupik peoples. Funding for  
433 DMA, RSP, EF, PL, and MLR was provided by grants from NSF Office of Polar Programs (OPP-  
434 1823002 and OPP-1733564) and NOAA's Arctic Research program (through the Cooperative  
435 Institute for the North Atlantic Region (CINAR; NA14OAR4320158 and NA19OAR4320074), and  
436 for DMA, KH, and KAL through NOAA's Center for Coastal and Ocean Studies ECOHAB

437 Program (NA20NOS4780195). Additional support was provided for DMA, MLR, and EF by the  
438 U.S. National Park Service Shared Beringian Heritage Program (P21AC12214-00). We also  
439 thank Natalie Renier (WHOI Graphic Services) and Emily Bowers (Northwest Fisheries Science  
440 Center) for creating figures. Any use of trade, firm, or product names is for descriptive purposes  
441 only and does not imply endorsement by the US Government. This is ECOHAB Contribution  
442 number 1007.

443

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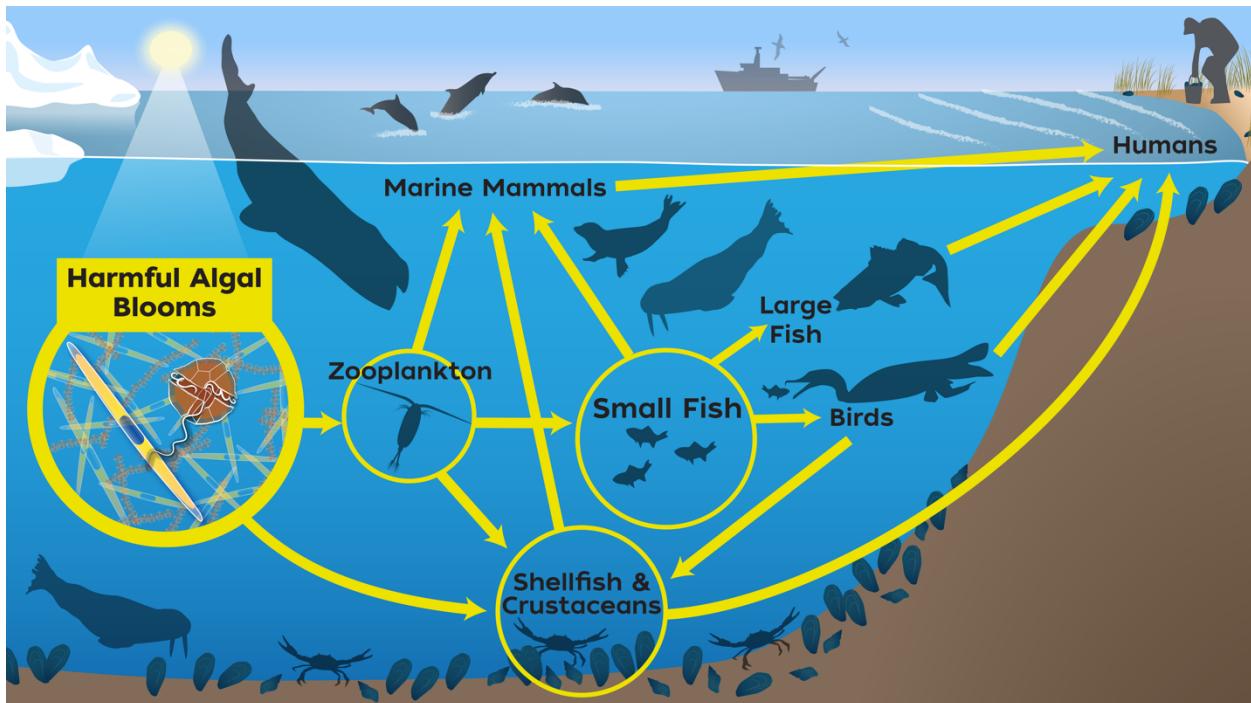
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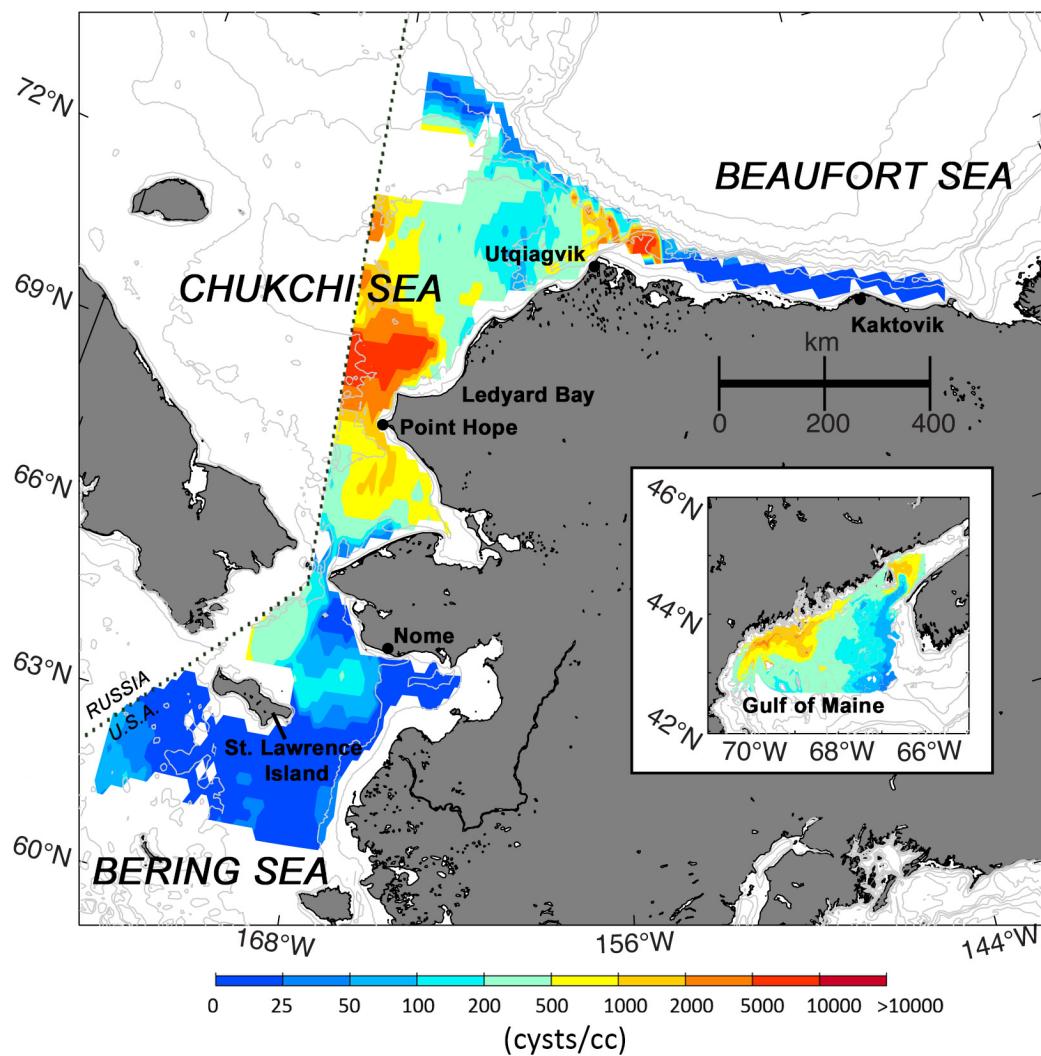
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585 **Figures:**



