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ARTICLE

Seasonal patterns in acoustic detections of marine mammals near Sachs Harbour, Northwest Territories[1]

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Abstract: The Arctic is changing rapidly, leading to changes in habitat availability and increased anthropogenic disturbance. Information on the distribution of animals is needed as these changes occur. We examine seasonal presence of marine mammals in the western Canadian Arctic near Sachs Harbour, Northwest Territories, using passive acoustic monitoring between 2015 and 2016. We also examined the influence of environmental variables (ice concentration and distance, wind speed) on the presence of these species. Both bowhead whales (*Balaena mysticetus*) and beluga whales (*Delphinapterus leucas*) arrived in late April, and belugas departed in mid-August, while bowheads departed in late October. Bearded seal (*Erignathus barbatus*) vocalizations began in October, peaked from April through June, and stopped in early July. Ringed seals (*Pusa hispida*) vocalized occasionally in all months, but were generally quiet. Whales migrated in as the ice broke up and migrated out before ice formed in the autumn. Bearded seals started vocalizing as ice formed and stopped once ice was almost gone. Given the importance of sea ice to the timing of migration of whales and vocalization by bearded seals, the trends that we present here may change in the future due to the increasing ice-free season caused by climate change. Our study therefore serves as a baseline with which to monitor future change.

Key words: climate change, conservation, passive acoustic monitoring, sea ice.

Résumé : L'Arctique change rapidement, menant à des changements dans la disponibilité des habitats et l'augmentation des perturbations anthropiques. Les informations sur la répartition des animaux sont nécessaires à mesure que ces changements surviennent. Nous examinons la présence saisonnière de mammifères marins dans l'ouest de l'Arctique canadien près du havre Sachs, dans les Territoires du Nord-Ouest, en faisant de la surveillance acoustique passive entre 2015 et 2016. Nous avons aussi examiné les effets des variables environnementales (la concentration et la distance de la glace, la vitesse des vents) sur la présence de ces espèces. Tant les baleines boréales (*Balaena mysticetus*) que les bélugas (*Delphinapterus leucas*) sont arrivés à la fin avril et les bélugas sont repartis à la mi-août, tandis que les baleines boréales sont reparties à la fin octobre. Les vocalisations de phoques barbus (*Erignathus barbatus*) ont commencé en octobre, ont atteint un niveau maximal d'avril à juin et se sont arrêtées début juillet. Bien qu'ils aient été généralement silencieux, les phoques annelés (*Pusa hispida*) ont vocalisé de temps à autre au cours de tous les mois. Les baleines ont migré dans la région lorsque la glace s'est dispersée et ont migré hors

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de la région avant la formation de la glace d'automne. Les phoques barbus ont commencé leurs vocalisations au moment ou la glace se formait et se sont arrêtés une fois que la glace était presque partie. Étant donné l'importance de la concordance de la glace de mer avec le moment de la migration des baleines et de la vocalisation par les phoques barbus, les tendances que nous relevons et présentons ici pourront à l'avenir changer en raison du changement climatique qui cause une augmentation de la durée de la saison d'absence de glace. Notre étude sert donc de conditions de base avec laquelle nous pourrons surveiller le changement futur. [Traduit par la Rédaction]

Mots-clés : changement climatique, conservation, surveillance acoustique passive, glace de mer.

Introduction

The Arctic is changing rapidly, leading to an important loss of sea ice (Stroeve et al. 2007); the Arctic might even be entirely ice-free during the summer by 2040 (Wang and Overland 2009). Sea ice is an important habitat feature for many Arctic marine animals: reproduction in Arctic zooplankton is linked to blooms in sea ice algae (Leu et al. 2011), Arctic cod (*Boreogadus saida* (Lepechin, 1774)), considered a keystone species in the Arctic food web (Bradstreet et al. 1986; Majewski et al. 2016), are often associated with sea ice (Gradinger and Bluhm 2004), ringed seal (*Pusa hispida* (Schreber, 1775)) movement behaviour is highly altered by the distribution of sea ice (Hamilton et al. 2015), and beluga whales (*Delphinapterus leucas (*Pallas, 1776)) modify migration timing and other behaviour in response to sea ice (O'Corry-Crowe et al. 2016; Hauser et al. 2017*a*). This loss of sea ice is also making the Arctic more accessible, making it prone to increased anthropogenic disturbance. Ship traffic has been increasing in the Arctic (Pizzolato et al. 2016), and many shipping routes through the Arctic that are not currently viable could be viable by 2050 if the current trend in sea-ice loss continues (Stephenson et al. 2011). Increased ship traffic not only represents a direct threat to marine mammals via ship strikes but also a threat from increased noise pollution and increased risk of other types of pollution such as oil spills (Huntington et al. 2015). Understanding the distribution of marine mammals (and other animals) in the Arctic before drastic changes in shipping traffic occur and as ice conditions continue to change should be a priority for wildlife managers.

The western Canadian Arctic (eastern Beaufort Sea and Amundsen Gulf) is home to four main species of marine mammals: two seasonally present cetacean species (bowhead whales (*Balaena mysticetus* Linnaeus, 1758) and beluga whales) and two year-round resident seal species (bearded seals (*Erignathus barbatus* (Erxleben, 1777)) and ringed seals). These bowhead whales are part of the Bering–Chukchi–Beaufort stock (Rugh et al. 2002) (also known as the western Arctic stock) and spend their winters in the Bering Sea and summers spanning from the Chukchi Sea to the eastern Beaufort Sea. Beluga whales are part of the eastern Beaufort Sea stock and spend their winters in the Bering Sea and their summers throughout the eastern Beaufort Sea (Richard et al. 2001; Citta et al. 2016). Both bowhead and beluga whales time their migration into the Beaufort Sea based on ice breakup (Clark et al. 2015; Hornby et al. 2016), typically migrating into the region in early spring. The western Canadian Arctic is an understudied area in the range of all four marine mammal species, particularly for studies documenting distribution and seasonal patterns, with a few sporadic studies using aerial surveys for bowhead (e.g., Harwood et al. 2010) and beluga whales (e.g., Harwood et al. 1996) and satellite telemetry studies for bowhead (e.g., Citta et al. 2015; Harwood et al. 2017) and beluga whales (e.g., Richard et al. 2001; Hauser et al. 2014). The distribution of both seal species has been studied periodically for the last 40 years (e.g., Stirling et al. 1977), although more effort has focused on ringed seals (e.g., Harwood and Stirling 1992). Bowhead whales are the only one of these species listed under

Canada's Species At Risk Act and are considered Special Concern (COSEWIC 2009). Under the management plan for bowhead whales (COSEWIC 2009), acoustic disturbance is listed as the top threat to the stock followed by ship strikes. For this reason, it is crucial to have an understanding of both their spatial distribution and their migration phenology so that risks from anthropogenic activities, particularly shipping, can be managed.

