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RESEARCH ARTICLE

Changes in sea ice and range expansion of sperm whales in the eclipse sound region of Baffin Bay, Canada

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Abstract

Sperm whales (*Physeter macrocephalus*) are a cosmopolitan species but are only found in ice-free regions of the ocean. It is unknown how their distribution might change in regions undergoing rapid loss of sea ice and ocean warming like Baffin Bay in the eastern Canadian Arctic. In 2014 and 2018, sperm whales were sighted near Eclipse Sound, Baffin Bay: the first recorded uses of this region by sperm whales. In this study, we investigate the spatiotemporal distribution of sperm whales near Eclipse Sound using visual and acoustic data. We combine several published open-source, data sets to create a map of historical sperm whale presence in the region. We use passive acoustic data from two recording sites between 2015 and 2019 to investigate more recent presence in the region. We also analyze regional trends in sea ice concentration (SIC) dating back to 1901 and relate acoustic presence of sperm whales to the mean SIC near the recording sites. We found no records of sperm whale sightings near Eclipse Sound outside of the 2014/2018 observations. Our acoustic data told a different story, with sperm whales recorded yearly from 2015 to 2019 with presence in the late summer and fall months. Sperm whale acoustic presence increased over the 5-year study duration and was closely related to the minimum SIC each year. Sperm whales, like other cetaceans, are ecosystem sentinels, or indicators of ecosystem change. Increasing number of days with sperm whale presence in the Eclipse Sound region could indicate range expansion of sperm whales as a result of changes in sea ice. Monitoring climate change-induced range expansion in this region is important to understand how increasing presence of a top-predator might impact the Arctic food web.

KEYWORDS
bioacoustics, Canadian Arctic, climate change, marine mammals, sea ice, sperm whales

1 | INTRODUCTION

Climate change is undoubtedly impacting Arctic marine environments (Ford et al., 2006; Hassol, 2004; Kattsov et al., 2005). This region is undergoing loss of sea ice, ocean warming, changes in stratification from the introduction of freshwater, and ocean acidification (Carmack & McLaughlin, 2011; Comiso et al., 2008; Jackson et al., 2010). Warming ocean temperatures and melting sea ice is leading to seasonal shifts of habitat use with some marine mammals showing increased presence and prolonged stays in areas that were historically covered in pack ice but are now open (Higdon & Ferguson, 2011; Insley et al., 2021; Laidre et al., 2015). Rapid changes in sea ice could benefit marine mammals that are normally restricted to ice-free regions by exposing new habitats.

Sperm whales (*Physeter macrocephalus*) are a cosmopolitan toothed-whale species found in all of the world's oceans. Although sperm whales are ice avoiding, they have been documented in high latitude regions like the Davis Strait, Bering Sea, Norwegian Sea, and British Isles at the northernmost extend of their distribution (Berzin, 1972; Christensen et al., 1992; Davidson, 2016; Evans, 1997; Madsen et al., 2002; Weir et al., 2001). More recently, they have been recorded and observed within the Arctic Circle at approximately 75° N in eastern Baffin Bay, off northwest Greenland, extending their known range significantly north of previous reports (Frouin-Mouy et al., 2017). And although there have been no formal surveys to monitor sperm whale populations in western Baffin Bay (Cucknell et al., 2015; Davidson, 2016), in 2014 the first sighting of a sperm whale was recorded by Inuit hunters in the Pond Inlet (PI) region (Cecco, 2018), followed by a second rare sighting by scientists in 2018 (Lefort et al., 2022). Traditional ecological knowledge about marine mammals in the Canadian Arctic is extensive (Ford et al., 2006; Stevenson, 1996; Worden et al., 2020), although little is known about sperm whales, even by experienced hunters in PI (Cecco, 2018), most likely due to their infrequent presence in the region.

Baffin Bay has seen longer ice-free periods with sea ice retreating 7 days earlier and sea ice advancing 5 days later per decade (Laidre et al., 2015). Walsh et al. (2017) reconstructed Arctic sea ice extent, including Baffin Bay, going back to 1850 and found no historical precedent for the minimum ice extent seen in the 21st century. Although patterns of sea ice loss differ between regions of the Arctic, the overall trend since 1990 shows a retreat of seasonal sea ice, with an acceleration during the last decades (Polyak et al., 2010). Loss of sea ice is so severe that climate simulations are predicting a seasonally ice-free Arctic Ocean as early as mid-century (Holland et al., 2006; Masson-Delmotte et al., 2020; Wang & Overland, 2009).

Rapid changes to the region as a result of climate change coupled with newly documented sightings of sperm whales in the basin highlight the importance of closely studying their high latitude habitat use. Since sperm whales were heavily whaled beginning in the 1700s (Evans, 1997), historical whaling records can also provide baseline information of whale distribution and presence. However, no records exist of sperm whales being caught in the Baffin Bay whaling grounds (Smith, 2021). More recent studies of sperm whales using traditional visual surveys and satellite-tags in the western Baffin Bay and Davis Strait region have sightings between 63° N and 70° N, usually associated with the continental shelf and slope (Davidson, 2016; Lefort et al., 2022), with no records as high north as the PI (72.7° N) outside of the 2014/2018 observations (Cecco, 2018; Lefort et al., 2022).

