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NOTE

Killer whale vocalizations and presence in the Beaufort Sea

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The Arctic marine ecosystem is rapidly changing: major losses in sea ice, increases in ocean temperatures, and increases in productivity are just a few of the many environmental changes that have been documented in this region (Ballinger & Overland, 2022; Kortsch et al., 2012; Kwon et al., 2019; Lameris et al., 2021). Arctic amplification, the increased rate of warming observed at Earth's poles, is influencing the chemical, physical, and biological systems of the Arctic (Borgå et al., 2022; Kortsch et al., 2015; Pecuchet et al., 2020). An additional critical manifestation of this amplification is the increase in subarctic species of marine mammals whose distributions have shifted northwards (Clarke et al., 2013; Gulland et al., 2022; Moore, 2016; Stafford et al., 2022; Willoughby et al., 2020).

One species that is expanding its range into the Arctic is the killer whale (*Orcinus orca*). In the eastern Canadian Arctic, where killer whales have been documented predating native species, sightings have been increasing in frequency and seasonality (Breed et al., 2017; Ferguson et al., 2010; Higdon & Ferguson, 2009; Matthews et al., 2020). While killer whales are endemic to the Pacific Ocean, with semi-regular sightings occurring in the northern Bering, southern Chukchi, and rare sightings documented from Traditional Ecological Knowledge in the eastern, Canadian Beaufort Seas (Higdon et al., 2011; Nerini et al., 1984), their spatiotemporal residency in the western Beaufort Sea appears to be increasing (Hannay et al., 2013; Stafford, 2018; Stafford et al., 2022).

In the past, killer whale sightings in the Pacific Arctic were relatively sparse. It is hypothesized that the heavy sea ice that historically extended south of the Bering Strait for much of the year restricted their range into the Arctic (Heide-Jorgensen, 1988; Higdon & Ferguson, 2009; Matthews et al., 2011). However, killer whales venturing further northwards from the Bering Strait than their historical range have been detected through methods like passive acoustic monitoring (Stafford, 2018).

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Since different marine mammal species or populations have distinct acoustic signals, listening to an environment allows scientists to determine which species are present (Fleishman et al., 2023). All killer whales emit echolocation clicks, whistles, and pulsed calls (Matkin et al., 2007; Riesch & Deecke, 2011). However, mammal-eating killer whales, referred to as Bigg's or transient killer whales, produce fewer pulsed calls and whistles and use echolocation less frequently, likely to avoid being detected by their marine mammal prey (Barrett-Lennard et al., 2011; Matkin et al., 2007; Riesch & Deecke, 2011; Sharpe et al., 2019). Additionally, the pulsed calls and whistles of transient killer whales are lower in frequency, narrower in bandwidth, and shorter in duration compared to those of resident killer whales (Deecke et al., 2005; Filatova et al., 2015). At present, all known acoustic recordings attributed to killer whales north of the Arctic Circle in the Pacific Arctic have been identified as transients (Madrigal et al., 2021; Stafford, 2018).

To monitor the migratory behavior of bowhead whales (*Balaena mysticetus*), passive acoustic data were recorded by six hydrophones in the Beaufort Sea that were deployed from 2008 to 2014 and 2016 to 2022 (Figure 1; Table 1). These data also recorded the sounds of other marine mammals, including killer whales, which led us to systematically survey them for the acoustic presence of killer whales.

Killer whale calls in the data were located by visually examining spectrograms (2,048 pt FFT, 50% overlap, Hann window, supplementary material) of these data using Ishmael (Mellinger, 2002), and aural analyses and expert review (KMS) were used to confirm vocalizations were produced by killer whales (Figure 2). The number of days with killer whale detections was identified for each hydrophone (Table 2). The total number of hours in which a killer whale vocalization was detected was compared to total hours of recorded effort per year to determine the annual ratios of killer whale presence (Figure 3). Additionally, since these data were collected on variable duty cycles (Table 1), killer whales may have been present and vocalizing at times that were not recorded by the hydrophones.

