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BRIEF REPORT

Bowhead whale (*Balaena mysticetus*) carcasses documented during the 2019 aerial surveys in the eastern Chukchi and western Beaufort seas: a follow-up to evidence of bowhead whale and killer whale (*Orcinus orca*) co-occurrence during 2009–2018

Amy L. Willoughby[1,2] · Megan C. Ferguson[2,3] · Raphaela Stimmelmayr[4,5] · Amelia A. Brower[1,2]

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Abstract
Information on factors contributing to the morbidity and mortality of the Bering–Chukchi–Beaufort seas stock of bowhead whales (*Balaena mysticetus*) is fundamental to its successful management and recovery. The Alaska Arctic coastline is remote and expansive, making monitoring for and gross examination of carcasses difficult. However, sighting data and imagery collected during aerial surveys in the eastern Chukchi (EC) and western Beaufort (WB) seas from 2009 through 2019 provide information on bowhead whale mortality. We present bowhead whale carcass data from the 2019 aerial surveys that add to the long series of consistent information on floating and beach-cast bowhead whale carcasses. The 2019 carcass data suggest an increased occurrence of probable killer whale (*Orcinus orca*) predation on bowhead whales in the WB. Eleven bowhead whale carcasses were photo-documented from July to October 2019 in the EC and WB study areas. Of the 11 carcasses documented, 7 had injuries consistent with probable killer whale predation—2 in the EC and 5 in the WB. Probable cause of death could not be assigned to four carcasses. No carcasses were associated with aboriginal subsistence hunting. Despite similar annual survey effort from 2009 to 2019, several compelling deviations in carcass numbers and locations were observed in 2019. Compared to 2009–2018, 2019 had the highest yearly number of documented carcasses and the most categorized as probable killer whale predation. Carcass locations exhibited a striking shift from the EC to the WB. Lastly, more carcasses were categorized as probable killer whale predation in the WB during 2019 than in 2009–2018 combined.

Keywords Bowhead whale · Killer whale · Predation · Arctic · Survey-aerial · Line-transect

Introduction

Information on factors contributing to the morbidity and mortality of a federally-protected species, such as the bowhead whale (*Balaena mysticetus*) of the Bering-Chukchi-Beaufort (BCB) seas stock, fundamentally contributes to informed management decisions intended to facilitate a robust recovery (NOAA 2021). The Alaska Arctic coastline is remote and expansive, with few coastal communities, making monitoring for and gross examination of reported bowhead whale carcasses difficult. However, broad-scale aerial surveys can search hundreds of kilometers of otherwise inaccessible Arctic (north of the Arctic Circle and seasonally ice-covered) marine habitat in a single flight. The Aerial Surveys of Arctic Marine Mammals (ASAMM) project's aerial sighting data and imagery for bowhead whale dead strandings are the most complete in this region. Investigating

✉ Amy L. Willoughby
a.willowb@gmail.com

1 Cooperative Institute for Climate, Ocean and Ecosystem Studies, University of Washington, Seattle, WA, USA

2 Marine Mammal Laboratory, Alaska Fisheries Science Center, NOAA, NMFS, Seattle, WA, USA

3 School of Fishery and Aquatic Sciences, University of Washington, Seattle, WA, USA

4 Department of Wildlife Management, North Slope Borough, Utqiaġvik, AK, USA

5 Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK, USA

imaged carcasses to ascertain the probable cause of death cannot fully replace gross post-mortem examinations. Still, aerial images of bowhead and gray (*Eschrichtius robustus*) whale carcasses have proven useful for understanding possible causes of death (Willoughby et al. 2020, 2022).

Bowhead whales are a vital resource for 11 Alaska Native whaling communities who are federally authorized to hunt them for subsistence purposes (Braund and Associates 2018; Suydam and George 2021). Non-harvest-related threats to bowhead whales include killer whale (*Orcinus orca*) predation, ship strikes, and entanglement in commercial fishing gear (George et al. 2017; Shpak and Stimmelmayr 2017; Willoughby et al. 2020, 2022).

