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Seasonal Patterns in Ocean Ambient Noise near Sachs Harbour, Northwest Territories

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ABSTRACT. Ocean ambient noise is a crucial habitat feature for marine animals because it represents the lower threshold of their acoustically active space. Ambient noise is affected by noise from both natural sources, like wind and ice, and anthropogenic sources, such as shipping and seismic surveys. During the ice-covered season, ambient conditions in the Arctic are quieter than those in other regions because sea ice has a dampening effect. Arctic warming induced by climate change can raise noise levels by reducing sea ice coverage and increasing human activity, and these changes may negatively affect several species of marine mammals and other acoustically sensitive marine fauna. We document ambient noise off the west coast of Banks Island near Sachs Harbour, Northwest Territories, to provide baseline noise levels for the eastern Beaufort Sea. Noise levels were comparable to those found in other studies of the Canadian Arctic and Alaska and were typically much lower than levels reported farther south. Stronger wind increased noise, whereas greater ice concentration decreased it, dampening the effect of wind speed. Future work should expand monitoring to other locations in the Arctic, model the impact of increased human activities on ambient noise levels, and predict the impact of these changing levels on marine animals.

Key words: marine acoustic environment; marine acoustic habitat; marine soundscape; passive acoustic monitoring; ambient noise; noise impact

RÉSUMÉ. Le bruit ambiant d’un océan est une caractéristique essentielle de l’habitat des animaux marins, car il représente le seuil inférieur de leur espace acoustique actif. Le bruit ambiant est modifié par le bruit provenant de sources naturelles, comme le vent et la glace, et de sources anthropiques, comme la navigation et les levés sismiques. Pendant la saison des glaces, les conditions ambiantes dans l’Arctique sont plus calmes que celles d’autres régions parce que la glace marine a un effet modérateur. Le réchauffement de l’Arctique provoqué par le changement climatique peut faire augmenter les niveaux de bruit en réduisant la zone maritime englacée et en augmentant l’activité humaine. Ces changements peuvent nuire à plusieurs espèces de mammifères marins et d’autres espèces marines sensibles sur le plan acoustique. Nous avons documenté le bruit ambiant au large de la côte ouest de l’île Banks près de Sachs Harbour, aux Territoires du Nord-Ouest, pour établir les niveaux de bruit de base dans l’est de la mer de Beaufort. Les niveaux de bruit étaient comparables à ceux trouvés dans d’autres études de l’Arctique canadien et de l’Alaska et étaient généralement beaucoup plus bas que les niveaux observés plus au sud. Les vents plus forts font augmenter le bruit, tandis que la plus grande concentration des glaces le réduit, ce qui atténue l’effet de la vitesse du vent. Des travaux futurs devraient étendre la surveillance à d’autres emplacements de l’Arctique, modéliser les répercussions de l’intensification des activités humaines sur les niveaux de bruit ambiant et prévoir les répercussions de ces niveaux changeants sur les animaux marins.

Mots clés : environnement acoustique marin; habitat acoustique marin; paysage sonore marin; surveillance acoustique passive, bruit ambiant; impact sonore

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INTRODUCTION

Ocean ambient noise is a crucial habitat feature for marine animals (Richardson et al., 1995; Au and Hastings, 2008; Tyack, 2008; Hildebrand, 2009; Merchant et al., 2015), especially for marine mammals that rely on sound for communication (Au and Hastings, 2008; Tyack, 2008; Hildebrand, 2009; Clark et al., 2015) and echolocation (Erbe, 2002; Soto et al., 2006; Tyack, 2008; Hildebrand, 2009), both of which evolved under specific ambient noise conditions (Tyack, 2008). Ambient noise is typically defined as noise from natural sources, but it can include anthropogenic noise that is a consistent aspect of background noise (e.g., aggregate shipping traffic; Richardson et al., 1995). Ocean ambient noise distribution can vary both temporally and spatially, but it does follow some general patterns. The lowest-frequency noises (1 – 20 Hz) are typically caused by seismic activity (e.g., earthquakes); low-frequency noises (20 – 1000 Hz) are generally caused by shipping and mysticete whales; medium-frequency noises (1 – 100 kHz) are generally associated with sea state (e.g., wave action); and

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high-frequency noises (> 100 kHz) result from thermal action (Wenz, 1962; Urick, 1975; Ross, 2005; Au and Hastings, 2008; Hildebrand, 2009).

