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RESEARCH

Less ice, more predators: passive acoustic monitoring shows variation in killer whale (*Orcinus orca)* presence in the U.S. Arctic with declining sea ice

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Abstract

Arctic sea ice has provided a historical barrier for killer whale (*Orcinus orca*) entry, but that barrier is now depleting as the sea ice melts due to global climate change. This study used passive acoustic monitoring to describe changes in broad-scale killer whale presence in the U.S. Arctic associated with declining sea ice. Passive acoustic data were analyzed for killer whale calls from eight monitoring sites throughout the Alaska Chukchi, northern Bering, and western Beaufort seas from 2011 to 2019 and correlated with sea ice coverage. Killer whale acoustic presence was significantly correlated with sea ice coverage in the U.S. Arctic at two sites directly north and south of the Bering Strait ($p = 0.04$, $t_7 = -5.34$; $p = 0.03$, $t_7 = -4.42$), and increased as sea ice decreased in the North Slope region along the Northern Alaska coast ($p < 0.01$, $t_7 = 4.49$). We also observed shifts in the spring arrival of killer whale calling over the time period of the study, which correlated with the timing of sea ice retreat. Killer whales shifted their time of arrival an average of 50 days earlier in the North Slope region and 32 days earlier in the Bering Strait region over the study period with 16.2 days (± 6.6 SD) lag between sea ice retreat and the first killer whale detection. These results point to an increased presence of an apex predator in the U.S. Arctic, which has the potential to impact the trophic dynamics of this region.

Keywords Killer whale · Climate change · Acoustics · Alaska · Bering sea · Trophic dynamics · Bowhead whale · Gray whale

Introduction

The Arctic Ocean, a region historically covered with sea ice for much of the year, is undergoing rapid warming, increasing by 4.5 °C from 1982 to 2021 (Nielsen-Englyst et al. 2023). These warming temperatures have resulted in rapidly decreasing sea ice extent; since 2000, sea ice has decreased by 3.4% per decade (Stroeve and Notz 2018) and climate models predict that the Arctic could be ice-free in a matter of decades (Notz and Stroeve 2018; Årthun et al. 2021). This shift has the potential to disrupt the life histories of sea ice-dependent Arctic resident species (Gilg et al. 2012) and bring new opportunities for sub-Arctic species such as killer whales (*Orcinus orca*).

Killer whales in the North Pacific are categorized into three ecotypes, all of which exhibit genetic distinction (Parsons et al. 2013) and exploit separate ecological niches (Herman et al. 2005). The "resident" ecotype inhabits nearshore habitats and primarily hunts fish (Ford et al. 2000). The "offshore" ecotype inhabits the outer continental coast, though will also come in to nearshore locations (Ford et al. 2014) and are known to eat fish, primarily sharks. The "transient" or Bigg's killer whale ecotype are mammal eaters that are mostly coastal and sometimes move long distances to follow prey species (Ford et al. 1998; Saulitis et al. 2000; Heise et al. 2003; Herman et al. 2005). They are prolific hunters

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with large and versatile ranges, giving them the potential to significantly impact the population numbers of their prey (Thomas et al. 1981; Higdon et al. 2012; Shields et al. 2018). They also are opportunistic hunters, often seeking prey sources that require the least amount of energy effort to hunt (Dalheim and White 2010).

The three killer whale ecotypes can be distinguished by morphological characteristics as well as acoustic signatures (Foote and Nystuen 2008). Each ecotype uses acoustic signals for various purposes, from coordinating hunting strategy to prey distribution among individuals (Ford and Fisher 1983; Ford 2019), and each ecotype has specific acoustic behaviors based on their ecological needs. As opposed to fish-eating resident killer whales, transient killer whales hunt other marine mammals, which are able to readily detect killer whale calls and may exhibit predator avoidance behavior if killer whales are detected (Cummings and Thompson 1971; Deecke et al. 2005). Likely to avoid alerting their prey, transient killer whales call far less frequently than other ecotypes and are thought to primarily call only after prey is captured (Deecke et al. 2005).

While transient killer whales have been well documented in Alaska waters south of the Bering Strait (Dalheim et al. 1997, 2008; Matkin et al. 2012; Zerbini et al. 2007), little is known about their range in the Alaska Arctic. Sea ice avoidance in Northern Hemisphere killer whales has been well-documented, including cessation of predation attempts in the presence of thick sea ice (Matthews et al. 2011). Unlike Arctic resident species, such as bowhead whales (*Baleana mysticetus*), whose morphology allows them to create air holes in ice up to 60 cm thick (Rugh and Shelden 2009), killer whales can only break through ice approximately 15 cm thick (Thomas et al. 1981), limiting where they can travel safely in the sea ice pack. Entrapment and suffocation in pack ice is a notable cause of mortality for killer whales (Westdal et al. 2017; Matthews et al. 2019). Nevertheless, Alaska Native sources have records of intermittent killer whale sightings in the Chukchi and Beaufort seas beginning in 1982 (George and Suydam 1998), though historical sightings north of the Bering Strait are extremely sparse by comparison to those south of it. Most visual and acoustic marine mammal surveys of the Chukchi and Beaufort seas rarely note killer whales, and few details are known about the killer whales that are observed (Hannay et al. 2013; Aerts et al. 2013; Kuletz et al. 2015; Clarke et al. 2020). Acoustic presence of killer whales in these areas has been limited to sea ice-free months, with the highest concentration of calls detected in September and October, and calls detected in June at the earliest (Stafford 2019; Stafford et al. 2022).

With increased access to the area as sea ice melts, the question follows if transient killer whales might be more consistently venturing into the Arctic following trends in global climate change. Higdon and Ferguson (2009) compiled a comprehensive look at killer whale presence in the Hudson Bay area over the last century in relation to a loss of sea ice. The authors hypothesized that the previously ice-covered straits provided a blockade to Hudson Bay, barring killer whales from entry. When this ice barrier decreased as temperatures warmed, they found an exponential increase in killer whale presence, to the point that the previously rarely observed killer whales are now an annual occurrence in the area.