In this study, we use passive acoustic monitoring (PAM) near Sachs Harbour, Northwest Territories, to examine seasonal trends in marine mammal vocalizations. PAM is an effective tool for studying seasonal patterns in marine mammal distribution and vocal behaviour, especially in remote areas like the Arctic (Moore et al. 2006). Fully autonomous acoustic recorders can be effectively used to determine the presence of species that are soniferous (such as marine mammals) over a long, continuous period (i.e., 1 year). Continuous data on species presence are not possible for other survey methods, such as visual surveys, in the Arctic due to sea ice. Indeed, PAM has been used throughout other areas of Arctic North America for monitoring marine mammals, including the Bering Sea (Moore et al. 2006; Munger et al. 2008; Stafford et al. 2010), western Beaufort Sea (Moore et al. 2006; Hauser et al. 2017*a*), Chukchi Sea (Delarue et al. 2009; Blackwell et al. 2012; Hannay et al. 2013; Jones et al. 2014; Clark et al. 2015; Frouin-Mouy et al. 2016), and Baffin Bay (Frouin-Mouy et al. 2017; Marcoux et al. 2017), and acoustic monitoring has even been used successfully as a tool for studying the distribution of seals under the ice in the winter (Calvert and Stirling 1985; Cleator and Stirling 1990; MacIntyre et al. 2013; Jones et al. 2014; Frouin-Mouy et al. 2016).

Methods

Hydrophone deployments

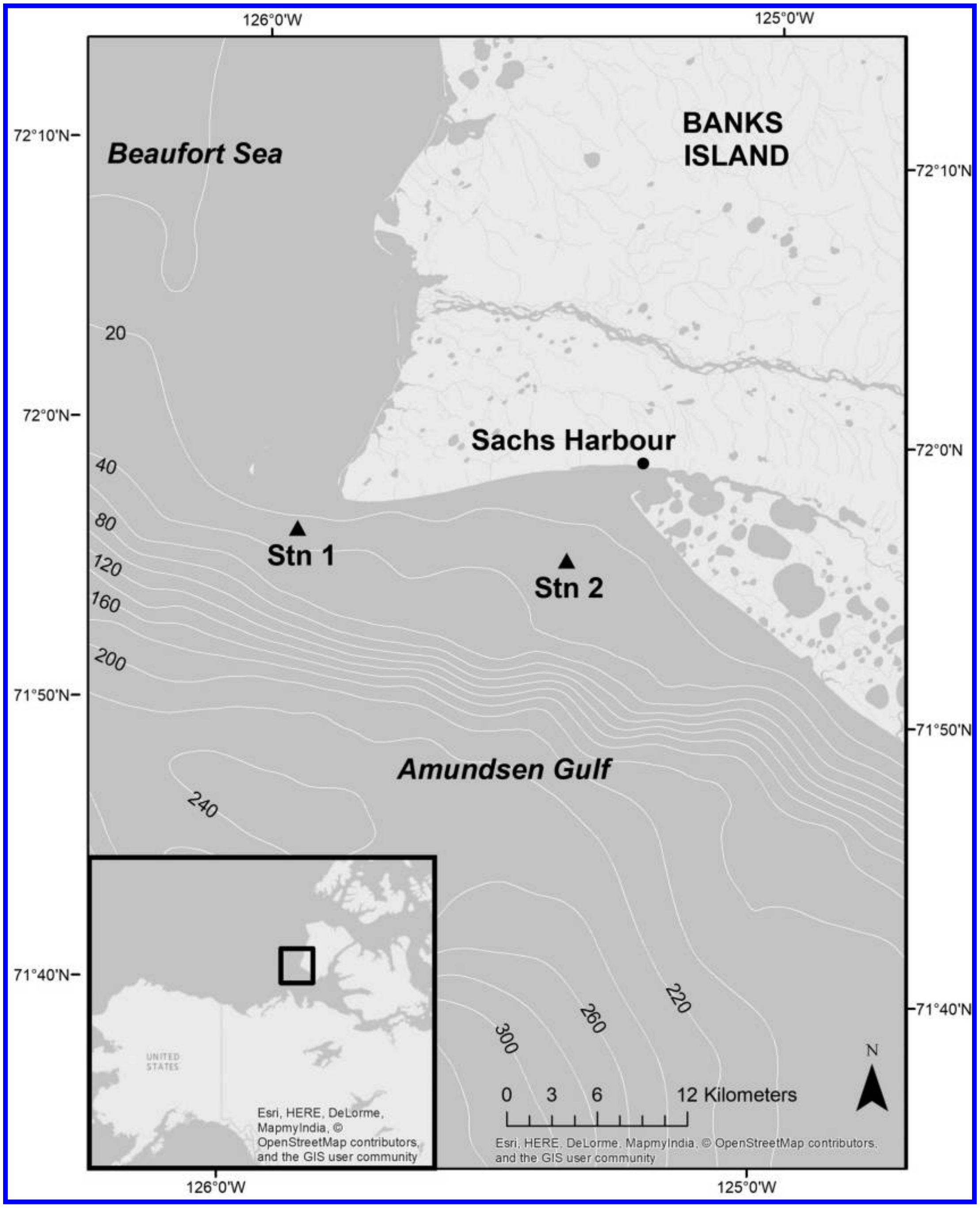
We used Wildlife Acoustics (Maynard, Maryland, USA) song meter SM3M submersible bioacoustics recorders fitted with low-noise HTI 92-WB hydrophones for all acoustic recordings. We deployed our first recorder 21 km west of Sachs Harbour (71°56.373′N, 125°54.622′W) from 18 May to 22 August 2015 (3 months), with the recorder set to continuous recording, a 32 kHz sampling rate, +12 dB of gain, and anchored at a depth of 23.5 m (water depth = 26.5 m) (Fig. 1). We deployed our second recorder 8 km west of Sachs Harbour (71°55.621′N, 125°23.447′W) from 20 August 2015 to 8 July 2016 (~1 year), with the recorder set to 5 min on, 30 min off duty cycling, a 38 kHz sampling rate, +12 dB of gain, and anchored at a depth of 28.5 m (water depth = 30 m). This duty cycle allowed us to sample different parts of each hour throughout the day. All data were collected under the authority of Aurora Research Institute Scientific Research Licence No. 15996.

Marine mammal detection, classification, and analysis

We processed all of our recordings through an automated detector and classifier (Spectro Detector; JASCO Applied Science Ltd, Victoria, British Columbia, Canada) (Mouy et al. 2013), which included automatic classifiers for bowhead whales, beluga whales, and bearded seals. We used a separate detector and classifier for ringed seals (PAMlab; JASCO Applied Science Ltd) (Martin et al. 2014). We then manually analyzed all files that had at least one automated detection for any of our species of interest and noted the presence of any species in the file visually based on the spectrogram (nonexhaustive list of example calls for each species in Fig. 2) and also aurally. Files for the 2015 deployment were 1 h long, whereas files for the 2015–2016 deployment were 5 min long. To verify the number of false negatives for the automated software, we also manually analyzed 5% of the files without any automatic detections for each deployment.