In this study, we use historical sighting and acoustic data to explore sperm whale presence in Baffin Bay. Published open-source data sets were synthesized to investigate the historical distribution of sperm whales in the region. Passive acoustic recordings from 2015 to 2019 in the Eclipse Sound were used to create a timeseries of recent animal presence in the region. Decadal scale changes in sea ice concentration dating back to 1901 were analyzed using a linear model, and the acoustic data were related to mean SIC near the recording sites to understand why the animals are expanding their northernmost boundaries. Results from this study confirm and provide more detail on the increasing presence of sperm whales in the Eclipse Sound, a historically rare habitat for these animals to exploit that may be linked to climate change.

2 | METHODS

2.1 | Historical sperm whale distribution in Baffin Bay

Sighting data were compiled from eight published data sets and studies to gain a better understanding of the historical distribution of sperm whales in Baffin Bay. Sampling effort for the sighting data was only available for two of the eight data sets. First, for the Programme Intégré de recherches sur les oiseaux pélagiques (PIROP) data set (CWS, 2021), effort was calculated by plotting the boundaries of where sperm whales were not sighted during their surveys between 1970 and 2000 (Gjerdrum et al., 2012). Second, data points for sperm whale sightings and survey effort area from Shell's marine mammal visual monitoring and mitigation program from 2012 to 2014 were extracted and replicated from Frouin-Mouy et al. (2017) using WebPlotDigitizer (Rohatgi, 2017).

Although there was no sampling effort available for the remaining six data sets they were included in the analysis as opportunistic sightings. Commercial whaling records for sperm whales were accessed on the Ocean Biodiversity Information System (OBIS) from the History of Marine Animal Populations (HMAP) Data Set 04: World Whaling (Smith, 2021). Opportunistic and incidental sightings of sperm whales were also retrieved from the Maritimes Region Whale Sightings Database (WSDB) from Fisheries and Oceans Canada (Whalesightings Database, 2021), the Incidental Sightings of Marine Mammals data set from the Institute of Marine Research (IMR) (Hartvedt, 2020), and from environmental surveys done by the Northwest Atlantic Fisheries Organization (NAFO, 2014). Opportunistic sightings from citizen scientists were included from the Happywhale database (Happywhale, 2021). One additional opportunistic sighting of a sperm whale in Eclipse Sound and tag data from sperm whales in Baffin Bay reported in Lefort et al. (2022) were also used. The synthesized data are given in an associated data publication in Dryad Digital Repository (https://doi.org/10.5061/dryad.c2fqz619z; Posdaljian et al., 2022).

2.2 | Acoustic data collection

We used passive acoustic recordings from two sites in the eastern Canadian Arctic near Eclipse Sound between July 2015 and September 2019 over the span of five deployments (Figure 1; Table 1). The temporal coverage among sites and between deployments varied as a result of field work timing to retrieve/deploy the instruments, the battery life and storage space of the instruments, and different duty cycle regimes discussed in further detail in the last Methods subsection. The two sites were approximately 23 km apart and have an approximate maximum detection range of 20 km for sperm whales based on previous studies (Tran et al., 2014). The Guys Bight (GB) instrument had one deployment at a depth of ~100 m in 2015. The depth of the instrument is not ideal for recording a deep-diving animal such as the sperm whale, but the recordings from 2015 were still included in the analysis as an opportunistic data set, in the sense that it was not necessarily acquired for this specific study. The instrument at PI was at depths between 670 and 800 m over four deployment periods from 2016 to 2019 (Table 1). We used data from two types of autonomous, bottom-mounted recording devices to collect passive acoustic recordings: Song Meter SM2M (SM2M; Wildlife Acoustics, Inc.) and High-frequency Acoustic Recording Package (HARP; Wiggins & Hildebrand, 2007). The SM2M was deployed at the GB site and recorded at a sampling rate of 192 kHz. The HARPs were deployed at the PI site and collected recordings at a sampling rate of 200 kHz. These two sampling rates were chosen to detect the high-frequency echolocation clicks of marine mammals, including but not limited to, sperm whales.

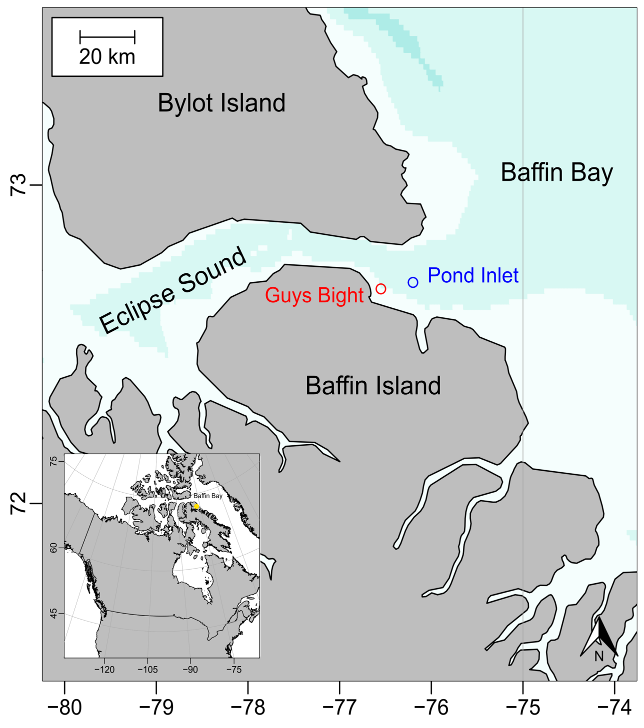

FIGURE 1 The Eclipse Sound region of Baffin Bay in the eastern Canadian Arctic with the Guys Bight recording site (red) and the Pond Inlet recording site (blue)