The Bering Strait in Alaska is hypothesized to have historically provided a similar barrier. As seasonal sea ice cover in the Bering Strait continues to decline, there may be more opportunities for killer whales to traverse into the Alaska Arctic ecosystem. Recent passive acoustic studies have found an increase of killer whales at sites in the southern Chukchi Sea near the Bering Strait from 2009 to 2016 (Stafford 2019) and on the northern Chukchi plateau beginning in 2016 (Stafford et al. 2022). More investigation is needed to determine if the trends observed at these two sites continue throughout the Arctic, as much of the wide expanse of the Alaska Arctic remains unexplored with regards to killer whale presence.

The Alaska Fisheries Science Center's Marine Mammal Laboratory's (AFSC/MML) extensive network of acoustic recorders throughout the U.S. Arctic and sub-Arctic make it possible to detect the year-round presence of marine mammals, including killer whales, over a broad spatial and temporal scale. This paper examines shifts in killer whale acoustic presence in the Pacific Arctic from the Southern Bering Strait area to the Western Beaufort Sea using passive acoustic monitoring during a period of overall warming, 2011 to 2019. In addition, we compared transient killer whale presence to sea ice presence, to test the hypothesis that the Bering Strait provides a barrier of access to killer whales during ice-covered seasons.

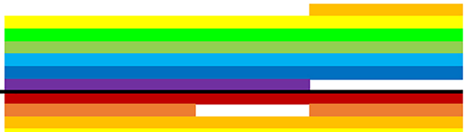
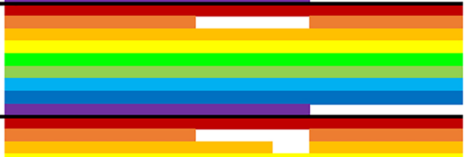
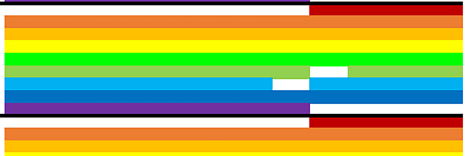
Methods

Data collection

We used passive acoustic data from an existing network of underwater long-term passive acoustic recorders maintained by AFSC/MML. Eight mooring sites were selected due to their location and consistency of data collection from 2011 to 2019 (Table 1).

Data used in this study were collected via Autonomous Underwater Recorders for Acoustic Listening M2 devices (AURALs, Multi-Électronique, Rimouski, QC, Canada). The AURALs were attached to sub-surface, bottom-mounted moorings throughout the Alaska Arctic and Bering Sea (Fig. 1).

Table 1 Site deployment information, including average latitude and longitude, average sensor depth, and all data included for each site Years with data present (2011–2019) are represented by color (where red = 2011 and purple = 2019). Months (January–December) with > 15 days of data gaps are represented with white

Site	Latitude (°N)	Longitude (°W)	Depth (m)	J F M A M J J A S O N D
BF02	71.751	154.471	98	
WT01	71.046	160.511	50	
PB01	71.205	158.019	48	
IC03	71.829	166.079	45	
IC02	71.229	164.214	41	
IC01	70.834	163.113	45	
PH01	67.908	169.194	59	
NM01	64.855	168.447	44	

The data collected by the AURALs consist of year-round acoustic recordings, at 16-bit resolution and 16 dB gain. Data were collected at a sampling rate of 16 kHz, and on a duty cycle of either 80 min (2012–2019) or 85 min (2011) of recording every 5 h, with the exception of the 2011 BF2 site, which had a sampling rate of 8 kHz and a duty cycle of 6 min every 20 min. The recordings have a flat frequency response from 10 Hz to 7.8 kHz (±3 dB) for the 16 kHz sampling rate and 10 Hz to 3.9 kHz (±3 dB) for the 8 kHz sampling rate. System sensitivity is − 63.7 dB counts/µPa (-164 dB V/µPa hydrophone sensitivity, 16 dB gain, and 84.3 dB count/V). Dynamic range was 90 dB and a spectral noise floor of approximately 52–55 dB re 1 µPa^2/Hz (Kinda et al. 2013 and empirically derived).

Data processing

Passive acoustic data

Raw data were converted into 10 min.wav files and spectrograms of these.wav files were analyzed using an in-house MATLAB-based program *SoundChecker* (for full details see Wright et al. 2019). Trained analysts visually and auditorily examined 90 s interval spectrograms for the presence/absence of Arctic and sub-Arctic species using stereotyped calls to identify each species (Fig. 2).

Over 350,000 h of acoustic data were manually analyzed for the presence/absence of marine mammals,