We did not detect killer whales in our data until 2017, although the changes in duty cycles and lack of data in 2015 may influence the interannual variability in detection probability. In 2017, we detected killer whales on hydrophones 2 and 3 on August 3 and September 20 (Figure 1). In 2019, hydrophone 1C recorded 7 h of killer whale activity on August 7. In 2021, we detected killer whales on hydrophones 4, 5, and 6; hydrophone 4 contained killer whale recordings on August 28, September 4, and September 5, 2021. Hydrophone 5 included recordings from September 8, 9, and 10, 2021 and hydrophone 2 recorded 20 h of killer whales on 8 September. Each recording containing killer whale sounds had no other detectable animals vocalizing.

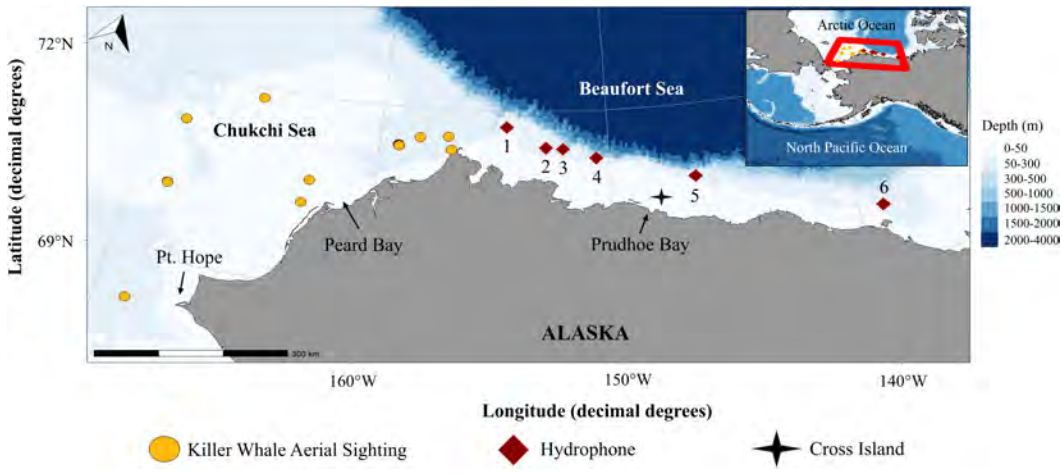

FIGURE 1 Map of mooring deployment locations (red diamonds) and aerial sightings of killer whales (yellow circles) in the Chukchi and Beaufort Seas. Smaller map in upper right corner indicates the locations within a broader global region (i.e., centered above Alaska). Map made in R with the "ggOceanMaps" (v 1.0.9) and "ggspatial" (1.1.7) packages.

TABLE 1 Programming data for each hydrophone.

Hydrophone	Location	Sample rate (kHz)	Duty cycle (min on/off)	Recording start date	Recording end date
3A	71.5 N 152.3 W	8.192	18 on/42 off	August 16, 2008	August 15, 2009
3B	71.4 N 152.5 W	8.192	18 on/42 off	August 17, 2009	August 12, 2010
3C	71.41 N 152.00 W	16.384	15 on/45 off	September 25, 2010	August 30, 2011
3D	71.4 N 152.0 W	8.192	10 on/20 off	September 1, 2011	August 28, 2012
3E	71.4 N 152.0 W	8.192	10 on/20 off	August 31, 2012	September 1, 2013
3F	71.4 N 152.0 W	8.192	10 on/20 off	September 7, 2013	July 18, 2014
3G	71.4 N 152.1 W	16.384	5 on/55 off	September 13, 2016	October 30, 2018
6	69.9 N 139.0 W	16.384	15 on/45 off	October 7, 2016	September 28, 2017
4	71.2 N 150.6 W	16.384	25 on/35 off	September 1, 2017	August 10, 2018
3H	71.4 N 152.0 W	16.384	9 on/21 off	November 05, 2018	July 23, 2020
1	71.8 N 154.5 W	16	70 on/230 off	September 16, 2020	November 11, 2021
5	70.8 N 146.4 W	48	9 on/21 off	August 23, 2021	August 17, 2022
2	71.4 N 152.7 W	48	9 on/21 off	September 5, 2021	August 26, 2022

Note: Locations, sample rates, duty cycle settings, and the start and end date of recordings listed. Table ordered chronologically by recording start date.