2.3 | Acoustic data analysis at the GB recording site

Sperm whales regularly produce high-frequency echolocation clicks (2–32 kHz) with a duration of 100 μs and are distinguishable from other high-frequency odontocetes (Goold & Jones, 1995; Møhl et al., 2000, 2003; Weilgart & Whitehead, 1988) (Figure 2). Trained analysts (N.P. and C.S.) manually screened the acoustic recordings from the GB site for sperm whale echolocation clicks using long-term spectral averages (LTSAs; averaged over 5 s and 100 Hz bins), which provide a compressed spectrogram view allowing large time series data sets to be analyzed (Wiggins & Hildebrand, 2007) (Figure 2a). Data were manually scanned in the custom software program *Triton* (Wiggins & Hildebrand, 2007) developed in *MATLAB* (MathWorks). Analysts viewed 1-h LTSA segments across a frequency range of 0–40 kHz to identify potential sperm whale encounters. Spectrograms of 10 s in length were used to confirm species identification (Fast Fourier transform length 2000 points, 75% overlap, bandwidth 40 kHz). A

TABLE 1 Summary of passive acoustic monitoring effort in the eastern Canadian Arctic between 2015 and 2019

Site	Location	Depth (m)	Recording dates	No. of recording days	Instrument type	Duty cycle	Sampling rate (kHz)	Data Owner
Guys Bight (GB)	72.65N, −75.56W	100	07/01/15–9/29/15	91	SM2M	5/60	192	ON
Pond Inlet (PI)	72.72N, −76.23W	800	5/28/16–10/05/16	130	HARP	–	200	SIO
		670	10/05/16–08/04/17	302		–		
		670	08/15/17–01/30/18	168		15/20		
		670	09/27/18–09/21/19	359		–		

Note: Dates are given as MM/DD/YYYY. Instrument type specifies either a Song Meter SM2M (SM2M) or a High-Frequency Acoustic Recording Package (HARP). If applicable, duty cycles are defined as the duration of the recording period (minutes on)/cycle period (minutes off). Data were collected by Oceans North (ON) and Scripps Institution of Oceanography (SIO).