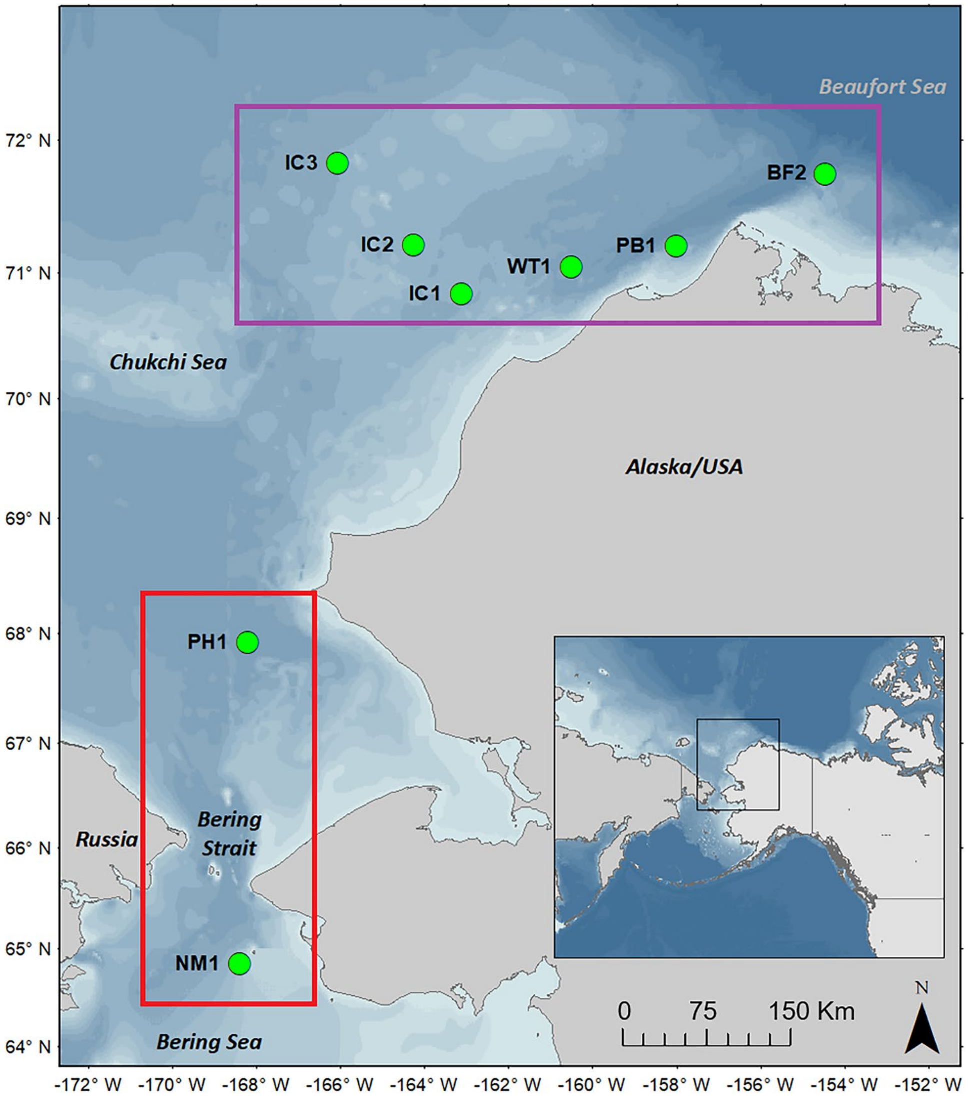


Fig. 1 Location of marine mammal mooring sites (green circles) used in this study. The red box designates the Bering Strait sites, and the purple box designates North Slope sites

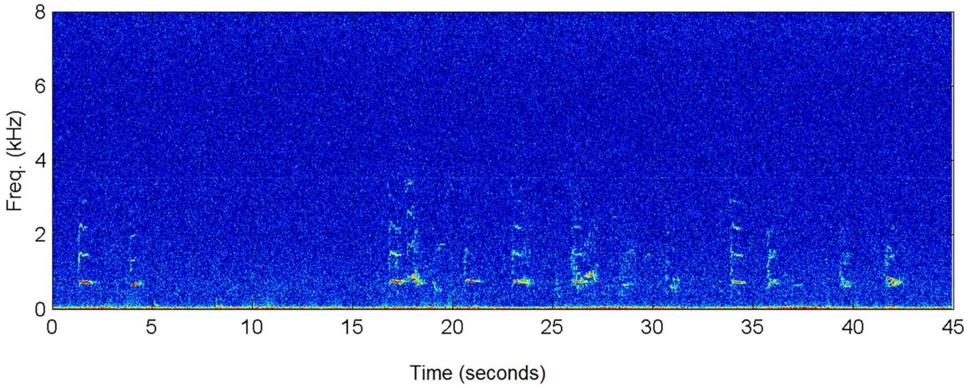


Fig. 2 Spectrogram showing transient killer whale pulsed calls recorded on July 3rd, 2013 from the PH1 site. Spectrogram: Hamming window, 95% overlap, 2048 FFT

including killer whales. Analysts marked "yes", "no", or "maybe" (where there was uncertainty in species classification) for all species present. Only "yes" calls (i.e., 100% certainty of species classification) were used in analyses and thus our results provide a metric of killer whale presence. All killer whale detections not analyzed by BMK were reviewed for accuracy by BMK.

Killer whales are commonly defined by three main sound types: clicks, whistles, and pulsed calls (Ford and Fisher 1983; Foote and Nystuen 2008; Riesch and Deecke 2011; Madrigal et al. 2021); these were used to identify killer whales in this study. Killer whale calls were distinguished from those of other species (e.g., beluga whales, *Delphinapterus leucas*) by variation in frequency modulation, call duration, and tone. Specific ecotypes of killer whales ("transient" vs. "offshore" vs. "resident") can be distinguished further based on calling rate, frequency, and regularity of certain call types (Foote and Nystuen 2008). The same recordings of killer whale calls from the PH1 site used in this study were analyzed and identified as transient killer whales by Madrigal et al. (2021). The killer whales at all sites north of PH1 are presumed to also be transient based on the far-reaching nature of transient killer whale movements relative to other ecotypes, and observations of frequency and call-type by expert analysts. The primary observed call at all sites was the pulsed call type found in patterns consistent with the results of the transient killer whale dialect analysis found in Madrigal et al. (2021).

Sound propagation modeling

The Monterey-Miami Parabolic Equation (Smith et al. 2007) was used to estimate sound propagation, and to determine any potential overlap in detection range between sites. A water column sound speed profile taken from CTD (conductivity, temperature, and depth) data at each site (P. Stabeno, Pacific Marine Environmental Laboratory, NOAA) was used to calculate propagation of the most commonly heard 3 kHz whistle call types with the assumption of a 10 m call depth (Baird 1994).

Sea ice data

We explored correlations between killer whale acoustic detection and sea ice timing during a period of rapid sea ice loss (2011–2019). Sea ice data were obtained from 25-km resolution satellite data from the National Snow and Ice Center (https://nsidc.org/data/nsidc-0079/versions/4; Meier et al. 2021; Comiso 2023) to determine sea ice presence throughout the Arctic. The haversine equation was then used in Python to calculate which of the 25 km grid cells were within 25 km of the mooring site. The values for these data points were then averaged to determine the total percentage of ice-cover, for each mooring site, per day. Using these daily percentages, the first day of "open water" for each year was determined using the first day of a 3-day period of $< 80\%$ sea ice cover that was not immediately followed by a $3+$ day period of $> 80\%$ sea ice cover for all mooring sites. The 80% sea ice cover was chosen because it is the approximate maximum sea ice cover percentage that killer whales and other sub-Arctic species have been observed to consistently enter (Ainley et al. 2017). Sea ice data were also presented in total annual extent in square kilometers (to determine pan-Arctic minimum and maximum extent) (Fetterer et al. 2017).