Killer whale vocalizations were recorded during the same hours (04:30 a.m. to 06:30 a.m.) on September 8, 2021, by hydrophones that were over 160 km apart. The presence of these concurrent killer whale signals clearly indicates that there were at least two different groups of killer whales in the Beaufort Sea at this time.

In addition to the acoustic detections reported here, other data sources reflect an increase in killer whale presence within the last two decades. A recent report of killer whale acoustic detections in the Pacific Arctic from 2011 to 2019 found an increase in killer whale detections in the Chukchi Sea and included detections in the western Beaufort Sea (hydrophone 4) in 2012, 2013, and from 2015 to 2019 (unpublished data[1]). The National Oceanic and Atmospheric Administration's database of Aerial Surveys of Arctic Marine Mammals had no sightings of killer whales in the northeastern Chukchi Sea before 2012 (Clarke et al., 2013). Between 2012 and 2019, all aerial survey sightings of killer whales were west of Point Barrow in the Chukchi Sea (Figure 1; Clarke et al., 2020). Killer whales were not seen during aerial surveys in the Beaufort Sea despite considerable effort in late summer and early fall (Clarke et al., 2020). In general, however, the number of subsistence harvested bowhead whales with killer whale rake marks has increased over time (Breed, 2021; George et al., 2017).

The number of acoustic detections reported here is certainly an underestimate of the presence of killer whales in the study area for two reasons. Firstly, transient killer whales tend to be quiet while hunting, and this may lead to pods going undetected by acoustic moorings (Deecke et al., 2005). Second, moorings were located offshore, and killer whales may be more common in near-shore waters because sea ice overlies offshore regions in spring and early summer and will sometimes cover moorings even in summer. Sea ice largely limits the distribution of killer whales because their large dorsal fins may affect their ability to surface in ice-covered waters. As such, if killer whales are more common near-shore, their presence may not always be detected by off-shore moorings (even if offshore moorings show a general pattern of expansion).

Some visual sighting data[2] exist for subsistence whaling communities along the northern coast of Alaska. These data, some unpublished and some reported in George et al. (1994) and George and Suydam (1998), suggest that

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[2]John Citta, March 2024, john.citta@north-slope.org, North Slope Department of Wildlife Management visual sightings database.

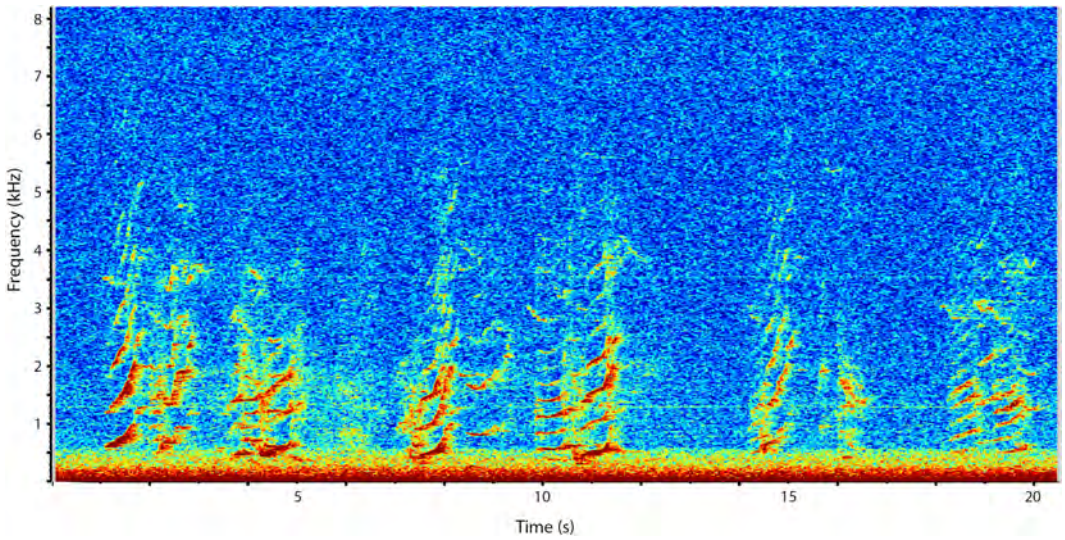

FIGURE 2 Spectrogram of killer whale vocalizations. Spectrogram recorded in September 2017 on hydrophone 4 (2,048 sample FFT, 94% overlap, 1,024 hop size, Hanning window). A wav file of the spectrogram is provided in the supplementary data.