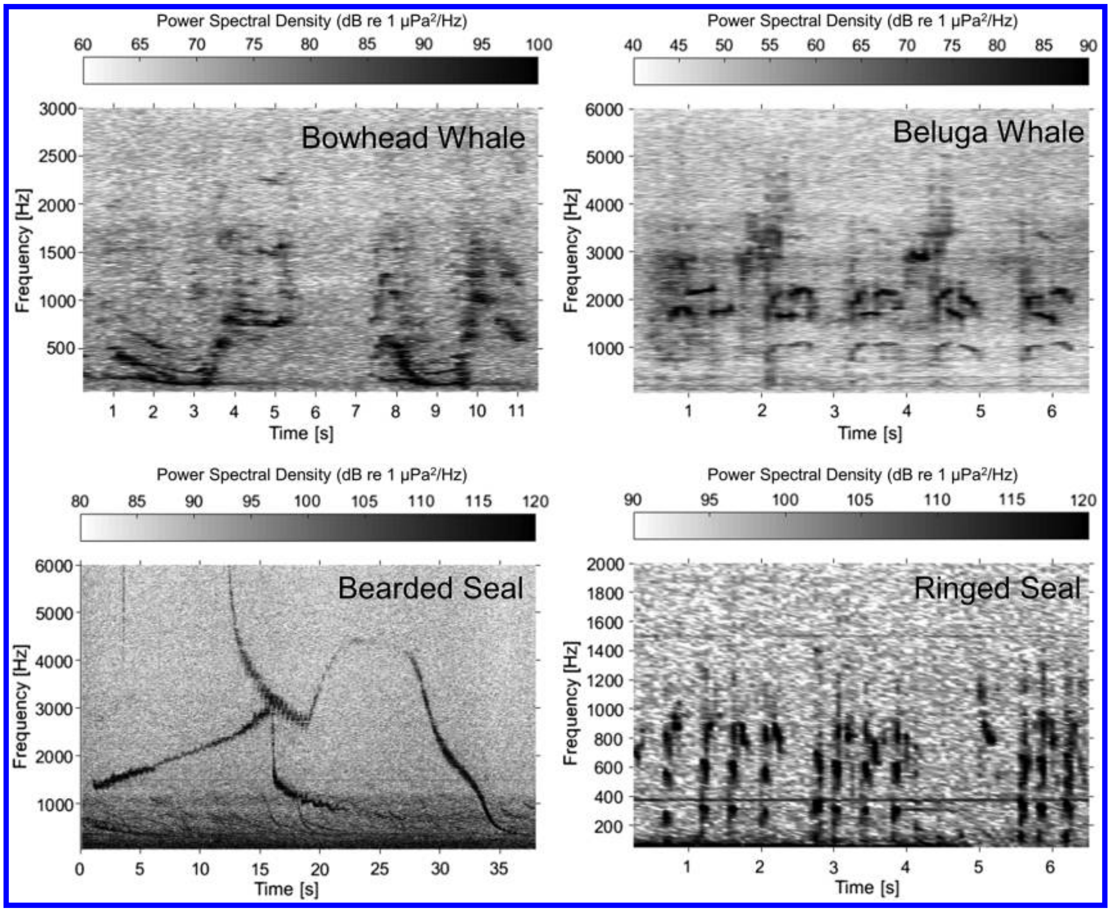
We summarized the detection data for each species as the number of hours per day where a vocalization from each species was detected (henceforth called DV). In this way,

Fig. 1. Map of the study area near Sachs Harbour, Northwest Territories. Stn 1 is the recorder deployed from 18 May to 22 August 2015 and Stn 2 is the recorded deployed from 20 August 2015 to 8 July 2016.



we can compare our deployment with continuous recordings to our deployment with duty cycling. For an analysis of the timing of vocalizations, we summarized the data as the number of hours within a 6 h period with a detection of each species (henceforth called QV). We split the day into quarters from 0000 to 0600, 0600 to 1200, 1200 to 1800, and 1800 to 0000.

Fig. 2. Spectrograms for typical vocalizations by bowhead whales, beluga whales, bearded seals, and ringed seals. Note that time (*x*-axis), frequency (*y*-axis) and power (the grey scale colour ramp) are on different scales for each spectrogram. Sample rate = 48 kHz and fast Fourier transform = 6000 for bowhead whales and bearded seals, 4000 for beluga whales, and 3000 for ringed seals. Each spectrogram has a 50% overlap and uses a Hanning window.



We determined seasonal trends in DV for each species in each deployment separately due to differences in duty cycle and deployment location (Fig. 1). We analyzed DV for each species in the summer 2015 deployment using analysis of variance in R (package: stats; function: aov) (R Core Team 2016) and using a Kruskal–Wallis test (package: stats; function: kruskal.test) for the 2015–2016 deployment. We used a Kruskal–Wallis test because the data were non-normal. To determine daily trends in vocalizations for each species, we examined data from the 2015–2016 deployment and analyzed QV by month, quarter of the day, and the interaction between month and quarter of the day using a Kruskal–Wallis test. For all analyses, we examined the distribution of residuals and tested for normality, homoscedasticity of variance, and other standard assumptions. For non-normal distributions, we applied an appropriate non-parametric analysis (such as the Kruskal–Wallis test). For the parametric analysis of variance, we examined significant effects using a post-hoc Tukey's honest significant difference test (package: stats; function: TukeyHSD), and for the Kruskal–Wallis test, we used a post-hoc Dunn's test with *p* values adjusted using the Benjamini–Hochberg method (package: FSA; function: dunnTest; method: bh) (Ogle 2017).

We compared monthly DV patterns in 2015 to monthly DV patterns in 2016 by comparing the months May through July for each species (the only 3 months examined each year) using analysis of variance with month, year, and their interaction as independent variables. We used a Kruskal–Wallis test for bearded seals for this analysis.

We also assessed the impact of environmental variables on DV. We obtained wind speed data for Sachs Harbour from Environment Canada's Historic Climate Database (Environment Canada 2016) for each hour that our recorders were deployed and summarized the wind speed per day as the minimum, maximum, and mean levels. We also measured daily ice concentration data and distance to the nearest ice edge using remote sensing data. Specifically, we used sea ice concentration data derived from the Advanced Microwave Scanning Radiometer 2 (AMSR2) satellite sensor, obtained from the Physical Analysis of Remote Sensing Images group at the University of Bremen (Spreen et al. 2008). These data represent the finest resolution (width = 6.25 km, area = 39.06 km^2) dataset available for a sea ice concentration product with daily coverage over the Arctic. We extracted the pixel value for sea ice concentration directly over each recorder for each day of their deployment. We also extracted daily sea ice concentrations at multiple scales centered over the location of the recorders, while masking out land areas, to capture ice dynamics at multiple scales around the recorder: 3 × 3 pixels (width = 18.75 km, area = 351.56 km^2), 5 × 5 pixels (width = 31.25 km, area = 976.56 km^2), and 17 × 17 pixels (width = 106.25 km, area = 11 289.06 km^2). We selected these scales to capture an expanding area around the recorders (first three scales) and to also capture >100 km around the recorders, which may represent the distances that bowhead whales that we record are calling from (Tervo et al. 2012; Abadi et al. 2014; Bonnel et al. 2014). We also used the daily ice concentration data to measure the distance from our recorders to open water. The shortest path to open water was calculated as a straight line from the recorder to the nearest pixel of 75% sea ice concentration or less. We calculated this distance using a combination of ArcGIS and python scripting tools with a geodesic method that factors in the curvature of the Earth and limits distortions caused by coordinate systems.

We analyzed DV for each species for the summer 2015 deployment by wind speed, ice concentration, and their interaction using multiple linear regression in R (package: stats; function: lm) (R Core Team 2016). We built 12 competing models for each species, where each model included one metric of wind speed (minimum, maximum, or mean), one scale of ice concentration (6.25, 18.75, 31.25, or 106.25 km), and their interaction. We then used Akaike's information criterion (AIC) (package: stats; function: AIC) (R Core Team 2016) to select the best model (Burnham and Anderson 2002) and considered competing models that were within 2 AIC units of the best model. If models were competing, we selected the most parsimonious model. We did not examine distance to the ice edge in this analysis because it was near zero throughout this deployment. We also did not examine month in this analysis (or in any analysis with environmental variables) because month is highly correlated with ice concentration and including it in the models added strong multicollinearity.