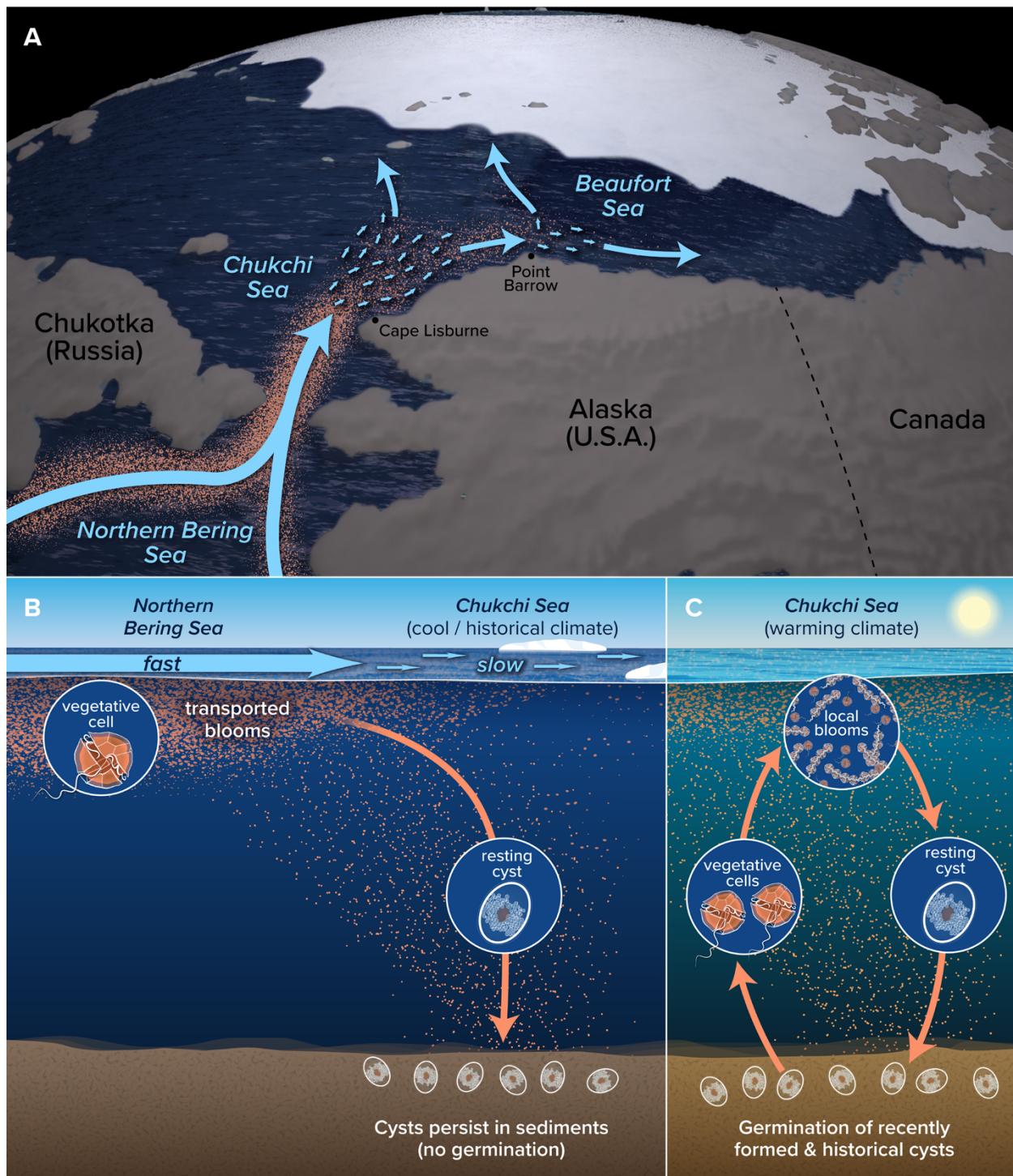
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587 Figure 1. Toxins produced by HABs can be accumulated and transferred throughout the food  
 588 web when algal cells are eaten by zooplankton, fish, and shellfish that are, in turn, consumed by  
 589 other animals and humans. At sufficiently high levels, these toxins can sicken or kill both  
 590 humans and wildlife. Illustration created by Natalie Renier, WHOI Graphic Services.