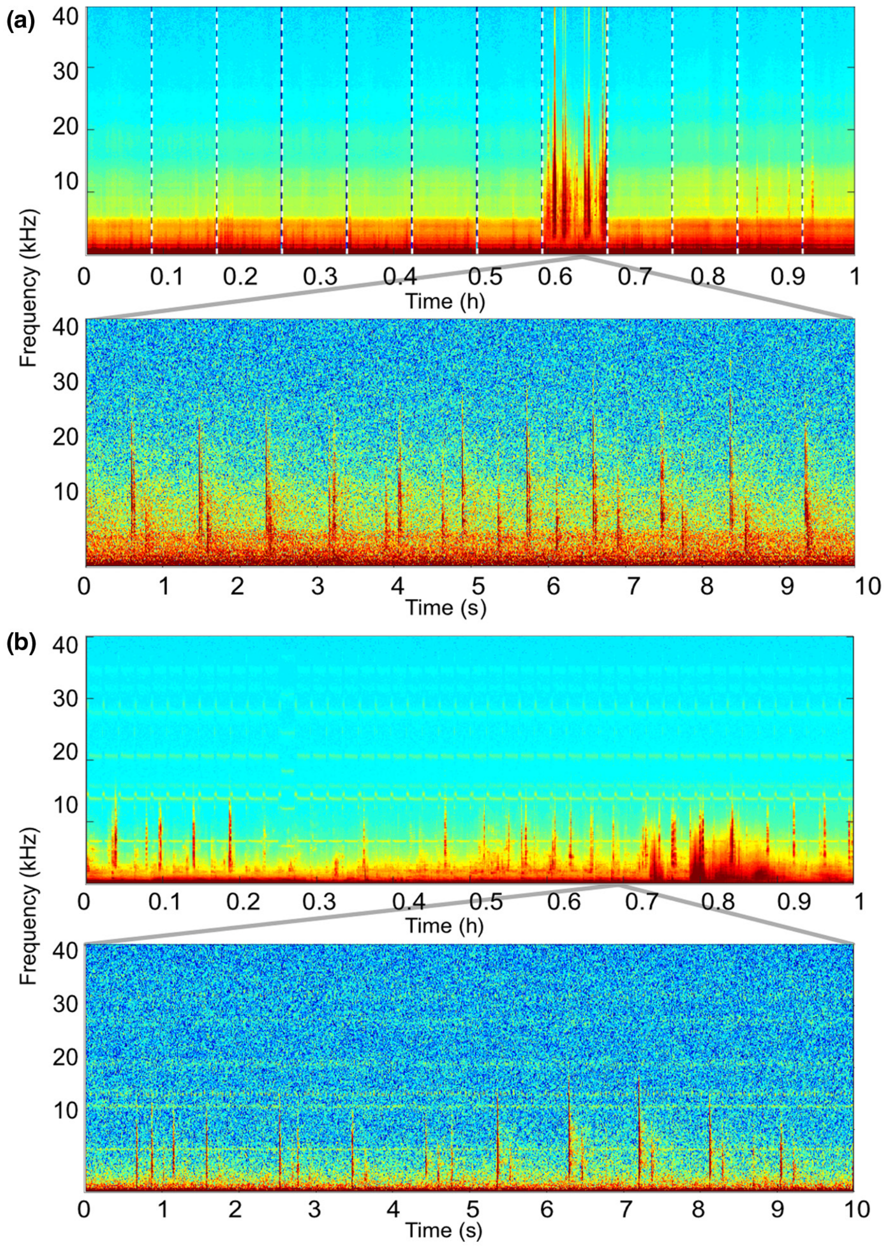

FIGURE 2 Sperm whale clicks from Guys Bight (a) recorded on September 23, 2015 and from Pond Inlet (b) recorded on August 8, 2019. The top panel from each site displays a long-term spectral average (LTSA) and the bottom panel displays the spectrogram. The Guys Bight LTSA (a) has vertical lines delineating gaps in the data as a result of the duty cycle. So although the LTSA displays 1 h of acoustic data, the overall length of the data shown encompasses 12 h

sperm whale encounter was defined as a series of clicks within a recording period of 5 min. The start and end times of these encounters were logged in *Triton* (Wiggins & Hildebrand, 2007) and used for further analysis.

Because all LTSA detections were visually verified by trained analysts, we assumed there were no false positives. And given the distinguishable echolocation clicks of sperm whales and the short duration of the data, we assumed negligible missed detections because of the feasibility of listening to and viewing all spectrograms of interest.

2.4 | Acoustic data analysis at the PI recording site

Clicks at the PI site were automatically detected using a multistep approach (Roch et al., 2011; Soldevilla et al., 2011; Solsona-Berga et al., 2020). This approach was developed for acoustic data that were sampled at 200 kHz (PI recording site), which is why manual analysis was conducted for the GB site that was sampled at 196 kHz (Table 1).

Because sperm whale clicks are characterized by multiple pulses approximately 5 ms apart (Møhl et al., 2000), clicks closer than 30 ms apart were merged. Band passing all acoustic data (5–95 kHz) minimized the effects of low-frequency noise from vessels or weather. Calculating the spectra of detected signals required 4 ms of data and a 512-point Hann window centered on the click with 50% overlap. To account for the frequency dependent instrument response of each deployment, spectra were corrected for the hydrophone transfer function.

Sperm whale echolocation clicks are similar to the impulsive signals from ship propeller cavitation, so an automated detector was used to exclude periods of ship passages in the PI data to reduce the number of false positive detections. The detector, developed by Solsona-Berga et al. (2020) identified potential ship passages from LTSAs. Average power spectral densities were computed in 2-h data blocks over low (1–5 kHz), medium (5–10 kHz), and high (10–50 kHz) frequency bands. Using received sound levels, transient signals such as odontocetes, ship passages, and weather, were compared in the three frequency bands. Trained acousticians (N.P. and C.S.) manually verified identified ship passages in *Triton* (Solsona-Berga et al., 2020; Wiggins & Hildebrand, 2007). Ship passage times were removed from further analysis and considered time periods with no recording effort.

Noise produced by the instruments and clicks produced by non-sperm whale odontocetes were also removed in the PI data to reduce the number of false positive detections. A basic classifier using spectral click shape and peak frequency was implemented, taking advantage of a sperm whale click's distinctive lower frequency spectral shape to remove clicks by delphinids and beaked whales, which occur at higher frequencies (Solsona-Berga et al., 2020). The remaining acoustic encounters at site PI, containing presumed sperm whale echolocation clicks, were manually reviewed with *DetEdit* (Solsona-Berga et al., 2020). *DetEdit* provides users with interactive data visualizations that aid in efficiently annotating data, allowing deletion of false detections. Sperm whale clicks were binned into 5-min intervals, and the number of 5-min bins with sperm whale detections per day was considered for further analysis. Daily averages of 5-min bins were calculated only for days with sperm whale presence since the time series was zero-inflated.

Only clicks exceeding a peak-to-peak received level (RL) of 125 dBpp re 1 μPa were included to provide a consistent detection threshold. This step of the detection process excluded clicks with low RLs. However, by binning clicks into 5-min intervals, the chances of missing presence within a bin was low for sperm whales who click regularly. The acoustic metadata are given in an associated data publication in Dryad Digital Repository (https://doi.org/10.5061/dryad.c2fqz619z; Posdaljian et al., 2022).

2.5 | Accounting for the duty cycle

Duty cycle regimes, or the process of turning an acoustic recorder on at specified intervals, are implemented to maximize the deployment duration by conserving battery power and storage space of the instrument (Au et al., 2013; Wiggins & Hildebrand, 2007). Duty cycle regimes can widely vary based on the desired deployment duration, the sampling rate, and the recording instrument. Two of the five deployments in this study had a duty cycle that was adjusted for.