Data analysis

Data were grouped into bins calculated by the number of 10-min intervals with calls divided by the total number of 10-min intervals for that day (i.e., daily calling activity), standardizing for effort by mooring and year. The resulting daily calling activity percentages were then averaged over each year to determine yearly calling activity.

To examine finer-scale trends, the recordings from the eight sites throughout the Arctic were grouped based on geographical location (Fig. 1). These two groups were as follows: (1) "Bering Strait"—sites directly north and south of the Bering Strait (PH1 and NM1, respectively); and (2) "North Slope"—sites following along the North Alaska coast in the northeastern Chukchi and western Beaufort seas (IC1, IC2, IC3, WT1, PB2, BF2). Both of these groups were analyzed for changes in daily calling activity, seasonality trends, and the direct temporal relationship of killer whales and sea ice.

Bering strait sites

The Bering Strait sites include NM1, approximately 100 km south of the Strait, and PH1, approximately 240 km north of the Strait (Fig. 1), encompassing the area through which all species must travel to enter the Arctic Ocean from the Bering Sea. This designation was selected based on the geographical placement of the sites and the historical documentation of killer whales in these areas, primarily as they hunt in and around Norton and Kotzebue Sounds for one of their most targeted prey species, gray whales (*Eschrichtius robustus*) (Ljungblad and Moore 1983; Barrett-Lennard et al. 2011; Willoughby et al. 2022). These sites were specifically used to examine the relationship between the timing of killer whale presence with the decrease of sea ice in the Bering Strait over the study period. To do this, we regressed the first Ordinal date of open water by the first Ordinal date with a killer whale call detected as well as calculated a paired single-tailed T-test between the two variables using Microsoft Excel (V. 1808). For each year, the lag between ice retreat and killer whale presence was also calculated by subtracting the first Ordinal date with killer whale presence from the first Ordinal date with open water.

North slope sites

The majority of the recordings used in this study are those taken from sites along the northwestern Alaska coast in the North Slope region, specifically IC1, IC2, IC3, WT1, PB2, and BF2 (Fig. 1). Due to gaps in the recordings, low calling rates of transient killer whales, and similar geographical and oceanographic attributes among North Slope sites (Stabeno et al. 2020; Stabeno and McCabe 2023), processed PAM data from these sites were grouped together for analysis.

This dataset was used to examine changes in the frequency of detection of killer whale calls from 2011 to 2019. Day, month, and year averages of binned data were calculated for each North Slope site individually and for all sites combined, for all years of data available. Yearly averages in killer whale calling activity were then compared against the Arctic sea ice minimum using a paired single-tailed T-test. Overall yearly trends in calling activity were then examined using regression analysis. The data were best fit using an exponential trendline and thus x-values were standardized as "years since 2010" to adjust for scale. Percentage change in calling activity was calculated by comparing the average calling activity between the first and last years with data available for the North Slope site, using the values extracted from the regression analysis.

In addition to acoustic presence, seasonality shifts in killer whale presence were also examined for North Slope sites. The average first day of killer whale presence at any of the sites in the area was calculated for each year, and yearly shifts were examined using linear regression. Trends in departure times were not analyzed due to data gaps.

Results

Sound propagation

Propagation distances of the most commonly observed 3 kHz whistle call type were estimated to be < 10 km for all sites, assuming a mean source call of 155 dB (Holt et al. 2011). As all sites used in this study are > 100 km apart, there was little chance of overlap in detection between sites.

Bering strait sites

Both of the Bering Strait sites (PH1 and NM1) showed a significant positive relationship between the first day of open water and the first day of killer whale presence ($p_{PH1} = 0.04$, $t_7 = -5.34$; $p_{NM1} = 0.03$, $t_7 = -4.42$). Linear regression revealed a significant positive trend for both earlier first day of open water ($p_{PH1} < 0.01$, $t_{7PH1} = -6.52$, $p_{NM1} = 0.02$, $t_{7NM1} = -3.37$) and earlier first day of killer whales ($p_{PH1} < 0.01$, $t_{7PH1} = -5.64$, $p_{NM1} = 0.05$, $t_{7NM1} = -2.56$) detected across the study period (Fig. 3).

The lag between sea ice retreat and first killer whale call ranged from 6 to 26 days, with a mean of 16.2 days (±6.7 SD) (Fig. 4a).

Killer whales arrived an average of 32 days earlier in the year from the beginning to the end of the study period. The number of analyzed time-bins with positive killer whale detections showed a slight decrease from 2012 to 2018, with an average decrease in calling activity of 17% (Fig. 5a), though this change was not found to be significant ($p = 0.08$, $t_7 = 2.38$).

North slope sites

When grouped, the North Slope sites (IC1, IC2, IC3, WT1, PB2, BF2) support an increasing trend in killer whale acoustic presence from 2011 to 2019 (Fig. 5b). Wherein 2011–2015 there was minimal to no acoustic killer whale presence detected, killer whale acoustic presence increased and remained consistently higher beginning in 2016 (Fig. 5b). Over the study period, there was a significant ($p = 0.03$, $t_7 = -2.95$) increase in average killer whale calling activity of 3,912% (an increase from 0.008% in 2011 to 0.31% in 2018) in the North Slope region. Each site from this region except WT1 showed an increase in killer whale calling activity over the study period (Fig. 4b). Though there is both inter-site and intra-site variability, the overall trend supports exponential growth of killer whale acoustic presence in the North Slope area (Fig. 5b). This trend has a significant inverse relationship with the pan-Arctic sea ice minimum ($p = 0.003$, $t_7 = 4.49$), supporting that killer whale presence increased as sea ice decreased in this region. In this region, there were also occasional instances of killer whale detections under ice cover. There were four days total throughout the study period where these detections occurred under conditions with over 80% ice cover, three of which were within one week of the sea ice break-up period (Fig. 5b).