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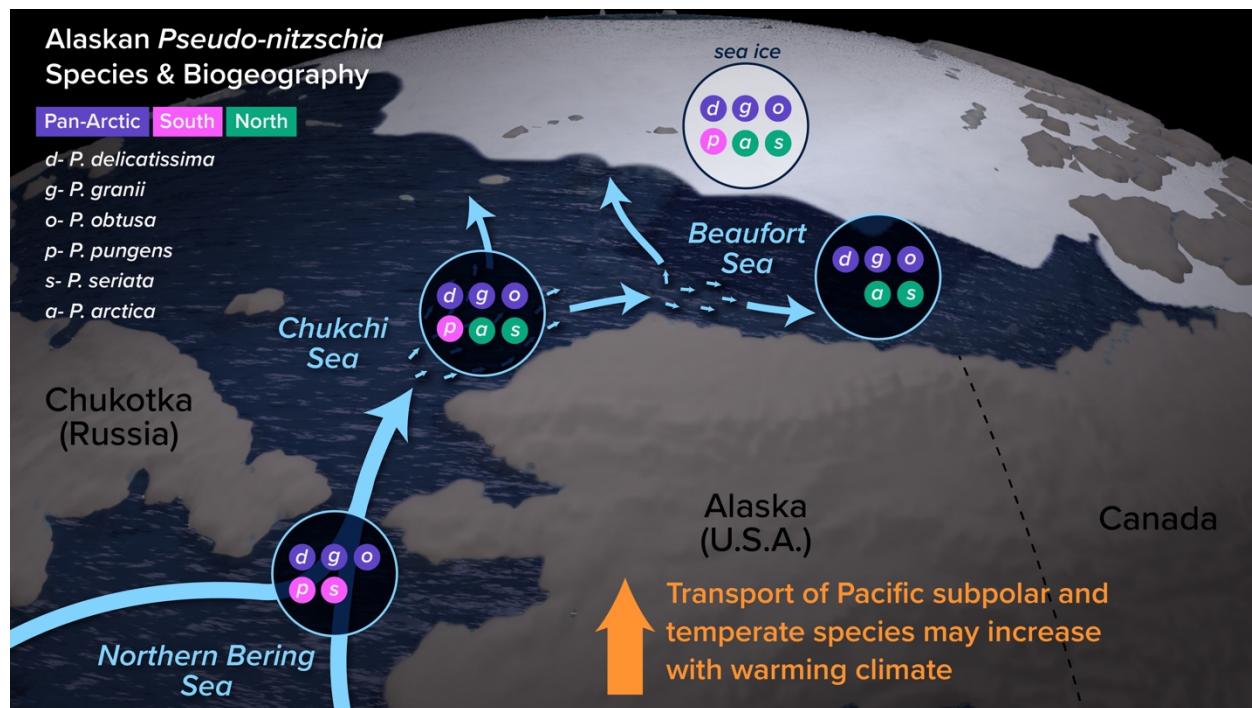
592 Figure 2. Alaskan (2018-2020) and Gulf of Maine (2004-2012) *Alexandrium catenella* cyst  
 593 abundance in surface sediments, depicted on the same scale (Albers Equal-Area Conic  
 594 projection). Sites visited across multiple years were averaged to create these composite maps.