The GB deployment had a duty cycle with a 5-min recording duration in a 60 min cycle (Table 1). Because there was only one deployment at this site, we had no continuous data to quantify the impact of the duty cycle. Instead, the number of 5-min bins with sperm whale detections per day was linearly adjusted based on the recording effort in the duty cycle.

The third deployment at the PI site also had a duty cycle with a 15-min recording duration in a 20 min cycle (Table 1). Because there was continuous data from three other deployments at this site, the duty cycle was evaluated on continuously sampled data from the first deployment (less presence of sperm whales) and the fourth deployment (more presence of sperm whales). Random samples of the 15/20 duty cycle were taken from the deployments, shifting the listening period by 1 min to find the proportion of overall recording effort. Sperm whale clicks in the 2017 PI deployment were linearly adjusted by 0.0839, resulting from the mean of forced duty cycles on the 2016 and 2019 deployments (0.0939 and 0.0738, respectively).

2.6 | Changes in sea ice concentration

A monthly gridded SIC product ranging from 1850 to 2017 was used to evaluate historical changes of sea ice within a 20 km radius around the PI recording site (Walsh et al., 2019). Only data from 1901 and beyond were included to avoid data sets that had non-observed data, which were supplemented with estimates. The 20 km radius was selected as a maximum detection range for sperm whales clicks based on a previous study (Tran et al., 2014) and distance within which most interactions with the surface would likely occur. Six ¼ degree latitude by ¼ degree longitude grid cells were within 20 km of the recording site and included in the analysis. This sea ice product merges 18 different data sources and provides a single mid-month day (MMD) average from each available source. The MMD average for the six grid cells near the recording site were averaged across the multiple sources (when available) to produce a single MMD average for the 20 km radius around the site. A linear regression was used to model the relationship between year and the median MMD SIC average by fitting a linear equation to the observed data in R Statistical Software (R Core Team, 2013).

A finer resolution of mean daily SIC was used to compare with daily presence of sperm whales during our recording period from 2015 to 2019. Daily Advanced Microwave Scanning Radiometer 2 (AMSR2) sea ice maps were obtained from the University of Bremen (Spreen et al., 2008) and processed using Windows Image Manager (WIM) and Windows Automation Module (WAM) software (Kahru, 2001) to produce an annual time series of mean daily SIC within a 20 km radius mask around the recording site. WAM software was used to compute the daily arithmetic mean, variance, and median of the SIC as a percent of the total mask area. The data excluded locations within 1 km from land to reduce edge effects and influence of snow on land.

3 | RESULTS

3.1 | Historical sperm whale distribution in Baffin Bay

Sperm whales have been historically observed throughout Baffin Bay. The highest concentration of sperm whales was seen in eastern Baffin Bay below 70°N, although they have been documented in eastern Baffin Bay as far north as 75°N (Figure 3). In northwestern Baffin Bay, a sperm whale was observed in September of 2018 in Eclipse Sound, 48 km west of the PI recording location (Lefort et al., 2022). All the northernmost sightings of sperm whales were documented within the last decade, supporting our hypothesis that sperm whale presence in Eclipse Sound is a recent phenomenon.

3.2 | Sperm whale presence

Daily sperm whale presence (total number of 5-min bins) was calculated from the GB site in 2015 and from the PI site during 2016–2019. Sperm whales were acoustically detected during late summer and early fall months. At site GB, whales were present for 4 days in September, with a median of nine 5-min bins per day (interquartile range [IQR] = 6). At site PI in 2016, sperm whales were present for 3 days in September, with a median of 24 five-minutes bins per day (IQR = 18). At site PI in 2017 and 2018 animals were present for 12 days in September and 6 days in October, respectively, with a median of nine 5-min bins per day (IQR = 17) in 2017 and 24 bins per day (IQR = 21) in 2018. At site PI in 2019, sperm whales were present for 17 days in July and August, with a median of 47 bins per day (IQR = 64) (Table S1; Figure 4).

3.3 | Changes in sea ice concentration

The yearly median MMD of SIC had a linear relationship with year with a negative slope and an equation of $y = 170 - 0.039x$. The variable year was significant and had a p-value of 1.41e-0.6 and an R^2 0.18 (Figure 5a). The number of months with an MMD average SIC of zero appears to increase over the decades. The 1910s and 1920s were the decades with the least number of months with a MMD average SIC of zero ($n = 3$–4) and the 2000s had the most number of months with an MMD average SIC of zero ($n = 24$) from decades with a complete data set (Figure 5b).

Mean daily SIC within a 20 km radius of the PI recording site ranged from nearly 0% to 100% mean daily SIC from 2015 to 2019. When sperm whales were present, the mean daily SIC was 2.1% (SD = 2.4), with the lowest mean daily SIC in 2016 (mean = 0.4%, SD = 0.1) and 2019 (mean = 0.8%, SD = 0.7 respectively) (Figure 4).