For the 2015–2016 deployment, we examined the effects of wind and ice on DV for each species in two ways. First, given that we did not detect three of the four species for multiple consecutive months, the DV data were highly zero inflated for the full deployment. We therefore transformed DV into a binary variable examining the presence–absence of vocalizations by a species during each day. We then analyzed these data using general linear models in R with a binomial distribution (package: stats; function: glm; family: binomial) and compared 12 candidate models that contained all combinations of the wind speed (mean, minimum, and maximum), ice concentration (6.25, 18.75, 31.25, or 106.25 km) variables, and their two-way interaction. We also examined an additional model that used ice concentration as a categorical variable where "no ice" was when ice concentration was <10%, "broken ice" was when ice concentration was between 10% and 90%, and "solid ice" was when ice concentration was >90%. We included distance to the ice edge and all interaction between distance to the ice edge and variables from the best model in the analysis with ice as a continuous variable. Distance to the ice edge was not included in the first set of models because it is strongly correlated with ice concentration, but by examining ice concentration as a categorical variable, we were able to get around this correlation.

For our second analysis of the 2015–2016 deployment, we examined DV for each species in months where they were present. The period for bowhead whales was August to October 2015 and May to July 2016, May to July 2016 for beluga whales, November 2015 to July 2016 for bearded seals, and August 2015 to July 2016 for ringed seals. Although many of the "zeros" were already removed from these data, the data were still very right-skewed for all species except bearded seals (which had a relatively normal distribution). For bearded seals, we used a general linear model with a normal distribution, and for all other species, we used general linear models with a negative binomial distribution (package: MASS; function: glm.nb) (Venables and Ripley 2002), which provided the best fit for the data. We first examined the effect of ice concentration and wind speed on DV and compared 12 candidate models that contained all combinations of the wind speed (mean, minimum, and maximum) and ice concentration (6.25, 18.75, 31.25, or 106.25 km) and their interaction. We then examined models that included ice concentration as a categorical variable, distance to the ice edge, wind speed, and all two-way interactions between these three variables.

Finally, we examined the efficacy of the automatic detector/classifier by comparing the presence–absence of a species in a file based on results from the automatic detector versus what we actually found in the file and included all files with detections plus the 5% of files without detections in this calculation. We calculated the precision (P) and recall (R) of the detectors based on the following equations (Hannay et al. 2013; Mouy et al. 2013):

$$(1)\quad P = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FP}}$$

$$(2)\quad R = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FN}}$$

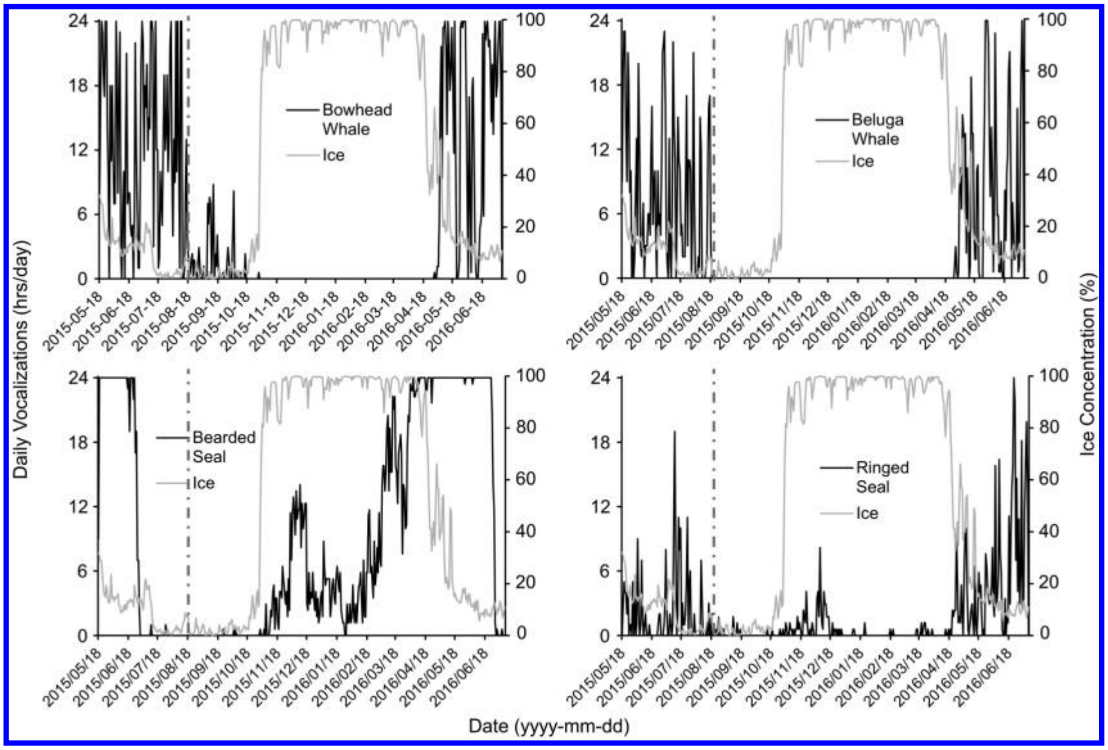
where TP is the number of true positives, FP is the number of false positives, and FN is the number of false negatives. An automatic detector and classifier that successfully detects and classifies all species within recordings would have $P = R = 1$. We calculated P and R for each species in each deployment because each deployment had different locations, sampling rates, gain settings, and duty cycles.

Results

Bowhead whales

In the summer of 2015, we detected bowhead whales in all months (Fig. 3; Appendix Table A1), with slightly lower DVs in June compared to May and July ($p < 0.01$), with a mean DV of 12 ± 0.8 h/day (±SE). For the 2015–2016 deployment, we detected bowhead whales in August through late October 2015 and then again in April (one detection late in the month) and May through July 2016 (Fig. 3). Mean DV in the 2015–2016 deployment was 8 ± 0.8 h/day for months when bowheads were present. When comparing detections in May through July in 2015 versus 2016, there was no significant difference in DV between 2015 and 2016 for bowhead whales ($p > 0.05$). Bowhead whales showed no diel patterns in QV throughout the 2015–2016 deployment.

Fig. 3. Seasonal patterns in daily vocalizations by marine mammals near Sachs Harbour, Northwest Territories, from 18 May 2015 to 8 July 2016 overlaid with daily ice concentration (calculated over 106 km around the recorder). Data from 18 May to 20 August 2015 are from Unit 1, which was 21 km west of Sachs Harbour, and data from 20 August 2015 to 8 July 2016 are from Unit 2, which was 8 km west of Sachs Harbour. The time series switches from Unit 1 to Unit 2 at the dashed-dotted grey vertical line.



During the summer of 2015, DV for bowhead whales decreased as mean wind speed increased (slope = −0.81 ± 0.18 h/day, $t_{89} = 4.5$, $p < 0.01$), but the effect of wind speed had a diminished impact on DV when ice concentration (scale = 106 km) was greater (interaction between mean wind speed and ice concentration: slope = 0.04 ± 0.01, $t_{89} = 2.89$, $p < 0.01$).