597 Figure 3. Schematic diagrams of *Alexandrium catenella* bloom dynamics in the Alaskan Arctic  
 598 region. The top panel (A) depicts the transport of blooms (orange dots) from the northern

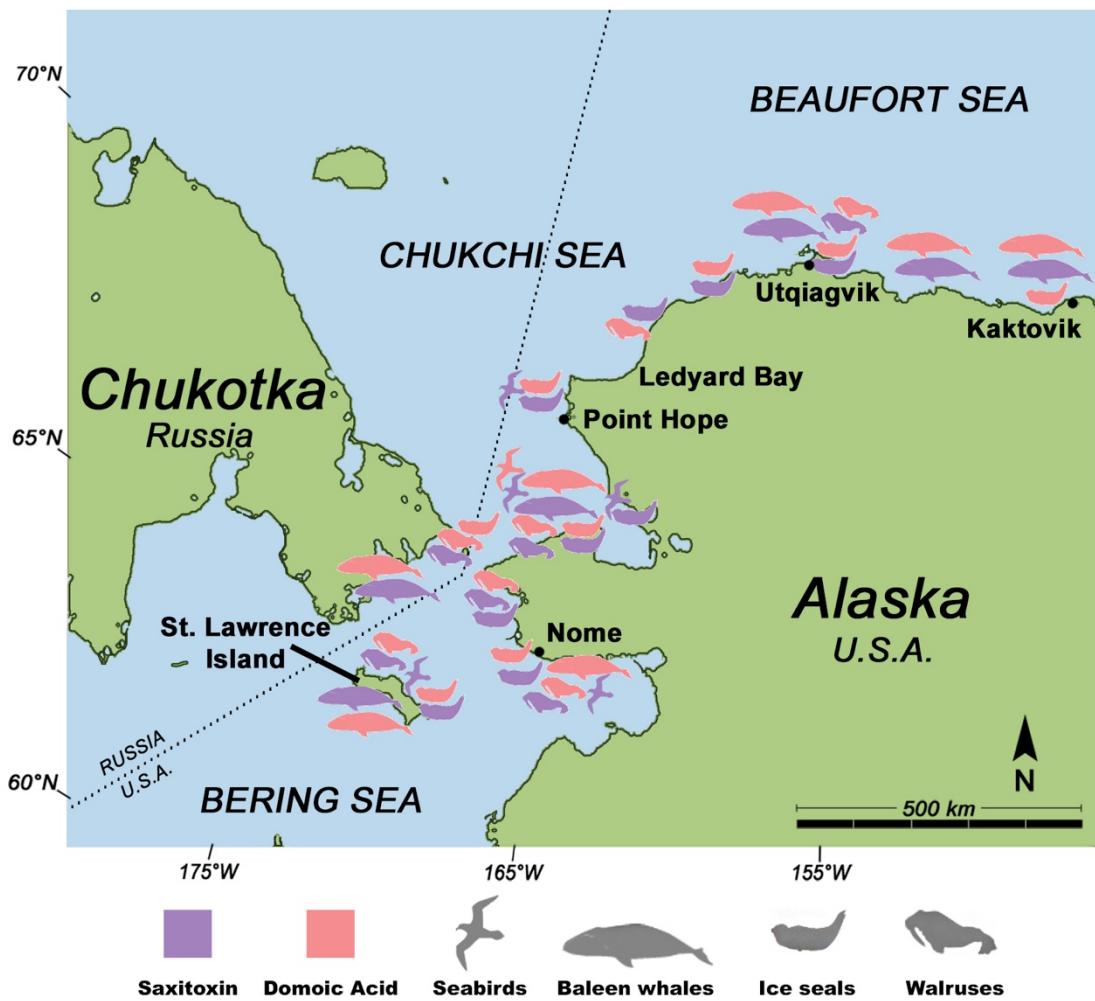
599 Bering Sea into the Chukchi Sea and beyond. North of Cape Lisburne and again east of Point  
600 Barrow, flow speeds decrease (represented by the smaller arrows), allowing *Alexandrium* cysts  
601 to be deposited (B). The bottom panel shows two scenarios for bloom and cyst dynamics. Left:  
602 Bottom waters were historically too cold to promote germination of cysts, which presumably  
603 cycled repeatedly through dormancy and quiescence. Meanwhile, continued deposition of new  
604 cysts occurred via blooms transported from the south. Such sustained inputs led to extremely  
605 dense cyst concentrations and a large cystbed. (C) With warmer bottom water temperatures,  
606 cysts are able to germinate and initiate local blooms that in turn deposit new cysts to sustain the  
607 process. These locally formed cysts are supplemented with those produced by transported  
608 blooms, again leading to large and dense cystbeds. Graphics created by Natalie Renier, WHOI  
609 Graphic Services.

