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Investigation of Algal Toxins in a Multispecies Seabird Die-off in the Bering and Chukchi Seas

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ABSTRACT: Between 2014 and 2017, widespread seabird mortality events were documented annually in the Bering and Chukchi seas, concurrent with dramatic reductions of sea ice, warmer than average ocean temperatures, and rapid shifts in marine ecosystems. Among other changes in the marine environment, harmful algal blooms (HABs) that produce the neurotoxins saxitoxin (STX) and domoic acid (DA) have been identified as a growing concern in this region. Although STX and DA have been documented in Alaska (US) for decades, current projections suggest that the incidence of HABs is likely to increase with climate warming and may pose a threat to marine birds and other wildlife. In 2017, a multispecies die-off consisting of primarily Northern Fulmars (*Fulmarus glacialis*) and Short-tailed Shearwaters (*Ardenna tenuirostris*) occurred in the Bering and Chukchi seas. To evaluate whether algal toxins may have contributed to bird mortality, we tested carcasses collected from multiple locations in western and northern Alaska for STX and DA. We did not detect DA in any samples, but STX was present in 60% of all individuals tested and in 88% of Northern Fulmars. Toxin concentrations in Northern Fulmars were within the range of those reported from other STX-induced bird die-offs, suggesting that STX may have contributed to mortalities. However, direct neurotoxic action by STX could not be confirmed and starvation appeared to be the proximate cause of death among birds examined in this study.

Key words: Bering Sea, Chukchi Sea, domoic acid, harmful algal bloom, Northern Fulmar, saxitoxin, seabird die-off, Short-tailed Shearwater.

Harmful algal blooms (HABs) are caused by phytoplankton species that produce toxins that can injure or kill marine consumers including seabirds, marine mammals, and humans (Landsberg et al. 2014). Although many factors influence the emergence of HABs, water temperature has been identified as an important driver (Moore et al. 2008; Gobler et al. 2017). This is particularly relevant in Arctic Alaska (US) where rapid ocean warming is causing dramatic shifts in marine ecosystems (Overland et al. 2018). Since 2015, the Bering and Chukchi seas have experienced unprecedented sea ice loss and rising temperatures (Duffy-Anderson et al. 2019; Stevenson and Lauth 2019), with HAB activity observed or projected to increase as a consequence (Natsuike et al. 2017a, b).

There are two HAB neurotoxins of concern to wildlife and humans in Alaska: saxitoxin (STX), a paralytic toxin responsible for paralytic shellfish poisoning, and domoic acid (DA), an excitotoxin that causes seizures and neurologic distress (Landsberg et al. 2014). Although STX and DA have historically been documented in the Bering Strait region (Lewitus et al. 2012; Natsuike et al. 2013; Lefebvre et al. 2016), changing oceanographic conditions may promote more frequent and intense HAB events (Natsuike et al. 2017a, b). Recent studies have documented STX and DA in Alaska marine mammals (Lefebvre et al. 2016) and seabirds (Van Hemert et al. 2020b), suggesting that these toxins occur throughout the food web and could present risks to wildlife as well as residents of coastal communities that rely on marine resources for nutritional, cultural, and economic uses (Fall