During the 2015–2016 deployment, the presence of bowhead whales in a day was less likely, as both minimum wind speed (slope = −0.17 ± 0.04, $z_{324} = 4.71$, $p < 0.01$) and ice concentration at 106 km increased (slope = −0.06 ± 0.01, $z_{324} = 7.24$, $p < 0.01$), although the interaction between wind speed and ice concentration did lead to increased presence of bowhead whales per day (slope = 0.002 ± 0.0008, $z_{324} = 2.22$, $p < 0.01$). When we examined ice concentration as a categorical variable, bowhead whales were more likely to be present during days when ice was low (concentration <10%) or broken (ice concentration between 10% and 90%) and were unlikely to be present when ice was solid (concentration >90%). Distance to the ice edge was only important when ice was broken, where bowhead whales were less likely to be present as distance to the ice edge increased (slope = $-3.67 \times 10^{-4} \pm 1.24 \times 10^{-4}$, $z_{324} = 2.95$, $p < 0.01$).

In the 2015–2016 deployment during the months when bowhead whales were present (August to October 2015, May to July 2016), daily DV decreased as mean wind speed increased (slope = −0.13 ± 0.02, $z_{142} = 5.61$, $p < 0.01$) but increased as the interaction between ice concentration at 106 km and wind speed increased (slope = 0.005 ± 0.001, $z_{142} = 4.26$, $p < 0.01$). Including ice as a categorical variable did not change these results.

Beluga whales

In the summer of 2015, we detected beluga whales in all months (Fig. 3; Appendix Table A2), with significantly lower DVs in August compared to May ($p < 0.05$), with a mean DV of 8 ± 0.7 h/day. For the 2015–2016 deployment, we only detected beluga whales in April (one detection late in the month) and May through July 2016 (Fig. 3). Mean DV in the 2015–2016 deployment from May through July was 9 ± 0.9 h/day. When comparing detections in May through July in 2015 versus 2016, there was no significant difference in DV between 2015 and 2016 for beluga whales ($p > 0.05$). Beluga whales showed no diel patterns in QV throughout the 2015–2016 deployment.

During the summer 2015 deployment, DV for beluga whales decreased as mean wind speed increased (slope = -0.44 ± 0.09, $t_{90} = 5.16$, $p < 0.01$) but increased as ice concentration at 106 km increased (slope = 0.32 ± 0.08, $t_{90} = 3.95$, $p < 0.01$).

During the 2015–2016 deployment, the presence of beluga whales per day decreased as mean wind speed increased (slope = -0.075 ± 0.028, $z_{324} = 2.71$, $p < 0.01$), decreased as ice concentration at 106 km increased (slope = -0.058 ± 0.011, $z_{324} = 5.00$, $p < 0.01$), but increased as both ice concentration and mean wind speed increased (interaction: slope = 0.0014 ± 0.0005, $z_{324} = 2.71$, $p < 0.01$). When we considered ice as a categorical variable, the impact of wind speed disappeared, beluga whales were most likely to be present when ice was broken rather than in ice-free or solid ice conditions, and as distance to the ice edge increased, beluga whales were less likely to be present (slope = $-3.52 \times 10^{-4} \pm 1.17 \times 10^{-4}$, $z_{324} = 3.02$, $p < 0.01$).

When we restricted our analysis to the periods when belugas were present (May through July 2016), DV decreased as minimum wind speed increased (slope = -0.14 ± 0.04, $z_{68} = 3.97$, $p < 0.01$) and increased as the interaction between minimum wind speed and ice concentration at 6 km increased (slope = 0.0011 ± 0.0005, $z_{68} = 2.11$, $p = 0.03$). Including ice as a categorical variable did not improve the model.

Bearded seals

In the summer of 2015, we only detected bearded seals in May and June (Fig. 3; Appendix Table A3), with a mean DV of 10 ± 1 h/day. For the 2015–2016 deployment, we detected bearded seals in November 2015 through June 2016 (Fig. 3). Mean DV in the 2015–2016 deployment from November through June was 13 ± 0.6 h/day. When comparing detections in May through July in 2015 versus 2016, there was no significant difference in DV between 2015 and 2016 for bearded seals ($p > 0.05$). Bearded seals showed diel patterns in QV ($p < 0.01$), with higher QV between 0000 and 1200 than between 1200 and 1800 in December and February, higher QV between 0000 and 0600 than between 1200 and 1800 in January, and higher vocalizations between 1800 and 1200 than between 1200 and 1800 in March.

During the summer 2015 deployment, DV for bearded seals increased as ice concentration at 31 km increased (slope = 0.47 ± 0.16, $t_{89} = 2.91$, $p < 0.01$), and DV increased as both minimum wind speed and ice concentration increased (interaction term slope = 0.045 ± 0.017, $t_{89} = 2.72$, $p < 0.01$).

During the 2015–2016 deployment, the presence of bearded seals per day was best predicted by ice concentration at 6 km, where increased ice concentration led to increased probability of bearded seal presence (slope = 0.048 ± 0.005, $z_{324} = 10.01$, $p < 0.01$). Including ice as a categorical variable did not change the result.

When we restricted our analysis to months when bearded seals were actively vocalizing (November to July), DV decreased as ice concentration at 106 km increased (slope = -0.17 ± 0.01, $t_{242} = 13.16$, $p < 0.01$). including ice concentration as a categorical variable did not affect the results.

Ringed seals

In the summer of 2015, we detected ringed seals in all months (Fig. 3; Appendix Table A4), with slightly higher DVs in July compared to June and August ($p < 0.01$), with a mean DV of 2 ± 0.3 h/day. For the 2015–2016 deployment, we detected ringed seals in all months (Fig. 3), but there were significantly more in May through July of 2016 than in all other months ($p < 0.05$). Mean DV in the 2015–2016 deployment was 2 ± 0.2 h/day. When comparing detections in May through July in 2015 versus 2016, DV was significantly higher in June and July of 2016 compared to 2015 for ringed seals ($p < 0.02$). Ringed seals only showed diel patterns during December, where there was higher QV between 0000 and 0600 than between 1800 and 0000.

During the summer 2015 deployment, DV for ringed seals decreased as minimum wind speed increased (slope = -0.18 ± 0.05, $t_{91} = 3.51$, $p < 0.01$) and was unaffected by ice concentration.

During the 2015–2016 deployment, the presence of ringed seals per day decreased as maximum wind speed increased (slope = -0.041 ± 0.011, $z_{324} = 3.83$, $p < 0.01$) and decreased as ice concentration at 106 km increased (slope = -0.01 ± 0.0028, $z_{324} = 3.63$, $p < 0.01$). When we included ice concentration as a categorical variable, results stayed essentially the same, but ringed seals were most likely to be present in broken ice compared to ice-free or solid ice conditions.