610



611  
612 Figure 4. Distribution of *Pseudo-nitzschia* species reported to occur in the Alaskan Arctic  
613 (Bering Sea, Chukchi Sea, Beaufort Sea, and sea ice) (Bates et al., 2018; Hubbard, submitted).

614 Species are color coded based on biogeography in the Alaskan Arctic, including distribution  
615 across all subregions shown (Pan-Arctic), those suspected to have a more southern origin (in  
616 pink), and those suspected to have a more northern origin (in green). Specific locations were  
617 not referenced for *P. pseudodelicatissima*, which may have been confounded with the recently  
618 described *P. arctica* (Percopo et al., 2016). For *P. seriata*, two genetically distinct populations  
619 are shown: one previously observed in temperate Pacific waters, and one observed in Atlantic  
620 Arctic waters. Illustration created by Natalie Renier, WHOI Graphic Services.

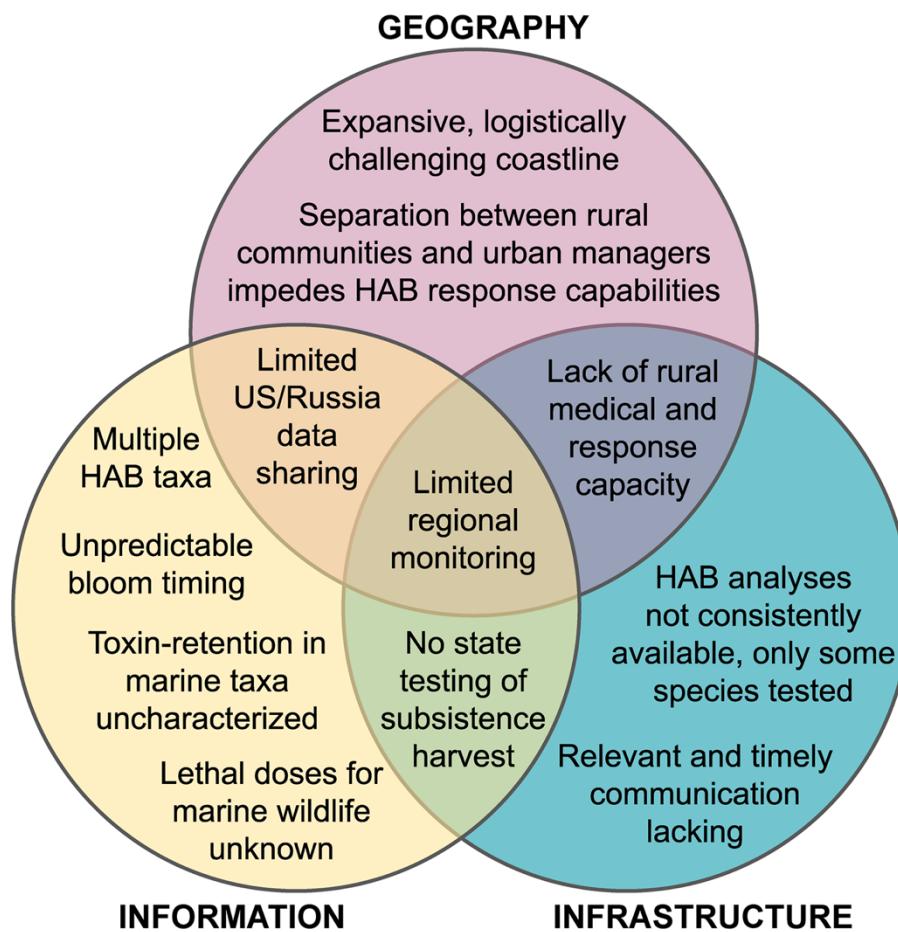


621  
622 Figure 5: Map of locations where stranded or subsistence harvested marine mammals and  
623 seabirds have tested positive for saxitoxin (purple) and/or domoic acid (red) in samples