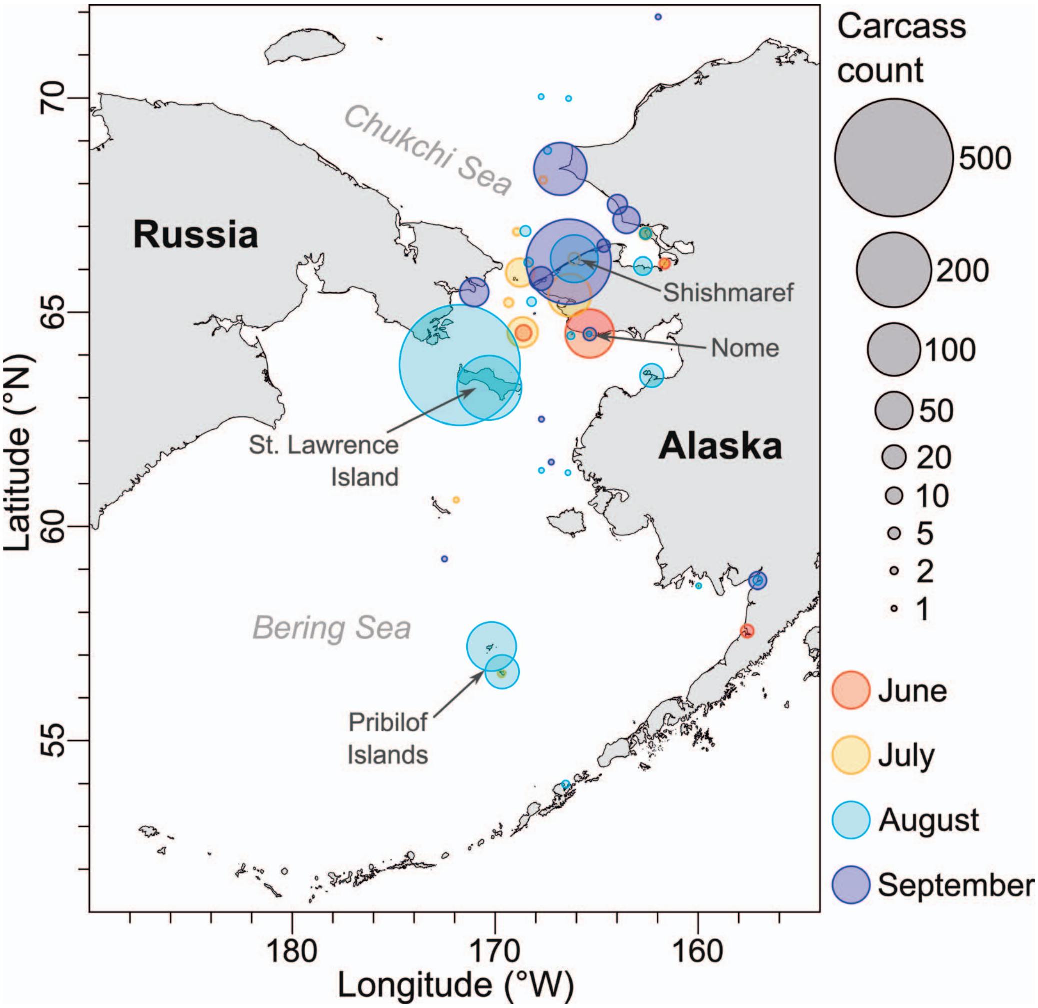

FIGURE 1. Map of estimated carcass counts during a multispecies seabird die-off in the Bering and Chukchi seas, June–September, 2017. Counts include observations from standard Coastal Observation and Seabird Survey Team surveys, opportunistic reports from communities, and at-sea surveys conducted by the US Fish and Wildlife Service.

2016). Elsewhere, bird die-offs have been attributed to STX and DA, with a diverse suite of species affected (Shumway et al. 2003; Gibble and Hoover 2018).

During June–September 2017, a multispecies seabird die-off occurred in northern and western Alaska (USGS 2019). Carcasses were observed along the Alaska coast of the Chukchi and Bering seas, primarily from Point Hope south to Bristol Bay, with the highest onshore counts recorded from Nome to Shishmaref and on St. Lawrence Island, Alaska (Fig. 1). Mortality data were compiled from three different sources: standardized Coastal Observation and Seabird Survey Team surveys, opportunistic reports from communities, and at-sea surveys conducted by the US Fish and Wildlife Service. Nearly 1,700 carcasses were counted (Table 1 and Fig. 2), which likely represented only a fraction of the total death toll. Reports peaked in August–September, consisting primarily of Northern Fulmars (*Fulmarus glacialis*; 41%) and Short-tailed Shearwaters (*Ardenna tenuirostris*; 35%; Fig. 1). Mortality was also observed in murres (*Uria* spp.; 15%), auklets

TABLE 1. Summarized counts and species composition of seabird carcasses reported June–September 2017. Counts include observations from standard Coastal Observation and Seabird Survey Team beach surveys, opportunistic reports from communities, and opportunistic reports from at-sea surveys conducted by the US Fish and Wildlife Service. Note that Common Murres and Thick-billed Murres cannot always be distinguished by species and are lumped for this analysis.

	Survey effort (n)		Carcass counts (n)				Species composition (%)			
Month	Surveys	Beaches	Survey (beach)	Opportunistic (community)	Opportunistic (at-sea)	Total	NOFU[a]	STSH[b]	COMU/TBMU[c]	BLKI[d]
June	21	16	42	71	0[e]	113	0	0	82	12
July	18	12	18	97	40	155	25	22	26	4
August	16	10	98	830	16	944	50	44	2	1
September	11	8	42	430	4	476	36	24	23	5
Total	66	19[f]	200	1,428	60	1,688	41	35	15	3

[a] NOFU = Northern Fulmar (*Fulmarus glacialis*).

[b] STSH = Short-tailed Shearwater (*Ardenna tenuirostris*).

[c] COMU/TBMU = Common Murre (*Uria aalge*)/Thick-billed Murre (*Uria lomvia*).