DV for ringed seals decreased as mean wind speed increased (slope = -0.062 ± 0.014, $z_{324} = 4.57$, $p < 0.01$) and decreased as ice concentration at 106 km increased (slope = -0.023 ± 0.003, $z_{324} = 8.70$, $p < 0.01$). Including ice concentration as a categorical variable showed the same result with decreasing DV as both mean wind speed and ice concentration increased but also demonstrated that DV increased as distance to the ice edge increased (slope = $5.5 \times 10^{-6} \pm 1.8 \times 10^{-6}$, $z_{324} = 3.00$, $p < 0.01$), a dampening effect of broken and solid ice on wind speed, where higher DVs were recorded when mean wind speed was high in either broken ice (slope = 0.098 ± 0.035, $z_{324} = 2.83$, $p < 0.01$) or solid ice (slope = 0.13 ± 0.039, $z_{324} = 3.38$, $p < 0.01$), and decreased DV when the interaction between mean wind speed and distance to the ice edge increased (slope = $-6.8 \times 10^{-7} \pm 2.4 \times 10^{-7}$, $z_{324} = 2.80$, $p < 0.01$).

Efficacy of automatic detectors/classifiers

Precision (number of true positives/(number of true positives + number of false positives)) for the 2015 deployment was low for beluga whales (65%) and ringed seals (59%) but was above 80% for bowhead whales and bearded seals. Recall (number of true positives/(number of true positives + number of false negatives)) was at or above 95% for all species in the 2015 deployment (Table 1). Precision for the 2015–2016 deployment was greater than 80% for all species, and recall was greater than 90% for all species (Table 1).

Discussion

PAM was a very useful tool for monitoring marine mammals at our study site. We successfully recorded all four species and documented seasonal trends in the presence of the migratory cetacean species as well as vocalization patterns by resident seal species. Patterns in May through July were consistent between 2015 and 2016 for all species except ringed seals, which suggests that these data represent a useful baseline for three of the species that were present. We now relate the trends that we documented for each species to what is known based on other studies.

Bowhead whales

We started detecting bowhead whales in late April and detected them frequently from May through August, with fewer detections in September, and the final detection in late

Table 1. Automatic detector performance for each deployment of acoustic recorders near Sachs Harbour, Northwest Territories.

	Bowhead whale	Beluga whale	Bearded seal	Ringed seal
Summer 2015				
Precision	0.81	0.65	0.98	0.59
Recall	0.96	0.95	1.00	0.96
2015–2016				
Precision	0.84	0.85	0.98	0.95
Recall	0.95	0.96	0.98	0.94

Note: Precision is the number of true positives divided by the number of true positives plus the number of false positives, and recall is the number of true positives divided by the number of true positives plus the number of false negatives.

October. This trend of arriving in the Canadian Beaufort Sea in late April and departing in October is consistent with telemetry studies of this population (Mate et al. 2000; Citta et al. 2015; Harwood et al. 2017) and long-term monitoring in Alaska (Braham et al. 1980). Citta et al. (2015) specifically demonstrated that bowhead whales use the polynya at Cape Bathurst early in the season, which stretches from the Tuktoyaktuk Peninsula to Cape Bathurst and north towards Banks Island, and later in the season, bowhead whales mostly use the shallow shelf adjacent to the Tuktoyaktuk Peninsula. These authors still identified the area around Sachs Harbour as a 95% core use area, but it was not as well used as the Cape Bathurst polynya or the Tuktoyaktuk Peninsula. Harwood et al. (2017) found similar core use areas for juvenile bowhead whales, but also found that juvenile bowhead whales spent quite a bit of time moving around Banks Island and identified a few core use areas farther north. One acoustic study (Clark et al. 2015) recorded in August and September 2009 and 2010 near Tuktoyaktuk found the presence of bowhead whale calls nearly every day, which confirms that bowhead whales stay in the Canadian Beaufort Sea into September.

Ice concentration was important for predicting the presence of bowhead whales during a day; bowhead whales left our study area as ice began to form in the autumn and did not return until the ice started breaking up in the spring. However, when bowhead whales were present (May through October), ice concentration on its own had little impact on their DV. Increased wind speed led to decreased detections of bowhead whales, but increased ice concentration counteracted the impact of wind speed. We similarly found this interaction between wind speed and ice concentration in our study of ambient noise levels at this study site (Insley et al. 2017), where increased wind speed had less effect on ambient noise levels when more ice was present. In this way, wind may generally be acting to increase ambient noise levels, which masks bowhead whale vocalizations, but under increased ice concentrations, this masking effect may decrease.

Beluga whales

We started detecting beluga whales in late April and continued detecting them consistently into August. This early departure is consistent with results from telemetry studies (Richard et al. 2001; Hauser et al. 2017*a*). However, no published studies that we are aware of have documented the arrival of beluga whales to this region, which therefore highlights the importance of our work. Harwood et al. (1996) documented the distribution of beluga whales in the Canadian Beaufort Sea and west Amundsen Gulf (including near Sachs Harbour) via aerial surveys in late July 1992 and found that a large number of individuals were within the Mackenzie estuary and near Cape Bathurst, but found no individuals near Sachs Harbour and only a few individuals near southern Banks Island. However, this study only had one aerial transect that went to Sachs Harbour, so the area around Sachs Harbour is underrepresented in the study. Asselin et al. (2011) presented much more extensive aerial survey data from mid-June 1975–1979, which covered the mainland coast of the Canadian Beaufort Sea and the south and west sides of Banks Island. These authors found beluga whales in heavy ice (>80% ice concentration) throughout the Canadian Beaufort Sea, including near Sachs Harbour and farther north along the west side of Banks Island. The utility of acoustic monitoring is very apparent when comparing to aerial surveys, where aerial surveys are logistically difficult, often provide a small snapshot in time, and are biased towards areas with open water. Our data demonstrate that beluga whales are near Sachs Harbour from May through August, which is not always apparent from aerial surveys. Telemetry studies, however, clearly show that beluga whales use areas around Banks Island, including near Sachs Harbour, at various times throughout the summer (Richard et al. 2001; Hauser et al. 2014). But given the small sample size of most telemetry studies and the transient nature of many of the beluga whales studied, these studies do not show the high frequency that beluga whales are around Sachs Harbour.

Beluga whales were detected more when ice was broken compared to ice-free and solid ice conditions. The lack of association with both solid ice and ice-free conditions is related to the timing of migration for beluga whales, where they migrate out of the region late in the summer as the region becomes ice-free (before bowhead whales migrate) and do not migrate back into the region until the ice begins to break in the spring. The association with broken ice has been documented with both aerial surveys (Asselin et al. 2011) and telemetry studies (Richard et al. 2001; Loseto et al. 2006; Hauser et al. 2017*b*) of this population, and pack ice is considered to be an important habitat feature for beluga whales, at least for the subset of the population that spends time away from the Mackenzie estuary before they migrate back to the Bering Sea (Loseto et al. 2006; Hauser et al. 2017*b*). As with bowhead whales, detections of beluga whales decreased as wind speed increased, and this may be due to increases in wind speed causing increases in noise levels, which then mask vocalizations. Alternatively, changes in wind can affect patterns in ocean current, which can then affect the distribution of beluga whales (Stafford et al. 2013). More work is therefore needed to fully examine why the negative correlation exists between wind speed and detections of these species.

Bearded seals

Bearded seals began vocalizing in October and November, drastically increased their calling in the spring, and stopped vocalizing in early July. This trend for increased vocalizations during the ice-covered season is relatively consistent with other studies from the Beaufort Sea (MacIntyre et al. 2013, 2015), Chukchi Sea (Hannay et al. 2013; Jones et al. 2014; Frouin-Mouy et al. 2016), and Baffin Bay (Frouin-Mouy et al. 2017; Marcoux et al. 2017), although there can be a lot of variation even at a site for seasonal vocalization patterns in this species (Hannay et al. 2013; Frouin-Mouy et al. 2016). Although bearded seals vocalize outside of the breeding season, their period of peak vocalizations (24 h/day in this study) occurs between April and June, which not only matched vocalization patterns from other studies (MacIntyre et al. 2015; Frouin-Mouy et al. 2016) but is also consistent with the timing of their breeding season (Cleator et al. 1989).