624 collected from St. Lawrence Island to the Beaufort Sea from 2001 to 2021. Taxa include  
625 seabirds, baleen whales, ice seals and walrus. Algal toxin detection limits for wildlife samples  
626 were approximately 4 ng DA/g for domoic acid and 3 ng STX eq./g for saxitoxin (Lefebvre et al.  
627 2016).

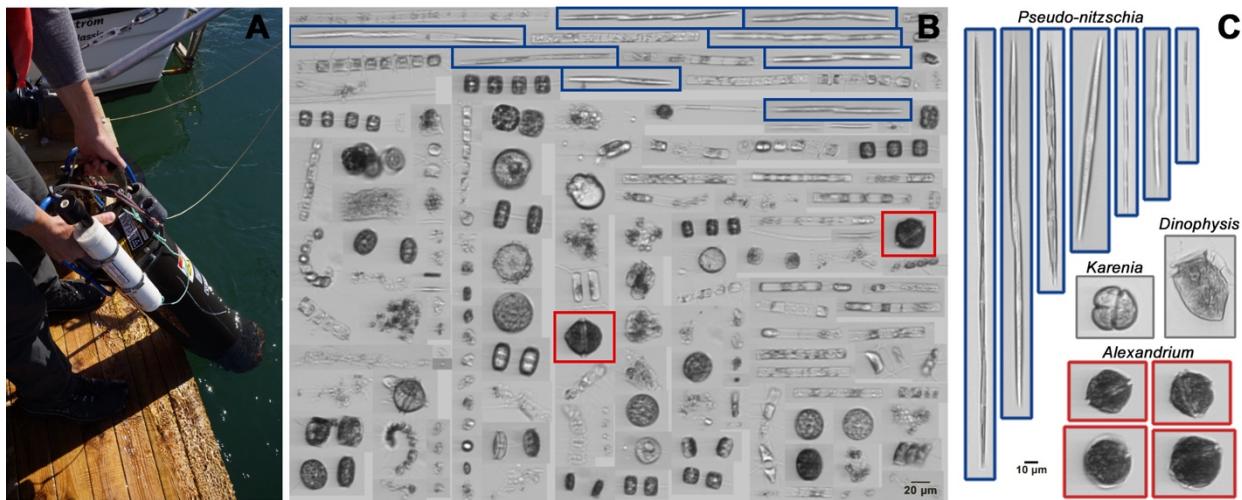
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631 Figure 6. Overview of challenges to HAB monitoring and management in the Alaskan Arctic.  
632 Challenges derive from lack of complete information, limitation of available infrastructure, and  
633 spatial logistics unique to the Alaskan geography.



636 Figure 7. An Imaging FlowCytobot (IFCB) (A, image: Michael Brosnahan, WHOI) and examples  
 637 of phytoplankton imaging data that the instrument produces. A single water sample collected  
 638 from shipboard underway seawater in the Chukchi Sea during an August 2018 cruise (B)  
 639 contained *Alexandrium* (red boxes) and *Pseudo-nitzschia* (blue boxes). Post-processing of IFCB  
 640 imagery classifies cells by type, allowing easy identification and quantification of HAB cells (right  
 641 panel) including *Alexandrium*, *Pseudo-nitzschia*, *Karenia* and *Dinophysis*.



642

643 Cover Photo: Young male Pacific walrus resting on beach, Chukchi Sea, Alaska. Photo courtesy  
644 of Anthony Fischbach, U.S. Geological Survey

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