Killer whales are distributed year-round throughout the Pacific Ocean and Bering Sea in open water and low sea ice conditions near the ice edge (Leatherwood and Dahlheim 1978; Forney and Wade 2007). Transient (mammal-eating) killer whales overlap spatially and temporally with bowhead whales in the Bering Sea and Bering Strait region during the summer and early autumn (Dahlheim 1997; Dahlheim and White 2010). Contemporary information on co-occurrence has been documented or inferred from large whale carcasses, visual observations from coastal residents and scientists, and passive acoustic recordings in the eastern Chukchi (EC) and western Beaufort (WB) seas (George and Suydam 1998; Stafford 2019; Stafford et al. 2022a, b; Willoughby et al. 2020, 2022).

The ASAMM project conducted aerial line-transect surveys to collect information on the distribution, behavior, and relative abundance of marine mammals. From July through October, surveys overlapped spatially and temporally with bowhead whales in the EC and WB seas. The 2019 field season was the final year for these annual broad-scale surveys. Data from bowhead whale carcasses collected in 2019 were added to the existing time series (2009–2018) (Willoughby et al. 2020).

We provide bowhead whale carcass counts and describe critical differences observed during 2019 compared to 2009–2018. Willoughby et al. (2020) reported 33 bowhead whale carcasses documented during July–October 2009–2018. We highlight their findings that are relevant to this paper: 18 carcasses had injuries consistent with probable killer whale predation based on aerial imagery investigation; 25 carcasses occurred in the EC compared to just 8 in the WB; 15 carcasses categorized as probable killer whale predation occurred in the EC and 3 in the WB.

Methods

The ASAMM study area encompassed the EC and WB seas from 67° N to 72° N and 140° W to 169° W, covering 242,000 km^2 (Fig. 1). Turbo Commanders equipped with left- and right-side bubble windows were used for the surveys. From 2 July through 30 October 2019, surveys were conducted daily, weather permitting. Two marine mammal observers (one stationed at each bubble window) reported sightings to a dedicated data recorder. In 2019, EC surveys were limited from 3 to 29 August to focus survey efforts in the Beaufort Sea (Clarke et al. 2020). Survey flights consisted of two main modes: (1) "survey effort" when observers were actively scanning for sightings; and (2) "deadhead" when observers were not scanning (Clarke et al. 2020). All carcasses were recorded during survey effort. Images of carcasses were obtained using a Canon DSLR camera with a 100–400 mm lens. For complete protocols, see Clarke et al. (2020) and Willoughby et al. (2020).

Using similar approaches as Willoughby et al. (2020, 2022), all bowhead whale carcass images from 2019 were evaluated by biologists (ASAMM; North Slope Borough Department of Wildlife Management [NSB-DWM]) and a wildlife veterinarian (NSB-DWM). Carcass analysis included body size, stage of carcass decomposition, and signs of human interaction (e.g., ship strike or entanglement) (Geraci and Lounsbury 2005; Moore et al. 2013). For injuries and wounds associated with killer whale interactions, a set of criteria was established based on peer-reviewed literature, local Indigenous knowledge, and knowledge gained from systematic investigations of baleen whale strandings by the NSB-DWM stranding response team (Lowry et al. 1987; Jefferson et al. 1991; George and Suydam 1998; Melnikov and Zagrebin 2005). Severe injuries and wounds attributed to killer whale interactions included torn throat; missing, exposed, fractured, or disarticulated jaw bone(s); missing tongue; blubber flensing; semilunar bite marks with varying degrees of tissue defects; evisceration of abdomen; and bone fractures. Secondary signs of killer whale predation included tissue bruising; tissue fraying around mouth opening, on pectoral flippers, and flukes; and killer whale tooth raking. Individual carcasses were categorized by possible cause of death in one of the three following ways:

1. *Probable killer whale predation* when images contained visual evidence of severe injuries consistent with killer whale predation to support that mortality was caused by killer whales or post-mortem scavenging (Online Resource 1 Fig. 1.1). Though scavenging contributed to our case material, we presume that wounds inflicted by killer whales represent fatal injuries from predation events rather than scavenging (for further discussion of this topic, see Willoughby et al. 2022).
2. *Aboriginal subsistence hunting* based on timing and proximity to a whale reported as struck but not retained (a "struck and lost" whale), when images contain visual evidence of hunting equipment (e.g., harpoon line and floats), or based on physical examination of the carcass.