TABLE 2 Details of killer whale detections recorded by each hydrophone.

Hydrophone	Killer whale detection dates	Hours of killer whale presence recorded	% of files with killer whale calls
6	September 28, 2017	2	.023
4	September 20, 2017	2	.024
3C	August 7, 2019	7	.047
1	September 5, 2021	5.7	.185
5	September 10, 2021	5	.058
2	September 8, 2021	20	.234

Note: Dates of the detections, the length of killer whale vocalizations, and the percent of each hydrophone's data set with killer whale calls are described.

since the 1980s, when record keeping began, killer whales were sighted between Peard Bay and Point Barrow (Figure 1), in the northeastern Chukchi Sea, during 21 out of 40 years (unpublished data[2]). The number of killer whale sightings in this region per year is variable, but most years, they were sighted only once or twice. However, in 1991, killer whales were sighted eight separate times between Peard Bay and Point Barrow. Although more rarely, killer whales were also sometimes found east of Point Barrow in the Beaufort Sea. Killer whales were sighted east of Point Barrow in 1994, 1995, 2019, 2021, and 2023. In 1995 and 2001, killer whales were sighted as far east as Cross Island, and, in 2023, killer whales were spotted as far east as Prudhoe Bay (unpublished data[2]). Hence, killer whales were periodically sighted near-shore in the western Beaufort Sea prior to when our study began in 2008. With that said, the sighting data do suggest that killer whales are becoming more commonly observed in the western Beaufort Sea, an idea that is also generally supported by Iñupiat hunters.

Many of these sightings describe pods hunting marine mammals, such as seals, walruses, bowheads, belugas, and, more recently, polar bears. In 2023, killer whales were seen chasing bowhead whales, and a predated whale was observed later during the same day (unpublished data[2]). Also in 2023, there was a sighting of a killer whale pod