[d] BLKI = Black-legged Kittiwake (*Rissa tridactyla*).

[e] No reports of dead birds at-sea were received in June; this may be due to limited survey efforts or an absence of carcasses available to count.

[f] Total number of unique beaches surveyed; multiple beaches were surveyed more than once from June to September 2017.

(*Aethia* spp.), kittiwakes (*Rissa* spp.), gulls (*Larus* spp.), puffins (*Fratercula* spp.), and Fork-tailed Storm-petrels (*Hydrobates furcatus*; USGS 2019). Clinical signs from moribund birds included weakness, lethargy, drooping heads, staggering, and lack of predator avoidance (USGS 2019); similar signs have been reported in other cases of HAB intoxication among birds (Shumway et al. 2003; Gibble and Hoover 2018). The large numbers of seabirds dying of unknown causes, combined with unusual behaviors that could be indicative of neurologic distress associated with HAB toxins, prompted our investigation of STX and DA in this event.

FIGURE 2. Northern Fulmar (*Fulmarus glacialis*) and Short-tailed Shearwater (*Ardenna tenuirostris*) found dead near the village of Gambell on St. Lawrence Island in the Bering Strait on 12 August 2017.

Local observers and biologists opportunistically collected carcasses during August–September 2017 from various locations on the Alaska coastline ranging from Point Hope (68°20′N, 166°50′W) to Unalaska Island (53°52′N, 166°32′W; Table 2). Frozen carcasses (n=26) were submitted to the USGS National Wildlife Health Center (Madison, Wisconsin, USA); a subset (n=18) of these was examined by a pathologist. For histopathologic examination, major organs were fixed in 10% neutral buffered formalin, processed routinely, sectioned at approximately 5 µm, and stained with H&E. Cloacal contents, intestinal contents, whole intestine, stomach contents, whole stomach, liver, and pectoral muscle were subsampled from National Wildlife Health Center submissions for algal toxin testing. All tissue types were not available from every individual and, in several instances, we pooled samples across multiple birds (Table 2). We analyzed for STX and DA using enzyme-linked immunosorbent assay methods

TABLE 2. Saxitoxin (STX) concentrations measured by enzyme-linked immunosorbent assay in tissues from seabird carcasses collected during a seabird die-off event in the Bering and Chukchi seas in August–September 2017. Tissue concentrations are reported in μg/100 g STX, except those below method detection limits (BD) or with detectable but not quantifiable values (DBNQ). — = No sample was available for testing.

				Saxitoxin concentration (μg/100 g)						
Bird ID	Species[a]	Location	Region	Cloacal contents	Intestinal contents	Intestine	Stomach contents	Stomach	Liver	Muscle
28313-001	Fork-tailed Storm-petrel	Unalaska Island	Aleutian Islands	Pooled[b]	—	—	Pooled[b]	—	DBNQ	—
28275-007	Common Murre	Shishmaref	N. Bering Sea	Pooled[b]	—	—	—	—	BD	—
28347-001	Common Murre	Unalakleet	N. Bering Sea	—	—	—	—	—	BD	BD
28346-002	Horned Puffin	Shishmaref	N. Bering Sea	Pooled[b]	—	—	BD	—	BD	BD
28275-001	Northern Fulmar	Gambell	N. Bering Sea	Pooled[c]	—	—	—	—	5.9	—
28275-003	Northern Fulmar	Gambell	N. Bering Sea	—	11.1	12.9	7.3	5.3	5.1	1.5
28275-006	Northern Fulmar	Shishmaref	N. Bering Sea	—	3.3	2.6	2.1	2.1	1.6	DBNQ
28275-008	Northern Fulmar	Shishmaref	N. Bering Sea	—	—	—	14.9	—	1.4	—
28275-010	Northern Fulmar	Shishmaref	N. Bering Sea	—	2.1	1.5	DBNQ	1.2	DBNQ	DBNQ
28275-002	Short-tailed Shearwater	Gambell	N. Bering Sea	—	—	—	BD	BD	BD	BD
28275-004	Short-tailed Shearwater	Gambell	N. Bering Sea	—	BD	BD	BD	BD	BD	BD
28275-005	Short-tailed Shearwater	Gambell	N. Bering Sea	—	BD	BD	BD	BD	BD	BD
28275-009	Short-tailed Shearwater	Shishmaref	N. Bering Sea	—	BD	BD	BD	BD	BD	BD
28324-001	Northern Fulmar	Point Hope	Chukchi Sea	—	—	—	Pooled[c]	—	BD	BD
28324-002	Northern Fulmar	Point Hope	Chukchi Sea	Pooled[c]	—	—	DBNQ	—	BD	BD
28324-003	Northern Fulmar	Point Hope	Chukchi Sea	Pooled[c]	—	—	Pooled[c]	—	—	—
28266-001	Northern Fulmar	St. Paul Island	Pribilof Islands	Pooled[d]	—	14.5	—	—	1.6	—
28266-002	Northern Fulmar	St. Paul Island	Pribilof Islands	—	—	DBNQ	—	—	BD	—
28266-003	Northern Fulmar	St. Paul Island	Pribilof Islands	Pooled[d]	—	—	—	—	1.8	—
28266-004	Northern Fulmar	St. Paul Island	Pribilof Islands	—	—	—	—	—	4.4	—
28266-005	Northern Fulmar	St. Paul Island	Pribilof Islands	—	BD	BD	BD	BD	BD	BD
28312-001	Northern Fulmar	St. George Island	Pribilof Islands	Pooled[d]	—	—	—	—	—	DBNQ
28312-002	Northern Fulmar	St. George Island	Pribilof Islands	Pooled[d]	—	—	—	—	—	DBNQ