Seasonal shifts in killer whale calling were also observed in this region, specifically in the timing of first call detected each year. Together, the North Slope sites show significantly earlier initial killer whale detection over the years of this study ($p < 0.01$, $t_7 = 5.72$), with an average arrival of 50 days earlier between the first year (2011) and the last (2019) (Fig. 6).

For both killer whale presence and seasonal timing, 2012 was a notable outlier, with killer whales detected earlier and more frequently than in the years immediately following. This exception to the trend supports a relationship between killer whale presence and sea ice, as the sea ice minimum

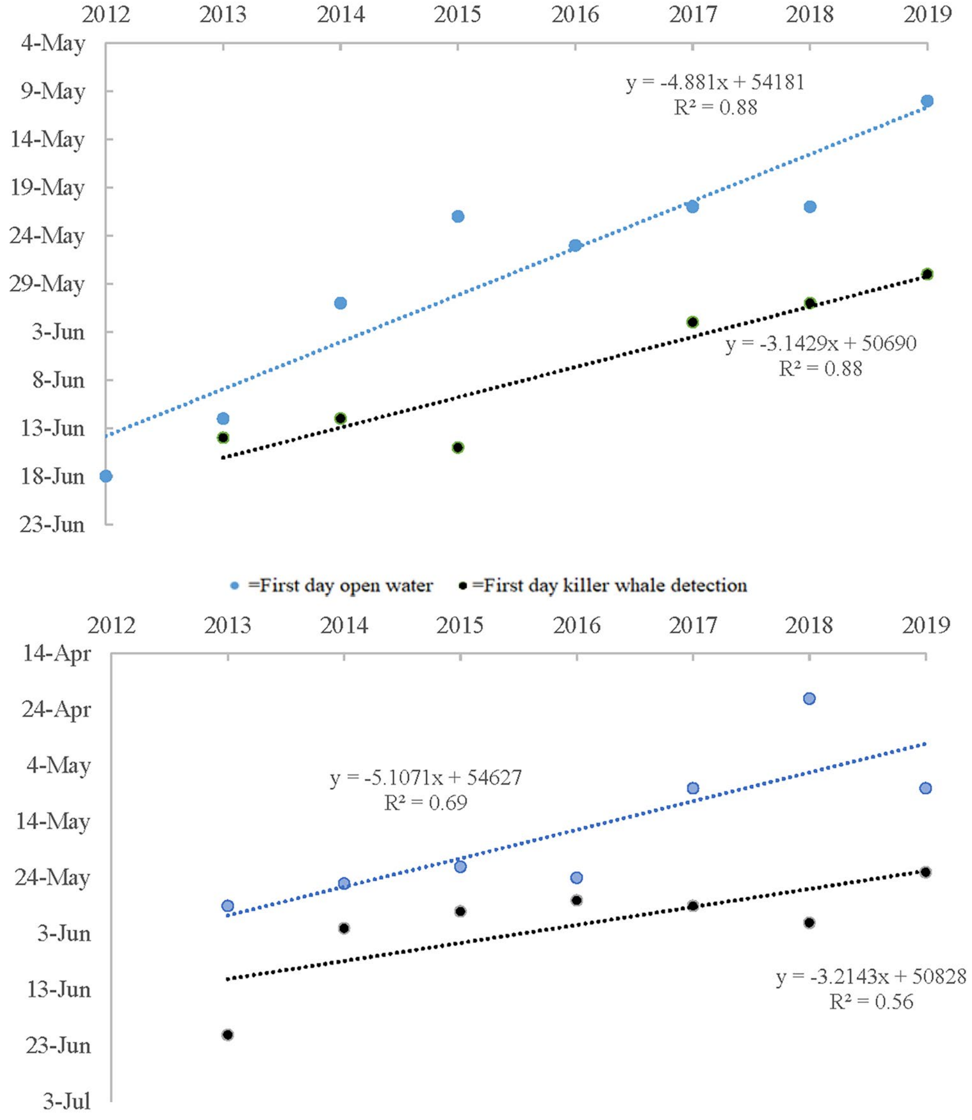


Fig. 3 Trends comparing first day of open water (blue) ($p_{PH1} < 0.01$, $t_{7PH1} = -6.52$, $p_{NM1} = 0.02$, $t_{7NM1} = -3.37$) and first day of killer whale acoustic detection (black) ($p_{PH1} < 0.01$, $t_{7PH1} = -5.64$, $p_{NM1} = 0.05$, $t_{7NM1} = -2.56$) at both Bering Strait locations (Top: PH1; bottom: NM1). Dashed-line denotes trend line calculated through linear regression

extent in 2012 was the lowest on record throughout years of the study.

Discussion

Together, findings from the two study areas—the North Slope and the Bering Strait—confirm a shift in killer whale acoustic detections from 2011 to 2019 as the Arctic Sea ice conditions changed. Near the Bering Strait, the timing of killer whale acoustic detections was positively correlated with the timing of sea ice retreat; killer whale vocalizations were heard outside of their expected late-summer/early fall distribution period, with detection at several sites beginning in mid-May. This is in contrast to Stafford (2019), whose 2009–2016 dataset recorded initial killer whale calling no earlier than June, indicating that our observation of spring occurrence is a recent development.