We also found that bearded seals showed a strong diurnal trend in their vocalizations between December and March, where they seemed most likely to call between 0000 and 0600, which is consistent with trends from other sites (Frouin-Mouy et al. 2016). Diurnal trends in vocalizations are expected during the mating season because there are diurnal trends in when females are most likely to be in the water (Cleator et al. 1989), yet we found no evidence of diurnal trends in vocalizations during the mating season. We possibly did not find any diurnal trends during the mating season because our metric (QV) was too coarse to show any diurnal trends when at least one individual is vocalizing during every hour of the day, as was the case during the breeding season.

Bearded seals did not start vocalizing until ice had formed and stopped vocalizing once ice was sparse. Bearded seal vocalizations peaked in the spring just after ice began to break. This reliance on sea ice has been well documented for bearded seals (Cleator et al. 1989; Jensen 2005; MacIntyre et al. 2015; Frouin-Mouy et al. 2016).

Ringed seals

We detected ringed seals throughout the year, although they were generally quiet for most of the year, except for a slight increase in calling in the spring (May through July) in both years. Other studies have similarly documented that ringed seals are generally detected throughout the year but are often quiet (Hannay et al. 2013; Jones et al. 2014). Ringed seals were less likely to be detected when wind speed increased and when ice concentration increased, although we detected them most when the ice was broken. The effect of wind speed is likely due to acoustic masking, as we suggested for bowhead and beluga whales.

Implications of vocalization range

Bowhead whale vocalizations have been recorded up to 34 km (Bonnel et al. 2014) and 40 km away (Abadi et al. 2014) off the north coast of Alaska and as far as 130 km away in Greenland (Tervo et al. 2012). Unlike bowhead whales, beluga whales have much shorter propagation distances due to their smaller body size and higher call frequency but can still be detected when 3 km away from a recorder (Simard et al. 2010). Surprisingly, bearded seals may still be heard when 45 km away (Stirling et al. 1983), although a typical vocalization likely only propagates 5–10 km (Cleator and Stirling 1990). No study has measured the propagation distance of ringed seal calls, to the best of our knowledge, but Stirling et al. (1983) suggested that propagation distance is at most a couple of kilometres. This wide variation in propagation distance between species has potentially important implications for our results. First, the bowhead whales that we detected could have been quite far away from our recorders. A bowhead whale with a 130 km propagation distance could be vocalizing near Cape Bathurst and detected by our recorders near Sachs Harbour. A loud bearded seal could potentially be heard 45 km away from our recorders, whereas beluga whales and ringed seals would need to be much closer to our recorders. However, at this time, we can only speculate on the locations of the calling individuals. Future work should use arrays of acoustic recorders to localize vocalizing Arctic marine mammals to more fully understand their distribution and spatial ecology within their summer range. This is most important for bowhead whales, given their large variation in propagation distance.

Scales of ice concentration

We included four different scales of ice concentration in our analyses of environmental effects. Ice concentration at the largest spatial scale (106 km) was always chosen via model selection (i.e., lowest AIC) for bowhead whales and ringed seals in all analyses and for beluga whales in all analyses except the analysis focusing on DV in May through July 2016, where the smallest scale (6 km) was chosen. Bearded seals had a different scale chosen for each analysis. The largest scale for ice concentration seems appropriate for bowhead whales, since they could be vocalizing from far away and may be selecting ice conditions that are not the same as those at our recorder. Similarly, since ice is the factor limiting the spring migration of both whale species, ice concentration at the largest spatial scale should best reflect this limiting factor, especially in our analysis of presence per day in the 2015–2016 recordings, where we examined the arrival time of both whales. The most appropriate scale of ice concentration for both seal species is less clear, especially since both species are present year-round, even if they only actively vocalize for part of the season. Indeed, our analyses of bearded seal vocalizations had three different scales of ice concentration that were important, yet the largest scale was the only scale important for ringed seal vocalizations. Not enough is understood about the vocalizations of either seal species at this time, and we can only speculate on why different scales of ice concentration are important for these species.

Efficacy of automatic detectors

Automatic detectors worked very well for detecting and classifying marine mammal vocalizations within our data, with precision generally >80% and recall >90%. Lower precision occurred for ringed seals and beluga whales in summer 2015. The beluga whale classifier often gave false positives on bearded seal vocalizations when bearded seal calls were very abundant in our recordings, which was the case for more than a third of our summer 2015 recordings. The ringed seal classifier gave false positives on faint bowhead whale moans, which caused its precision to be lowest for our summer recordings.

Conservation implications

Climate change has been causing a decrease in sea ice throughout the Arctic (Stroeve et al. 2007). Our results confirm that sea ice is related to the timing of migration for bowhead and beluga whales and also for vocalization timing by bearded seals. One potential implication of this relationship between vocalizations and sea ice concentration is that the western Canadian Arctic will be accessible earlier in the spring and later in the autumn for whales (Laidre et al. 2015), allowing for earlier spring migration and later fall migration. However, some studies have demonstrated that habitat selection by beluga whales is strongly influenced by sea ice (Loseto et al. 2006; Asselin et al. 2011; Hauser et al. 2017*b*), which may have important implications for their summer distribution as sea ice distribution changes. It also seems that sexual segregation and site fidelity may be strong geographic and phenological factors independent of ice cover (Loseto et al. 2006; Hauser et al. 2017*b*). The autumn migration of beluga whales, however, seems to be unaffected by trends in sea ice (Hauser et al. 2017*a*), which may mean that the beluga autumn migration will remain unchanged. Bearded seal vocalizations are also highly correlated with ice presence (Cleator et al. 1989; MacIntyre et al. 2013; Frouin-Mouy et al. 2016), so a longer ice-free season may mean that bearded seals will start calling later in the autumn and stop calling earlier in the spring. Finally, ringed seal movement behaviour is linked to ice concentration (Hamilton et al. 2015), so a longer ice-free season may lead to fewer ringed seal detections because they seem to be less sedentary when there is less ice. These predictions can only be confirmed with long-term, year-round monitoring and analyzing yearly patterns based on patterns in ice concentration. Our results represent a first step in that process, but many more years of data must be collected to monitor the effects of sea ice loss, and the study area must be expanded to include more of each species' range.

Climate change is also opening up the Arctic for increased anthropogenic activity because the longer ice-free season allows for increased access by vessels (Arctic Council 2009). Shipping is considered a major threat for bowhead whales, via both acoustic disturbance and ship strikes (COSEWIC 2009). The shipping season in the western Canadian Arctic also occurs late in the summer and during the autumn migration of bowhead and beluga whales. The shipping corridor through the area tends to follow the coastline (Dawson et al. 2016) and overlaps with the migration route of both whale species (Citta et al. 2015; Harwood et al. 2017; Hauser et al. 2017*a*). Ships traveling the current corridor pose risks for these marine mammals, including risks of ship strikes and acoustic impacts (Reeves et al. 2014; Halliday et al. 2017). We recommend the need for policies minimizing the impacts of increased anthropogenic activities on these marine mammals.