Table 2. Continued.

				Saxitoxin concentration (μg/100 g)						
Bird ID	Species[a]	Location	Region	Cloacal contents	Intestinal contents	Intestine	Stomach contents	Stomach	Liver	Muscle
28312-003	Northern Fulmar	St. George Island	Pribilof Islands	Pooled[d]	—	—	63.3	—	BD	BD
28312-004	Northern Fulmar	St. George Island	Pribilof Islands	—	DBNQ	2.2	DBNQ	DBNQ	DBNQ	DBNQ
28266-006	Short-tailed Shearwater	St. Paul Island	Pribilof Islands	Pooled[b]	—	—	—	—	BD	—

[a] Northern Fulmar (*Fulmarus glacialis*), Short-tailed Shearwater (*Ardenna tenuirostris*), Common Murre (*Uria aalge*), Fork-tailed Storm-petrel (*Hydrobates furcatus*), and Horned Puffin (*Fratercula corniculata*).

[b] Pooled cloacal and stomach contents from multiple species (28275-007, 28313-001, 28346-002, 28266-006) from Unalaska Island, Shishmaref, and St. Paul Island with detectable but not quantifiable values.

[c] Pooled cloacal and stomach contents for Northern Fulmars (28275-001, 28324-001, 28324-002, 28324-003) from Point Hope and Gambell = 4.6 μg/100 g saxitoxin.

[d] Pooled cloacal contents for Northern Fulmars (28266-001, 28266-003, 28312-001, 28312-002, 28312-003) from St. Paul and St. George Islands = 30.5 μg/100 g saxitoxin.

for seabird tissues, which provide high-throughput, rapid screening and detection of relatively low concentrations of toxin (Van Hemert et al. 2020b). Based on previous results from Alaska seabirds (Van Hemert et al. 2020b), we prioritized testing of STX over DA when sample volume was limited. Samples with measured values >10 μg/100 g STX by enzyme-linked immunosorbent assay were subsequently analyzed by high-performance liquid chromatography (HPLC) to determine congener profiles; due to the higher detection limits (about 10 μg/100 g), samples with STX concentrations less than this cannot be reliably quantified by HPLC (Lawrence et al. 2005; Van Hemert et al. 2020b).

For the 18 carcasses examined by a pathologist, birds were generally in poor body condition with depletion of fat stores (*n*=16) and evidence of drowning (*n*=14). Gastrointestinal tracts were mostly empty except for three Northern Fulmars containing squid beaks, two Northern Fulmars containing avian tissues, and one Horned Puffin (*Fratercula corniculata*) containing fish; many contained digested blood (*n*=11), which is often associated with starvation.

We detected STX in 15 of 25 (60%) carcasses, including 14 of 16 (88%) Northern Fulmars, the species most frequently recorded in carcass counts (Table 2 and Fig. 3). Quantifiable STX concentrations in Northern Fulmars ranged from 1.2 to 63.3 μg/100 g (Table 2). Among the limited number of other species tested, only a single Fork-tailed Storm-petrel had a detectable but not quantifiable concentration of STX in liver tissue, as did pooled stomach and cloacal contents from individuals of four other species (Table 2). Concentrations of STX were highest in samples from the gastrointestinal tract, although detectable concentrations were also measured in liver and muscle (Table 2). Among samples tested for specific congener profiles by HPLC, most consisted entirely or largely of STX, but four other congeners were also detected (C1C2, GTX5, GTX1,4, NEO; Table 3). In contrast, dcGTX2,3, GTX2,3, and dcSTX were not detected in any samples. We

FIGURE 3. Map showing locations and numbers of seabird carcasses tested for saxitoxin (STX) during a 2017 multispecies die-off in the Bering and Chukchi seas. Solid (red) indicates individuals with detectable levels of STX (n=15); empty (white) indicates individuals with no detectable STX (n=10). Carcasses were collected opportunistically and surveying efforts were not consistent across regions; however, all available samples were tested from each location.

did not detect DA in any tissues (n=36 from 22 individuals; Van Hemert et al. 2020a).