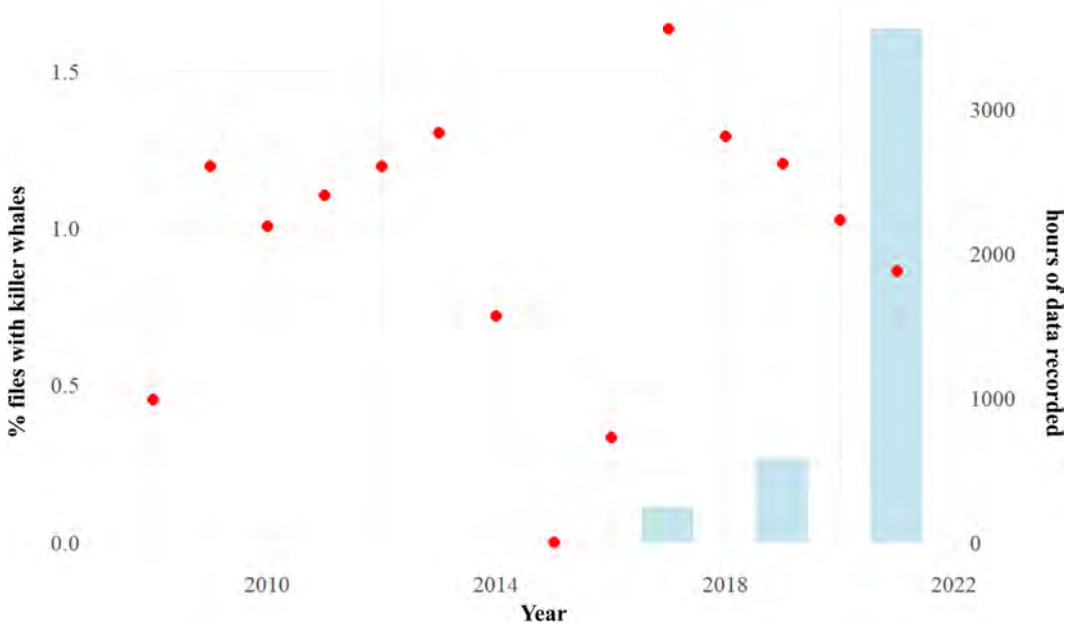

FIGURE 3 Time series showing the percent of files with killer whale calls from 2008 to 2021 and the number of hours of data recorded per year. The blue bars represent the percentage of files with killer whale calls, and the red points reflect the number of hours of data recorded per year, as a proxy for effort. In 2015, there were no acoustic data recorded.

predating one adult and two juvenile polar bears in Prudhoe Bay (unpublished data[2]). These reports of killer whales chasing marine mammals supports the assumption that the ecotype observed is indeed transient killer whales. Although killer whales have been relatively rare in the Beaufort Sea in the past, the combination of acoustic data, aerial survey sightings, and local sightings from Alaskan and Canadian villages supports the claim that killer whales are (and have been) expanding into the northern Pacific Arctic.

Killer whales, like other marine mammals, are considered sentinels for ecosystem change (Moore, 2008). They are widely regarded as one of the world's most efficient apex predators (Ferguson et al., 2010; Ford, 2009). It seems clear that killer whales are increasing their presence in the Beaufort Sea; whether the same individuals or groups are returning to the Beaufort Sea each year, and how long they remain, is unknown. The easternmost hydrophones from this study only extended as far east into Canada as Herschel Island (139° W). Therefore, although there have been few killer whale sightings as far east as Ulukhaktok, Canada (Higdon et al., 2013), we cannot determine how far east killer whales traveled into the Beaufort Sea during the times we report here. Higdon et al. (2013) summarized observations from interviews with residents in the Canadian Beaufort region and documented roughly 2.6 sightings per decade of killer whales in nearshore regions. Those authors suggested that these animals were likely following beluga whales (*Delphinapterus leucas*) from the Chukchi and western Beaufort seas. While we cannot state with certainty that the vocalizations were produced by the transient ecotype of killer whales, the bulk of the evidence supports the hypothesis that these signals were made by transient whales.

The biggest question remaining is how an increasing presence of killer whales will affect the Pacific Arctic ecosystem. Indigenous communities on the Beaufort coast harvest marine mammals for subsistence and a number of these species have been targeted by killer whales. Studies in the eastern Canadian Arctic suggest that killer whale presence may drive alterations in Arctic marine mammal distribution (Matthews et al., 2020). For example, although the Bering-Chukchi-Beaufort population of bowhead whales has more than doubled between 1993 and 2011 (Muto et al., 2021), survival rates for bowhead calves and juveniles could be affected by the increased presence of a novel predator (Breed, 2021; Givens et al., 2021). Other marine mammals in the Beaufort Sea, such as gray whales (*Eschrichtius robustus*) and beluga whales, are likely targets of killer whale predation (Higdon et al., 2013; Melnikov &

Zagrebin, 2005; Willoughby et al., 2022). Detailed analyses of call structure are required to definitively attribute the signals we recorded to the transient ecotype. While we cannot predict how this novel predator will affect the balance of the ecosystem, their increasing presence could potentially disrupt current ecosystem dynamics (Breed et al., 2017; Estes et al., 1998; Jorgensen et al., 2019) and therefore should continue to be monitored.

AUTHOR CONTRIBUTIONS

Hannah L. Sawyer: Conceptualization; formal analysis; investigation; methodology; visualization; writing – original draft; writing – review and editing. **Angela R. Szesciorka:** Methodology; visualization; writing – review and editing. **John J. Citta:** Data curation; writing – review and editing. **Brynn M. Kimber:** Data curation; writing – review and editing. **Kathleen M. Stafford:** Funding acquisition; investigation; methodology; project administration; resources; writing – original draft; writing – review and editing.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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