Over this same time period, killer whale acoustic detections occurred earlier and more often at the North Slope sites, where the increased acoustic presence was significantly correlated to minimum Arctic sea ice extent. These results support the hypothesis that sea ice in the Bering Strait is acting as a barrier, preventing killer whales from accessing the U.S. Arctic from the Bering Sea—similar to the chokepoint phenomenon observed in the Hudson Bay region by Higdon and Ferguson (2009). Earlier sea ice retreat at this Bering Strait chokepoint grants transient killer whales access to an area that they historically rarely used (George and Suydam 1998; Higdon et al. 2012; Aerts et al. 2013; Hannay et al. 2013; Kuletz et al. 2015), allowing them to arrive earlier and disperse into the Arctic. In addition, the majority of days (96%) with killer whale detections at the North Slope sites occurred when sea ice concentration was less than 80%, which agrees with the observations from Ainley et al. (2017). The remaining days with killer whale

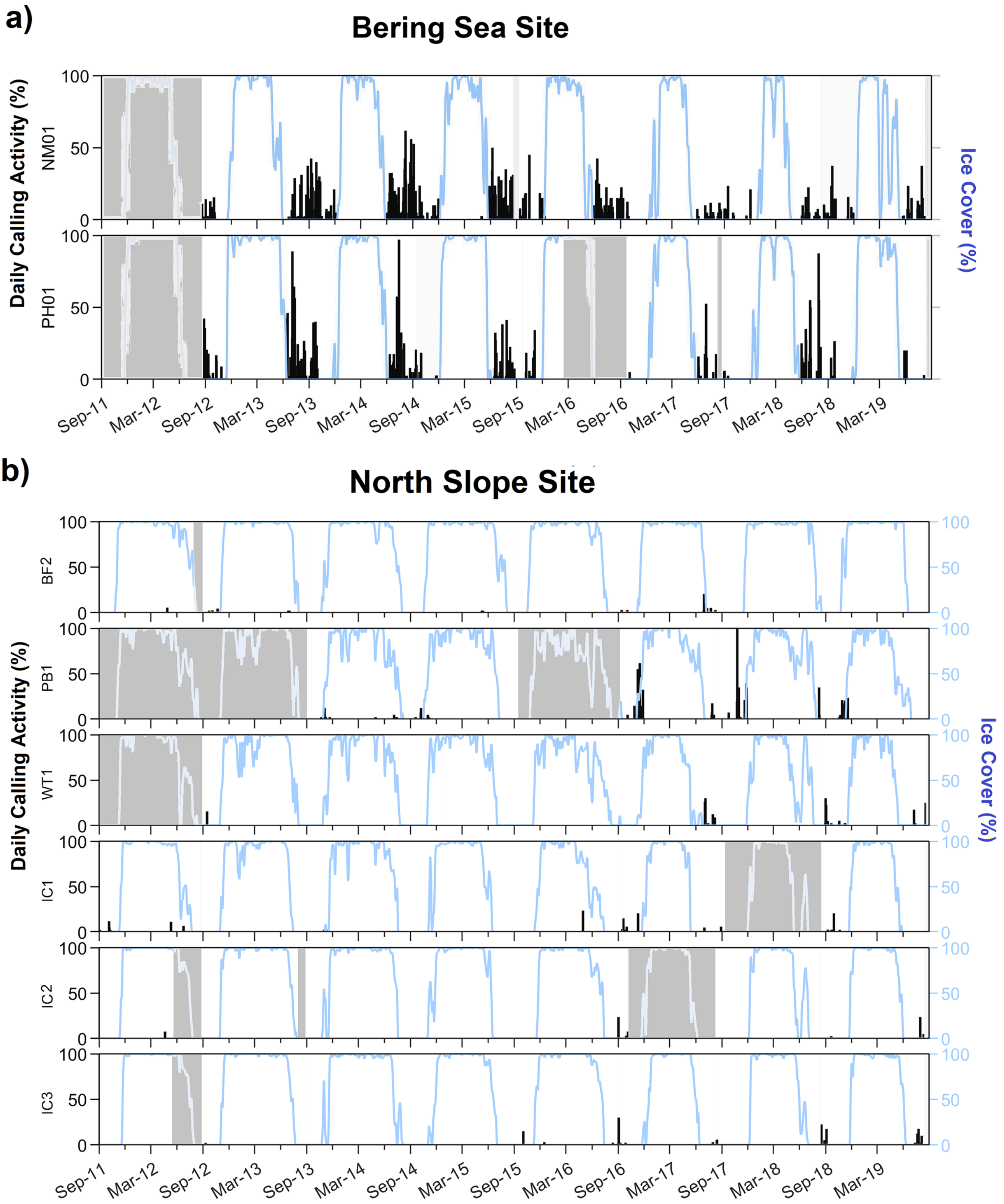


Fig. 4 Killer whale calling activity (black bars, presented as the percentage of 10-min time intervals per day with calls, adjusted for recording effort) from 2011to 2019 for each of the Bering Sea (**a**) and North Slope (**b**) site locations. Sites are arranged latitudinally from north to south for Bering Sea locations and longitudinally from east to west for North Slope locations (see Fig. 1 for map of locations of each site). Blue line (right Y-axis) indicates the percentage of ice cover (zero-phase, 3-day moving average). Gray shading indicates no acoustic data available