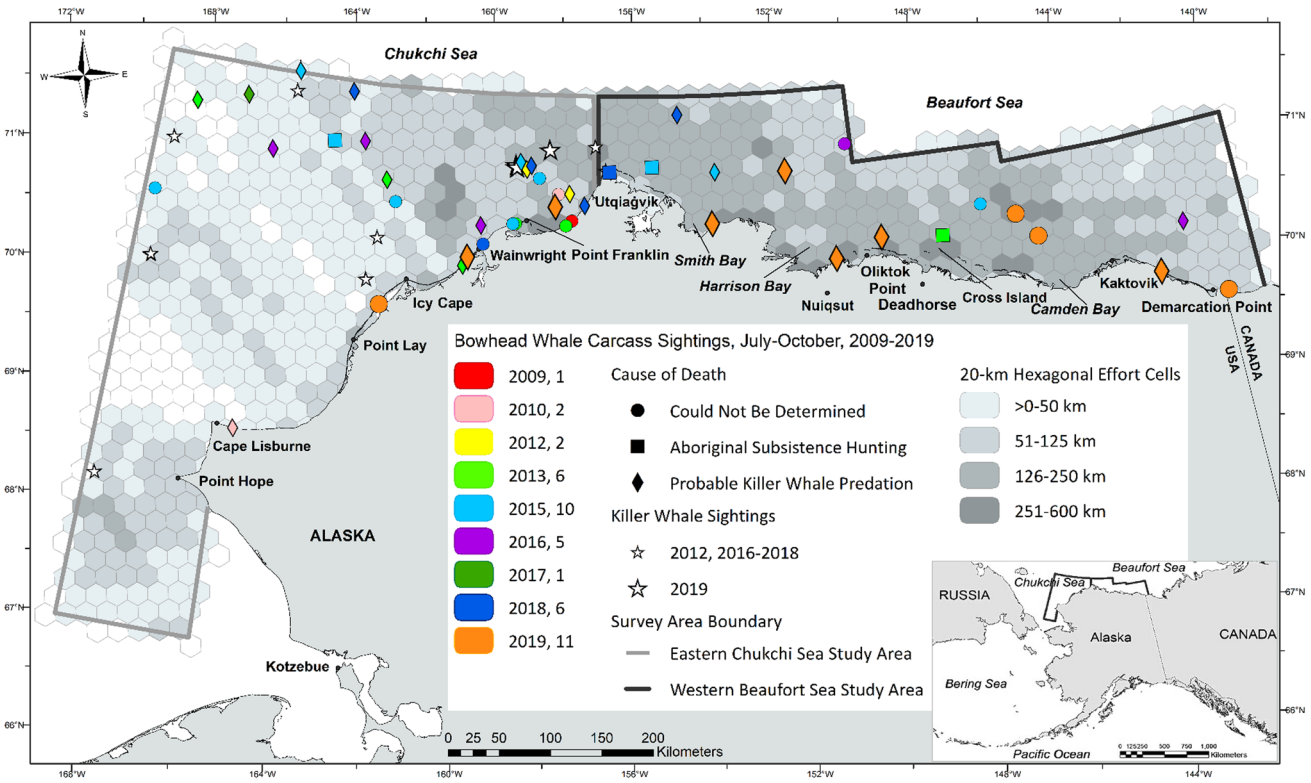

Fig. 1 The eastern Chukchi Sea study area (EC; 2009–2013: 68° N–72° N, 157° W–169° W; 2014–2019: 67° N–72° N, 157° W–169° W) and the western Beaufort Sea study area (WB: south of 71.2° N, 140° W–146° W; south of 71.3° N, 146° W–150° W; and south of 72° N, 150° W–157° W). The light to dark gray 20-km hexagonal cells depict the amount of survey effort in 2019, where lighter cells had the least survey effort and darker cells had the most. Bowhead whale (*Balaena mysticetus*) carcasses and killer whale (*Orcinus orca*) sightings overlay the hexagonal survey effort cells. Bowhead whale carcasses are color-coded by year (2019 carcasses are shown in large orange symbols). Symbol shapes depict the cause of death category: circles depict could not be determined; squares depict aboriginal subsistence hunting; and diamonds depict probable killer whale predation. Large white stars indicate killer whale sightings from 2019. Smaller white stars depict killer whale sightings from 2012 and 2016 to 2018

The latter was the case for one bowhead whale in 2018 (Willoughby et al. 2020).