4 | DISCUSSION

Based on our acoustic data, there is clear evidence that sperm whales are frequenting the Eclipse Sound region of Baffin Bay in the late summer and fall months when SIC is at its lowest. Our findings are similar to Frouin-Mouy et al. (2017) who observed

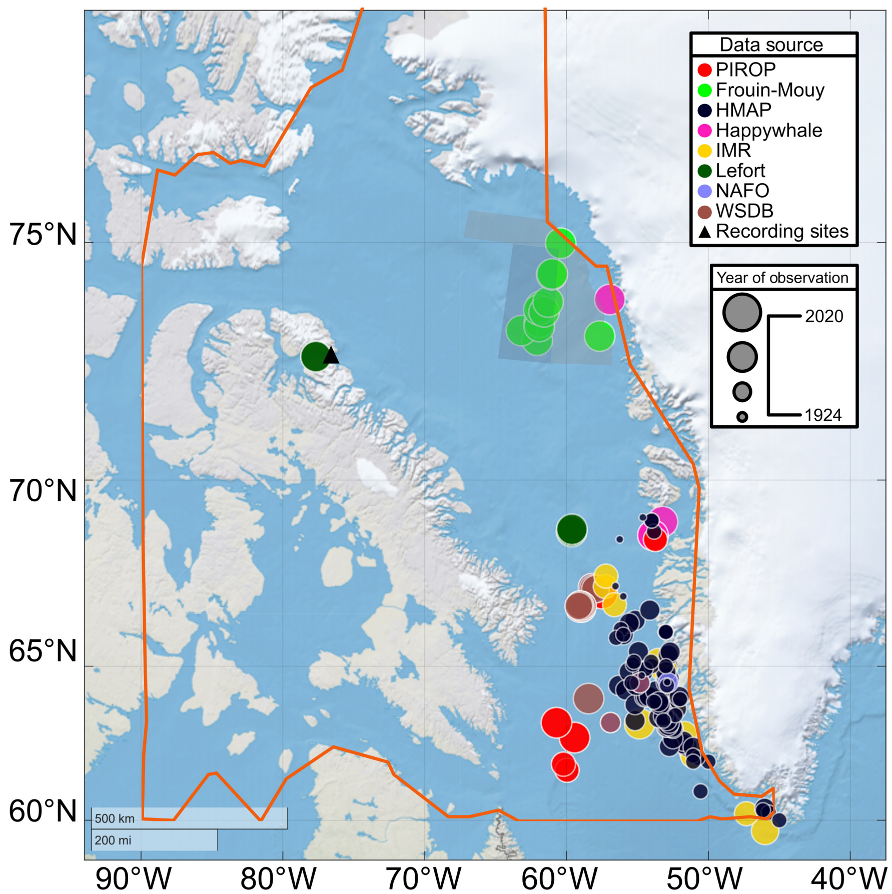

FIGURE 3 Sperm whale sightings in Baffin Bay from opportunistic survey sightings, historical whaling data, citizen science, and visual monitoring programs represented in different colors based on the source of the data. The orange boundary represents the spatial sampling effort for the PIROP surveys (Gjerdrum et al., 2012). The gray sampling area represents the boundaries of the visual monitoring program for Shell and other exploration licenses (Frouin-Mouy et al., 2017). The size of the bubbles represent the year the observation was made, with smaller bubbles indicating observations made earlier in time