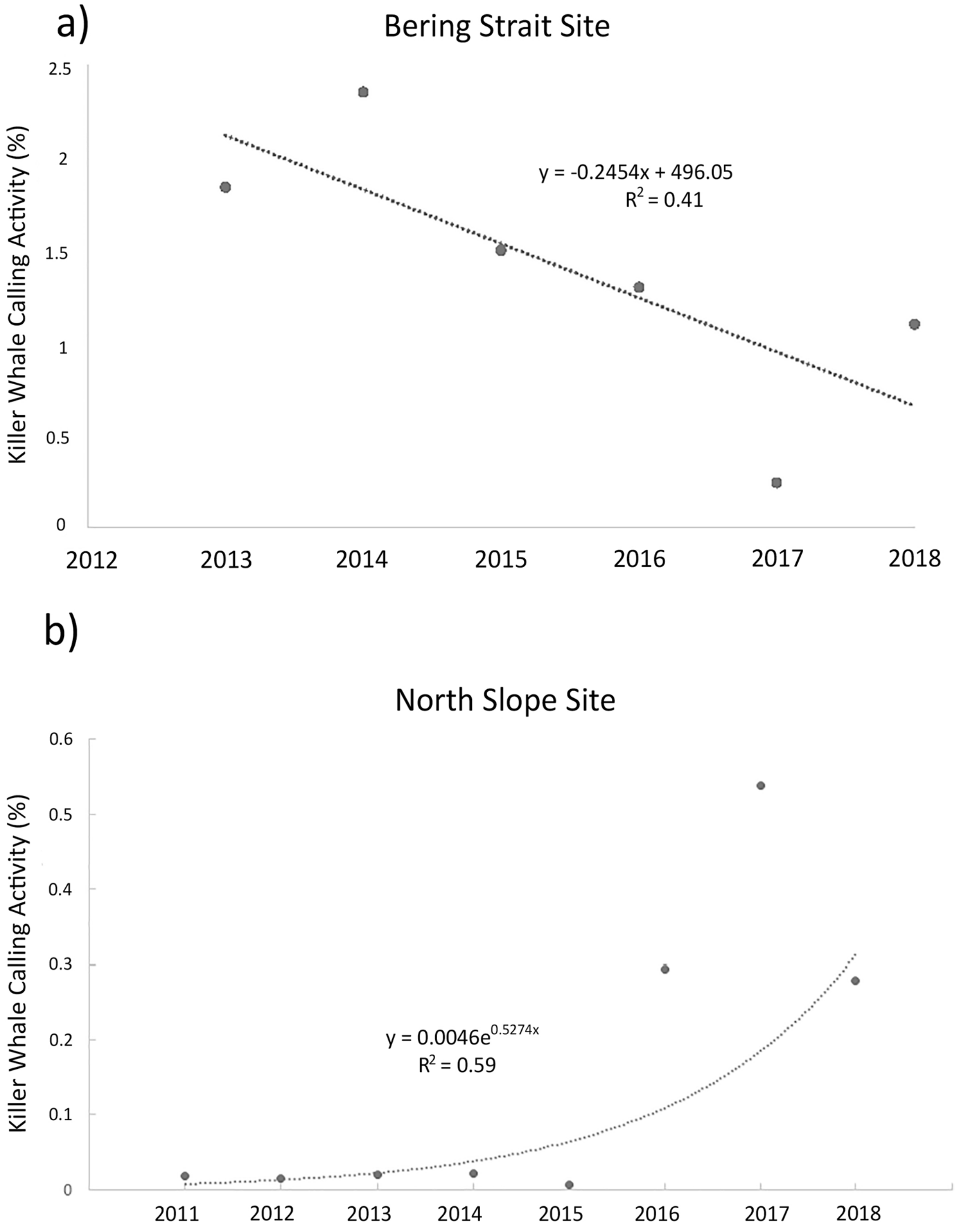


Fig. 5 Calling activity of killer whales, averaged across all sites in the Bering Strait (**a**) ($p=0.08$, $t_7=2.38$), and the North Slope area (**b**) ($p=0.03$, $t_7=-2.95$) throughout the study period. Calling activity is defined as the percentage of 10-min bins that contained a killer whale call averaged per year. The dashed gray line denotes trendlines calculated through polynomial regression. Note difference in Y-axis scale. X-axis in Fig. 5b has been scaled to "years since 2010", and reverted to corresponding year for ease of viewing. Data were analyzed only through the end of the 2018–2019 deployment (i.e., September 2019), therefore 2019 is incomplete and not included on this plot

detections occurring under higher ice concentration were likely due to the limits of the resolution of the sea ice data, which is too coarse to capture leads or other fragmentation.

The complementary trends in killer whale acoustic presence in both regions also reinforces this chokepoint hypothesis. The overall slight decrease in killer whale acoustic presence in the Bering Strait area coupled with the large increase in presence in the North Slope area suggests that the killer whales were able to traverse past the chokepoint site that previously blocked their entrance further into the Arctic during much of the year. These results agree with those of Stafford et al. (2022), who examined killer whale presence on the Chukchi plateau and found an increasing trend beginning in 2016, suggesting that increased dispersal into the Arctic is not limited to the North Slope sites. The decrease of killer whale detections in the Bering Strait area from 2012–2018 may allude to a shift of prey distribution from the Bering Strait area and into the Arctic. Gray whales, one of the primary prey species for killer whales (Rice and Wolman 1971; Ljungblad and Moore 1983), have been shown to have changing distribution through the Arctic, with decreasing presence in the Bering Strait area (Moore et al. 2022). It is possible that the motive behind some of the killer whale movement observed in this study could be to follow this important prey species. However, because transient killer whales are opportunistic predators with the tendency to shift hunting strategies based on which prey is the most efficient to

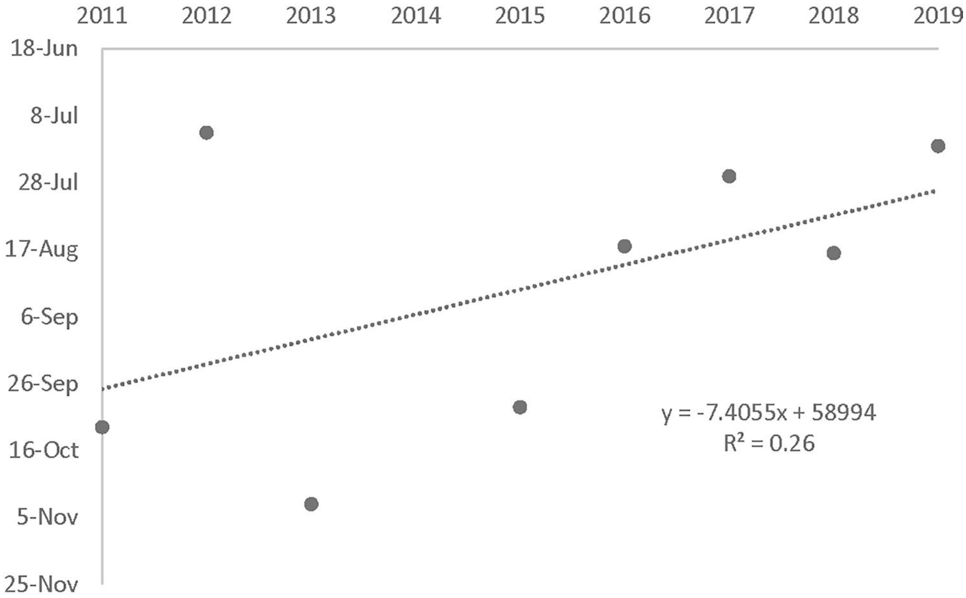


Fig. 6 Date of earliest killer whale acoustic detection each year across all sites in the North Slope area. The dotted line represents the trend line calculated through linear regression ($p < 0.01$, $t_7 = 5.72$)

hunt (Dalheim and White 2010), killer whales may also be seeking new prey sources in the Arctic outside of the species they previously have regularly hunted.