3. *Could not be determined* when an injury could not be categorized as probable killer whale predation, when the carcass was too decomposed or lacked visible external injuries, or the image quality was too poor to determine probable cause of death (Online Resource 1 Fig. 1.1).

For this analysis, we divided the ASAMM survey area into two study areas: the eastern Chukchi Sea (EC: 67° N–72° N and 157° W–169° W) and the western Beaufort Sea (WB: south of 71.2° N, 140° W–146° W; south of 71.3° N, 146° W–150° W; and south of 72° N, 150° W–157° W) study areas (Fig. 1). Sighting rates (SR: number of bowhead whale carcasses [n] per 1000-km of survey effort) were computed to provide an index of relative occurrence and to evaluate the annual variability in carcass sightings between the EC and WB study areas. Visual sightings of killer whales observed in 2019 were summarized by group size and date.

Results

In 2019, 11 bowhead whale carcasses were documented during ASAMM aerial surveys (Fig. 1, Online Resource 2 Table 2.1). Six carcasses were found floating and five were beach-cast. Carcasses were distributed across the study areas from 140.9° W to 162.6° W and 69.6° N to 71.4° N (Fig. 1). Three carcasses occurred in the EC and eight were documented in the WB (Fig. 1, Online Resource 2 Table 2.1, Fig. 2.1). Seven carcasses were categorized as probable killer whale predation: two in the EC and five in the WB (Fig. 1, Online Resource 2 Table 2.1, Fig. 2.1). The cause of death could not be determined for the remaining four carcasses. No carcasses were attributed to aboriginal subsistence hunting in 2019.

The most carcass sightings (n) in a single year was observed in 2019 ($n = 11$), followed by 2015 ($n = 10$, of which two were attributed to aboriginal subsistence hunting), and 2013 and 2018 ($n = 6$ each year, of which one each year was attributed to aboriginal subsistence hunting)

(Fig. 1, Online Resource 2 Table 2.1). In 2019, more carcass sightings occurred in August; before 2019, most carcasses were sighted in September, except for 2009 (August) and 2015 (October) (Online Resource 2 Tables 2.1, 2.2). When carcass sightings were corrected for survey effort, the highest annual carcass sighting rate (SR) for the EC and WB study areas combined occurred in 2019 (SR = 0.1846 carcasses per 1000-km) (Online Resource 2 Table 2.3). The maximum monthly sighting rate in any given year and region occurred in August 2019 in the WB (SR = 0.6660) (Online Resource 2 Table 2.2). The highest annual carcass sighting rate in any given year and region was in the WB in 2019 (SR = 0.2166) (Online Resource 2 Table 2.2). The annual sighting rate for carcasses categorized as probable killer whale predation in the EC and WB study areas combined was highest in 2019 (SR = 0.1175) (Online Resource 2 Table 2.4, Fig. 2.2). Lastly, in 2019, the WB study area experienced the maximum sighting rate for carcasses categorized as probable killer whale predation in any given year and region (Online Resource 2 Table 2.4, Fig. 2.2).

Inter-annual comparisons of bowhead whale carcasses in the WB demonstrated differences between 2019 and previous years. First, the eight carcasses documented in the WB during 2019 were equal to the 2009–2018 combined carcass count (Fig. 1, Online Resource 2 Table 2.2, Fig. 2.1). Second, there were more carcasses attributed to probable killer whale predation in the WB during 2019 ($n = 5$) compared to 2009–2018 ($n = 3$) (Online Resource 2 Table 2.4). Lastly, 2019 was the first and only year that more bowhead whale carcasses were documented in the WB than in the EC (Fig. 1, Online Resource 2 Tables 2.1, 2.2, 2.4, Fig. 2.1, 2.3).

During 2019, killer whales were seen by ASAMM observers in the EC on two days: two killer whales on 30 August and three sightings of 13 total killer whales on 17 September (Fig. 1, Online Resource 2 Table 2.1).