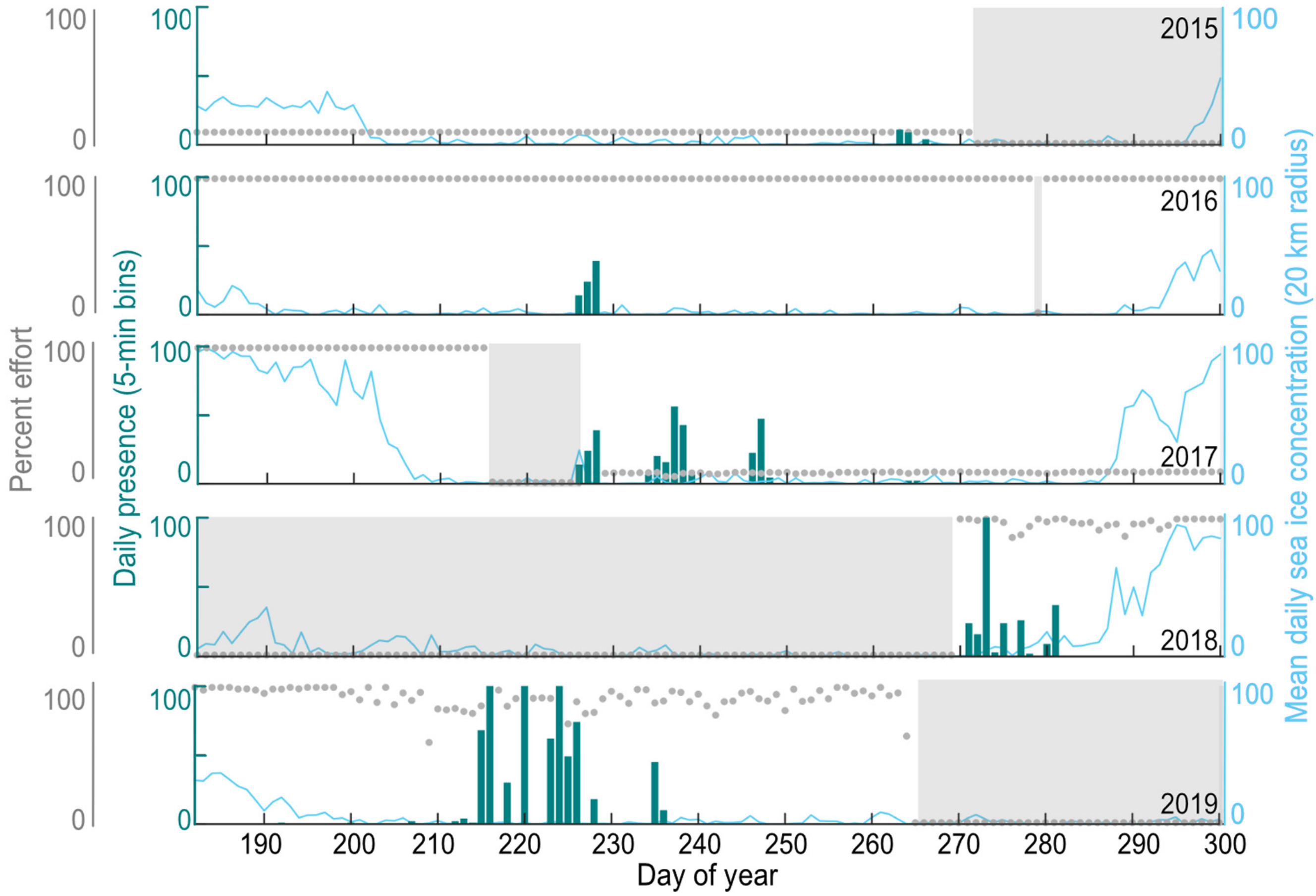

FIGURE 4 Daily presence of sperm whales (sum of 5-min bins) in teal from the Guys Bight recording site (2015) and the Pond Inlet recording site (2016–2019) between the 190th and 300th day of the year when there were sperm whale detections. Percentage of recording effort per day with gray dots. Time periods without recordings shaded gray. Mean daily sea ice concentration for a 20 km radius area centered on the Pond Inlet recording site in light blue

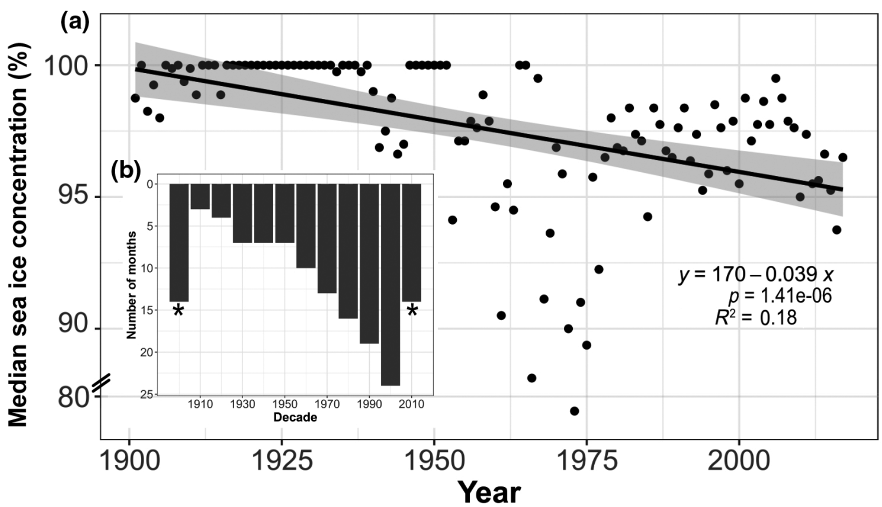

FIGURE 5 (a) The yearly median mid-month day sea ice concentration from 1901 to 2017 with a regression line (black) and the standard error of the estimate (gray shading). The equation for the linear regression, the p-value for the variable year, and the R^2 are on the right side of the plot. The hash lines on the y-axis represent an omission in median sea ice concentration values to reduce the amount of empty space in the plot. (b) The inset plot shows a histogram of the number of months with a mid-month day average sea ice concentration of zero for each decade beginning from the 1900s to the 2010s. The black asterisks denote decades that are incomplete (1900s—missing 1 year, 2010s–missing 2 years) and recorded sperm whales in northeastern Baffin Bay for the first time at a latitude of 75°N in the summer and fall months between 2012 and 2014. There were no records of sperm whales in northwestern Baffin Bay (outside of the 2018 observation) from published information or open-source data sets. One sperm whale was reportedly sighted in 2014 in Eclipse Sound by residents of the community of PI (Cecco, 2018), but documentation of this occurrence has not been published to date and, therefore, was not included in Figure 3. According to the unpublished MS thesis by Davidson (2016), sperm whales were observed as far north as 70°N in western Baffin Bay during R/V Pâmiut annual surveys from 1999 to 2014. Survey lines from the R/V Pâmiut do indicate sampling effort as far north as 75°N, including waters directly outside of the Eclipse Sound, where no observations of sperm whales were made (Davidson, 2016).

The distribution of sperm whales from the open-source data sets are biased by sampling effort. Because most of the data collection was opportunistic and ship tracklines and visual effort are not available, observations cannot be adjusted for sampling. It is likely that effort was not consistent throughout the region and was concentrated in the southern half or eastern region of Baffin Bay. However, sightings and sampling effort from the R/V Pâmiut annual surveys do provide some evidence that sperm whales were not using habitats as far northwest as Eclipse Sound before 2014 (Davidson, 2016). In addition, given that Inuit hunters, who are very familiar with this region and its marine mammals, were also surprised by the initial 2014 sighting provides further evidence that sperm whales are inhabiting new regions of Baffin Bay.