Toxicity levels have not yet been established for seabirds, but previous studies of algal toxins in wild birds provide a useful context for interpreting our results. The STX concentrations in fulmars from this study were within the range of values reported from other STX-induced bird mortality events. Excluding potentially compromised samples, STX concentrations of 2.8–100 µg/100 g have been associated with saxitoxicosis in marine birds, including an incident among Kittlitz's Murrelet (*Brachyramphus brevirostris*) nestlings

TABLE 3. Saxitoxin (STX) congeners measured by high-performance liquid chromatography in tissues from Northern Fulmar (*Fulmarus glacialis*) carcasses collected August–September 2017 during a multispecies seabird die-off event in the Bering and Chukchi seas.

		STX toxicity equivalence factor (µg/100 g STX-eq.)[a]					
Bird ID	Tissue	C1C2	GTX5	STX	GTX1,4	NEO	Cumulative STX-eq.
28266-001	Intestine	BD	BD	13.1	BD	BD	13.1
28275-008	Stomach contents	BD	BD	9.8	6.7	3.0	19.5
28312-003	Stomach contents	2.0	1.0	19.9	14.3	14.1	51.2
28275-003	Intestinal contents	BD	BD	11.8	BD	BD	11.8
28275-003	Intestine	BD	BD	14.0	BD	BD	14.0
Pooled[b]	Cloacal contents	10.0	BD	11.9	BD	BD	21.9

[a] BD = below detection.

[b] Pooled cloacal contents for Northern Fulmars (26266-001, 28266-003, 28312-001, 28312-002, 28312-003). See Table 2 for details.

near Kodiak, Alaska (Levasseur et al. 1996; ICES 1998; Shearn-Bochsler et al. 2014). Saxitoxin has also been detected in carcasses collected from other recent marine bird die-offs in Alaska, although it is unclear whether HABs contributed to these events (Jones et al. 2019; Van Hemert et al. 2020b). Common Murres (*Uria aalge*) experienced a massive die-off in Alaska from 2015–16 (Piatt et al. 2020); one third of carcasses sampled had detectable levels of STX (up to 10.8 μg/100 g; Van Hemert et al. 2020b). During a Tufted Puffin (*Fratercula cirrhata*) die-off on St. Paul Island in the Bering Sea in 2016–17, trace levels of STX (<1.0 μg/100 g) were found in stomach or cloacal contents of four sampled birds (Jones et al. 2019). Interpretation of STX values from field-collected samples is challenging because the toxin can depurate rapidly (Lagos and Andrinolo 2000) and pharmacokinetics in birds are poorly understood. It is probable that higher concentrations of STX were present in seabird tissues but had been metabolized, excreted, or degraded prior to sample collection; thus, reported values likely represent a minimum range.

Changes to the food web in the Bering and Chukchi sea ecosystems likely contributed to the 2017 die-off (Duffy-Anderson et al. 2019; Stevenson and Lauth 2019). Although starvation appeared to be the proximate cause of death among birds examined in this study, STX may have also played a role in this event, either directly or indirectly. We cannot assign causality due to limited knowledge about STX toxicity in seabirds and the opportunistic nature of our sampling, but the high prevalence (88%) and elevated concentrations in multiple individuals warrant consideration. Northern Fulmars have diverse diets (Mallory et al. 2020), including certain forage taxa known to concentrate STX (Deeds et al. 2008; Lopes et al. 2013; Oyaneder-Terrazas et al. 2017). It is unclear whether Northern Fulmars are routinely exposed to STX in Alaskan waters or other parts of their annual range; however, results from a previous study in the Gulf of Alaska indicated that Northern Fulmar prey species, such as forage fish and euphausiids, can serve as vectors (Van Hemert et al. 2020b).

Further research on STX in birds, including experimental dosing and food web studies, is needed to determine toxicity levels and identify ecologically relevant sources of exposure. Given the projected increase in HAB events in northern regions, algal toxins should be considered in any future assessments of seabird populations, including potential implications for food security and human health.

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