Discussion

In 2019, the most frequent cause of death for bowhead whale carcasses in the ASAMM imagery was probable killer whale predation. The higher number of WB carcasses in 2019 compared to 2009–2018 cannot be explained by differences in survey effort (Online Resource 2 Tables 2.2, 2.3, Fig. 2.3). In addition to contrasting bowhead whale carcass patterns in 2019 compared to previous years, sighting rates of living bowhead whales were low and their autumn migration was farther offshore than typical (Clarke et al. 2020). It is unclear if the differences observed in 2019 are related. Survey effort in the EC was limited in August 2019; however, few bowhead whales are typically seen in the EC during August and this deviation is not believed to have affected the 2019 results. Because wind and water can transport carcasses, some of the carcasses documented in 2009–2019 may be an unknown distance from where the whale died. The drift direction and speed of four floating bowhead whale carcasses were best explained by prevailing wind direction and mean current circulation (S. Okkonen, University of Alaska Fairbanks, pers. comm. 10 April 2019) (Online Resource 3 Fig. 3.1).

The shift to the WB in 2019 is unusual compared to 2009–2018. Since 2019 was the final year of these surveys, we do not have comparable data for 2020 and 2021. However, along the WB in 2021, six bowhead whale carcasses were documented; three each by the NSB-DWM stranding team and NSB Autumn Aerial Surveys project, of which four had severe injuries consistent with killer whale predation (Stimmelmayr et al. 2022). These numbers were high for the WB compared to 2009–2018 combined; therefore, 2019 may represent a shift toward extended killer whale presence in the WB. Additionally, in 2021, Nuiqsut subsistence hunters sighted and reported killer whales in the WB near Cross Island, Alaska (B. Adams, NSB-DWM, pers. comm., 6 September 2021). The shifts observed in the WB coincide with the Unusual Mortality Event declared in early 2019 for Eastern North Pacific gray whales, a known prey species of killer whales (Rice and Wolman 1971; NOAA 2019; Willoughby et al. 2022). The gray whale population has decreased by 38% since 2016, and calf production has been low since 2019 (Eguchi et al. 2022a, b). The increase in bowhead whale carcasses attributed to probable killer whale predation in the WB may be in response to the decline of gray whales; however, testing this hypothesis is impossible without more data.

In 2019, ASAMM observers saw killer whales in the EC for the fourth consecutive year (2016–2019) (Fig. 1, Online Resource 2 Table 2.1). Passive acoustic detections beginning in 2007 show increased killer whale presence throughout the EC which coincides with the northward retreat of summer sea ice and warming seawater, with killer whale calls now recorded as far north as 75° N (Hannay et al. 2013; Stafford 2019; Wang and Overland 2015; Stafford et al. 2022a, b). As apex predators, killer whales can elicit changes in marine communities by influencing their prey's abundance, distribution, and behavior (Williams et al. 2004; Barrett-Lennard et al. 2011). The impacts killer whales may have on the bowhead whales here is unknown. Potential effects may include "predator-mediated" behavioral and habitat shifts by bowhead whales in the EC and WB when exposed to "perceived predation risks" (Matthews et al. 2020). These are known as "nonconsumptive effects," which Matthews et al. (2020) described and measured for eastern Canadian Arctic bowhead whales who altered their behavior and habitat use when killer whales were present. Alternatively, carcasses of predated bowhead whales become an energy source for

an array of species, ranging from polar bears (*Ursus maritimus*) to microbial communities, and become a source of carbon as "whale-falls" on the seafloor (Roman et al. 2014; Smith et al. 2015). Furthermore, the use of freshly dead beach-cast and drifting bowhead whales as food is a longstanding practice among many coastal communities in western and northern Alaska, as is the collection of hard parts for use in traditional crafts, tooling, and building materials (Carroll 1976; Stimmelmayr and Sheffield 2022).

Data collected in 2019 provided additional information on BCB bowhead whale mortality in the eastern Chukchi and western Beaufort seas. Findings from aerial imagery revealed an increase in killer whale predation events on bowhead whales in the western Beaufort. The contributions made by inferred co-occurrence from imaged carcasses and killer whale sightings, combined with passive acoustic data improves our understanding of killer whale distribution and residency, as well as the threats these predators pose to bowhead whales in this portion of their migratory range.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00300-022-03097-2.

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Author contributions AW and RS conceived and designed the study. MF coordinated and managed the Aerial Surveys of Arctic Marine Mammals project in 2019. AW, AB, and MF contributed to the collection of these data. AW and RS investigated Bowhead whale (*Balaena mysticetus*) mortality. AW wrote the manuscript with participation from AB, MF, and RS. AW created the figure and table. All authors reviewed the manuscript.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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