Over the span of the acoustic recording period from 2015 to 2019 the number of days with sperm whale presence appears to increase. In 2015 and 2016, they were only recorded for a few days but by 2019, sperm whales were in the area for at least 17 days. The instrument stopped recording on September 21, 2019, so it is possible that we did not capture their entire stay in the area. Although there were only 4 days with presence in 2015, we cannot quantify the difference in presence between 2015 and 2016, since differences in detectability of sperm whales between the two instruments (SM2M and HARP) and at the two sites is unknown. The shallow depth (100 m) of the opportunistic SM2M instrument at the GB site could also affect detectability of these deep diving animals. Sperm whales are more often found in deeper waters but sperm whale detections at our shallow site may be explained, at least partially, by the use of shallow habitats by male sperm whales in higher latitudes (Teloni et al., 2008).

Sperm whale presence during periods of lowest SIC, as described in this study, is similar to findings by Frouin-Mouy et al. (2017) who recorded sperm whales only before sea ice formation and after the sea ice had disappeared. The first known sightings of sperm whales in northern Baffin Bay occurred within the last decade (NE Baffin Bay—2012; NW Baffin Bay—2014). This coincides with the results of this study, which reveal a decrease in the yearly median MMD SIC in Eclipse Sound and the increase of the number of months with a MMD average SIC of zero, particularly in the last decade. On a larger scale, Arctic sea ice extent has likely decreased for every month of the year since 1979 with the most reduction (~40%) seen in September months. Several climate projections even anticipate at least one practically sea ice free September before 2050 (Masson-Delmotte et al., 2020).

Loss of sea ice and longer open water seasons will likely benefit sperm whales who appear to be expanding their range further north than previously known. Similar northern expansions have already been recorded in other marine mammals in the eastern Canadian Arctic such as killer, humpback, and minke whales (Higdon & Ferguson, 2009, 2018). There is also evidence of northerly expansion of sperm whales in the Russian Arctic significantly beyond their range end (Popov & Eichhorn, 2020) and in Svalbard waters (Storrie et al., 2018). These observations in higher latitudes may also be related to reduced ice cover, increased open water seasons, increasing ocean temperatures, and changes in their prey distributions. Like other marine mammals, sperm whale distribution is closely related to the distribution of their preferred prey of fish and cephalopods. Several species of cephalopod that sperm whales prefer, particularly the armhook squid (*Gonatus fabricci*), have already been recorded in high but patchy concentrations throughout Baffin Bay including in Eclipse Sound (Davidson, 2016; Gardiner & Dick, 2010). With lower SIC and longer open water seasons, sperm whales may be expanding their range to specific northern areas like the Eclipse Sound to take advantage of the particularly high cephalopod concentrations.

Increased presence of a top predator in the northern region could impact the Arctic food web and increase competition for other toothed whales and fisheries species who consume cephalopods. Narwhals and belugas are endemic to the Arctic region and have a cultural and socioeconomic importance for Inuit hunters (Lee & Wenzel, 2006). In Eclipse Sound during the summer when sperm whales are also present, stomach contents of narwhals and belugas reveal that they mostly consume Arctic cod, Greenland halibut, and in more recent years, Capelin (Finley & Gibb, 1982; Watt & Ferguson, 2015). Narwhals are extremely common in Eclipse Sound (Jones et al., 2022), and although 92% of narwhals had armhook squid beaks in their stomachs, they were not representative of recent intake but more likely intake earlier in the summer (Finley & Gibb, 1982). Belugas are considered rare in Eclipse Sound (Jones et al., 2022) and although they consume armhook squid among other prey items in their wintering areas, they mostly prey on Arctic Cod in the Canadian Arctic during the summer (Gardiner & Dick, 2010; Heide-Jørgensen & Teilmann, 1994). This could imply that although sperm whales, narwhals, and belugas can be found in the same region and both consume the same species of squid, their prey preference does not overlap spatially or temporally. The Greenland halibut fishery is extremely important to Baffin Bay and Davis Strait. Since both sperm whales and halibut prey on cephalopods, including armhook squid (Orr & Bowering, 1997; Dawe et al., 1998), it will be important to monitor how increasing sperm whales in the region could impact the fishery (Davidson, 2016; Gardiner & Dick, 2010).

Long-term passive acoustic monitoring from this study increased our knowledge of sperm whale presence in a remote region that is difficult to study with traditional marine mammal monitoring techniques such as visual surveys. Acoustic data from this study, as well as Frouin-Mouy et al. (2017), reveal the highest latitudinal occurrence for sperm whales in the Baffin Bay. This study also provides evidence of increasing temporal occurrence of sperm whales in Eclipse Sound, Baffin Bay in the late summer and fall months when SIC is at its lowest. Our results highlight the effectiveness of passive acoustic monitoring in remote regions and the importance of a dedicated acoustic or visual survey for sperm whales in this region to improve understanding of their ecology at their range boundary and create a baseline knowledge of their spatiotemporal distribution in a rapidly changing ecosystem.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.c2fqz619z.

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