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Appendix A

Tables A1–A4 appear on the following pages.

Table A1. Final model output for analyses of bowhead whale daily vocalizations and presence in a day for recorders near Sachs Harbour, Northwest Territories.

Parameter	Estimate	SE	*t*/*z*	*p*
Summer 2015, DV				
Intercept	25.79	3.61	7.14	<0.01
Mean wind speed	−0.81	0.18	4.51	<0.01
Ice 106 km	−0.58	0.29	1.97	0.05
Wind:ice	0.04	0.01	2.89	<0.01
2015–2016, daily presence (ice continuous)				
Intercept	2.69	0.44	6.12	<0.01
Minimum wind speed	−0.17	0.04	4.71	<0.01
Ice 106 km	−0.06	0.009	7.24	<0.01
Wind:ice	0.002	0.0008	2.22	0.03
2015–2016, daily presence (ice categorical)				
Intercept	1.60	0.39	4.15	<0.01
Minimum wind speed	−0.12	0.03	4.34	<0.01
Ice 1	0.33	0.39	0.85	0.40
Ice 2	−5.30	0.89	5.98	<0.01
Ice edge	2.39×10^{-6}	2.87×10^{-6}	0.83	0.40
Ice 1:ice edge	-3.67×10^{-4}	1.24×10^{-4}	2.95	<0.01
Ice 2:ice edge	NA	NA	NA	NA
August–October 2015, May–July 2016 (ice continuous)				
Intercept	3.62	0.50	7.28	<0.01
Mean wind speed	−0.13	0.02	5.61	<0.01
Ice 106 km	−0.02	0.02	0.68	0.50
Wind:ice	0.005	0.001	4.26	<0.01
August–October 2015, May–July 2016 (ice categorical)				
Intercept	3.01	0.42	7.22	<0.01
Mean wind speed	−0.08	0.02	4.55	<0.01
Ice 1	1.00	0.27	3.76	<0.01

Note: In models where ice is treated as a categorical variable (third and fifth sections in the table), intercept = ice concentration <10%, ice 1 = ice concentration between 10% and 90%, and ice 2 = ice concentration >90%.

Table A2. Final model output for analyses of beluga whale daily vocalizations and presence in a day for recorders near Sachs Harbour, Northwest Territories.

Parameter	Estimate	SE	*t*/*z*	*p*
Summer 2015, DV				
Intercept	13.31	1.88	7.07	<0.01
Mean wind speed	−0.44	0.09	5.16	<0.01
Ice 106 km	0.32	0.08	3.96	<0.01
2015–2016, daily presence (ice continuous)				
Intercept	1.30	0.58	2.24	0.03
Mean wind speed	−0.07	0.03	2.71	<0.01
Ice 106 km	−0.06	0.01	5.00	<0.01
Wind:ice	0.001	0.0005	2.71	0.03
2015–2016, daily presence (ice categorical)				
Intercept	−0.42	0.55	0.77	0.44
Mean wind speed	−0.04	0.02	1.83	0.07
Ice 1	2.04	0.39	5.24	<0.01
Ice 2	−16.3	1225	0.01	0.99
Ice edge	-3.52×10^{-4}	1.17×10^{-4}	3.02	<0.01

Table A2 (*concluded*).

Parameter	Estimate	SE	*t*/*z*	*p*
May–July 2016 (ice continuous)				
Intercept	3.05	0.33	9.20	<0.01
Minimum wind speed	−0.14	0.04	3.97	<0.01
Ice 6 km	−0.006	0.005	1.14	0.25
Wind:ice	0.001	0.0005	2.11	0.03
May–July 2016 (ice categorical)				
Intercept	2.74	0.22	12.65	<0.01
Minimum wind speed	−0.08	0.02	3.62	<0.01

Note: In models where ice is treated as a categorical variable (third section in the table), intercept = ice concentration <10%, ice 1 = ice concentration between 10% and 90%, and ice 2 = ice concentration >90%.

Table A3. Final model output for analyses of bearded seal daily vocalizations and presence in a day for recorders near Sachs Harbour, Northwest Territories.

Parameter	Estimate	SE	*t*/*z*	*p*
Summer 2015, DV				
Intercept	4.18	1.82	2.30	0.02
Minimum wind speed	−0.15	0.17	0.89	0.38
Ice 31 km	0.47	0.16	2.91	<0.01
Wind:ice	0.05	0.02	2.72	<0.01
2015–2016, daily presence (ice continuous)				
Intercept	−1.27	0.24	5.36	<0.01
Ice 6 km	0.05	0.005	10.01	<0.01
2015–2016, daily presence (ice categorical)				
Intercept	−1.26	0.26	4.85	<0.01
Ice 1	2.79	0.39	7.23	<0.01
Ice 2	4.66	0.52	8.90	<0.01
November 2015 – July 2016 (ice continuous)				
Intercept	25.44	1.07	23.84	<0.01
Ice 106 km	−0.17	0.01	13.16	<0.01
November 2015 – July 2016 (ice categorical)				
Intercept	21.04	1.88	11.21	<0.01
Ice 1	−1.04	2.08	0.50	0.62
Ice 2	−12.49	1.97	6.34	<0.01

Note: In models where ice is treated as a categorical variable (third and fifth sections in the table), intercept = ice concentration <10%, ice 1 = ice concentration between 10% and 90%, and ice 2 = ice concentration >90%.

Table A4. Final model output for analyses of ringed seal daily vocalizations and presence in a day for recorders near Sachs Harbour, Northwest Territories.

Parameter	Estimate	SE	*t*/*z*	*p*
Summer 2015, DV				
Intercept	3.92	0.60	6.58	<0.01
Minimum wind speed	−0.18	0.05	3.51	<0.01
2015–2016, daily presence (ice continuous)				
Intercept	1.41	0.40	3.54	<0.01
Maximum wind speed	−0.04	0.01	3.83	<0.01
Ice 106 km	−0.01	0.003	3.63	<0.01

Table A4 (*concluded*).

Parameter	Estimate	SE	*t*/*z*	*p*
2015–2016, daily presence (ice categorical)				
Intercept	0.95	0.44	2.16	0.03
Maximum wind speed	−0.05	0.01	4.54	<0.01
Ice 1	1.85	0.35	5.27	<0.01
Ice 2	−0.54	0.32	1.69	0.09
August 2015 – July 2016 (ice continuous)				
Intercept	2.49	0.33	7.65	<0.01
Mean wind speed	−0.06	0.01	4.57	<0.01
Ice 106 km	−0.02	0.003	8.70	<0.01
August 2015 – July 2016 (ice categorical)				
Intercept	3.41	0.56	6.04	<0.01
Mean wind speed	−0.15	0.03	5.41	<0.01
Ice 1	−1.17	0.72	1.63	0.10
Ice 2	−4.03	0.72	5.61	<0.01
Ice edge	5.45×10^{-6}	1.82×10^{-6}	3.00	<0.01
Wind:ice 1	0.10	0.03	2.83	<0.01
Wind:ice 2	0.13	0.04	3.38	0.01
Wind:ice edge	-6.79×10^{-7}	2.43×10^{-7}	2.80	0.01

Note: In models where ice is treated as a categorical variable (third and fifth sections in the table), intercept = ice concentration <10%, ice 1 = ice concentration between 10% and 90%, and ice 2 = ice concentration >90%.