If transient killer whales are seeking new prey species in the Arctic, the increase in their presence could cause changes in trophic level dynamics in the Alaska Arctic ecosystem. Transient killer whales are efficient, prolific hunters, with the ability to dramatically affect the population numbers of their prey species. In the Canada Arctic, Ferguson et al. (2010) found that a continued increase of killer whale presence had the potential to negatively affect narwhal (*Monodon monoceros*) populations and many other Arctic prey species. In addition, transient killer whales in Washington state been observed to consume 2% of harbor seals (*Phoca vitulina*) in the area, and have been considered a means of regulating the population numbers of these seals (Shields et al. 2018). Moreover, around 20% of humpback whales (*Megaptera novaeangliae*) in east Australia waters have evidence of scarring from killer whale attacks (Naessig and Lanyon 2004), and killer whales were observed to have a minimum 40–60% success rate at killing targeted humpback whale calves (Pitman et al. 2015). The increase of killer whale presence in the Alaska Arctic could similarly have a noticeable effect on Arctic species population numbers, and there is already evidence that killer whales may be shifting prey species and increasingly targeting Arctic resident species. Between 2009 and 2018, Willoughby et al. (2020) found 18 bowhead whale carcasses that had evidence of killer whale attacks, and notably only eight of those carcasses were identified as calves, suggesting that killer whales are not limited to attacking young whales. Further research is necessary to determine what effects killer whales might have on potential prey species throughout the Arctic.

In addition to an increase in transient killer whales at our North Slope sites, we also found a shift in the temporal presence of transient killer whales in the area, with an average 50-day earlier arrival time to the area through the study period, sometimes far outside of their expected summer transitory period. An increase of temporal overlap of killer whales with key prey species in the Arctic could affect important seasonal events, such as mating and calving, as described in Matthews et al. (2020). Calving season for bowhead whales in the Alaska Arctic is documented through the months of March-August, with a notable peak in May (Nerini et al. 1984). Previously, the ice pack was such that there was little chance that killer whales would be able to access bowhead whales during the vital spring calving period. However, killer whales in our study were detected as early as mid-May at several site sites north of the Bering Strait, directly overlapping with the distribution and seasonality of bowhead whale calving. Transient killer whales are known to target cetacean calves, with a 35% success rate killing gray whale calves in areas of the Eastern Pacific (Sumich 2014), making killer whales a notable cause of natural mortality in gray whales (Rice and Wolman 1971; Ljungblad and Moore 1983). Specific temporal targeting of young prey species has been observed in British Columbia, where transient killer whales were observed to time their arrival to the area during harbor seal pupping season, and successfully capture pups (Baird and Dill 1995). Thus, it is plausible that transient killer whales in the Arctic would target prey species such as bowhead whales during their calving season. Though the BCB (Bering–Chukchi–Beaufort) bowhead whale stock is stable, bowhead whales are an important subsistence species for many Indigenous communities and face various threats such as entanglement, ship strike, and changes in behavior due to vessel noise (Young et al. 2023). An increase in predation due to killer whales could further threaten this important species, as well as other Arctic subsistence species.

In addition to direct predation effects, there are numerous indirect effects that transient killer whale presence can have on other species. The marine mammal prey species are often highly attuned to transient killer whale presence and will exhibit avoidance behavior if killer whales are detected (Jefferson et al. 1991; Curé et al. 2013, 2015; Aguilar de Soto et al. 2018; Burnham and Duffus 2019). For example, bowhead whales have long been noted by Inuit peoples to exhibit fear responses such as moving into shallow waters and hiding under ice when in proximity to killer whales (as discussed in interviews with eastern Nunavut communities in Ferguson et al. 2012). Similarly, Matthews et al. (2020) found that bowhead whales in the eastern Canadian Arctic will traverse into heavily ice-covered areas specifically when killer whales are around, despite the fact that these areas provide lower foraging success and less of their preferred food type. In addition to foraging impacts, bowhead whales could also be experiencing additional stress and missing mating opportunities or other social interactions due to the avoidance of killer whales (Matthews et al. 2020). Not only would the bowhead whales themselves be affected by these changes, the Indigenous communities who rely on bowhead whales for subsistence could also be affected by increased hunting challenges if bowhead whales are driven into areas farther from shore.

The presence of transient killer whales in the Arctic is increasing, and these prolific predators are shifting the timing of their entry into the rapidly changing Arctic ecosystem. Further research is needed to understand the full extent of the impacts of an increased killer whale presence in the Arctic. Direct predation pressure, increased calf mortality, increased stress, and decreased feeding opportunities are just some of the effects to consider. These effects give killer whales notable potential for causing impacts to the population of Arctic species, many of which are imperative for the food security of Indigenous communities. In Nunavut, Canada, interviews with Indigenous hunters have proven useful in assessing changes in killer whale abundance (Higdon et al. 2014), and similar techniques could be deployed to further understand this topic. As such we recommend further studies of killer whale spatio-temporal distribution as a part of future Arctic ecosystem management efforts, and particularly note the need of incorporating research with local Alaskan knowledge and observations in order to maintain this vital ecosystem.

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Declarations

Conflict of interests The authors declare no competing interests.

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