Increases in global shipping and oil exploration have led to increased noise in the 20–1000 Hz bands; Ross (2005) estimated that ambient noise levels have increased by ½ dB (re 1 μPa throughout unless otherwise stated) per year because of increases in anthropogenic noises, and McDonald et al. (2006) measured a 10–12 dB increase over 40 years. While increased shipping has created a consistent increase in ocean ambient noise, anthropogenic sources (including shipping and other forms of transportation) also create short-term increases in noise (Veirs et al., 2016). Other sources of anthropogenic noise include geophysical surveys, dredging and construction, sonars, explosions, oil and gas drilling, and ocean science studies (Richardson et al., 1995). The additive impact of these short- and long-term changes in noise has a variety of effects on marine mammals (Southall et al., 2007; Ellison et al., 2012). One effect is masking, in which the audibility threshold of one sound is raised by the presence of another sound (Moore, 1982; Clark et al., 2009). Various changes also occur in the vocal behaviour of mammals, such as the animals making louder sounds (Scheifele et al., 2005; Holt et al., 2009), changing their rate of calling or cessation of calling (Melcón et al., 2012). Noise also affects general behaviour (Southall et al., 2007; Gomez et al., 2016), causing animals to avoid noise sources and altering their surface and respiration cycles (Richardson et al., 1995; Tyack, 2008), as well as increasing their stress levels (Rolland et al., 2012).

The Arctic Ocean is particularly vulnerable to changes in ocean ambient noise (Moore et al., 2012). The Arctic soundscape has historically been shaped by a long, ice-covered winter and a very short ice-free season (Roth et al., 2012), but the rapid changes in ice conditions due to climate change in recent years (Stroeve et al., 2007) have important implications for ambient noise levels (Moore et al., 2012; Roth et al., 2012). Areas with intact sea ice are typically quieter than areas without sea ice (Greene, 1995). For example, Diachok and Winokur (1974), who examined sound pressure levels (SPL) under compact ice, near the ice edge, and in open water away from the ice, found that SPLs were lowest under the ice, highest at the ice edge, and intermediate in open water. Sea ice does, however, cause a large variety of different signals that contribute to ambient noise levels: changing temperatures can cause ice to crack, currents and winds cause ice to compress or break up, and melting ice creates small bubbles (Greene, 1995). Low-frequency ice noise (< 100 Hz) is created by wind-driven collisions between ice chunks (Makris and Dyer, 1986, 1991; Zakarauskas et al., 1990), and other noises between 100 and 600 Hz are caused by ridging, shearing, cracking, and vibrations (Xie and Farmer, 1991; Greening and Zakarauskas, 1994). Kinda et al. (2015), who examined the correlations between different transient ice signals and environmental variables, found that transients were noisiest when wind speed was high, shear rates were high, and temperature was low. These transients affected ambient noise levels from under 50 Hz to above 4 kHz (Kinda et al., 2015).

Arctic marine environments are also typically quieter than other areas because there is less human activity (Moore et al., 2012). However, as the climate warms, sea ice in the Arctic is typically breaking up earlier in the summer and freezing later in the fall than in past years, allowing for a longer season with open water (Stroeve et al., 2007). These changes in ice affect ambient noise levels both directly (Roth et al., 2012; Kinda et al., 2013, 2015) and indirectly, by allowing ships to access the water more frequently and earlier in the season (Moore et al., 2012). In fact, the Arctic is becoming so ice-free in the summer that the Northwest Passage may become a viable commercial shipping route in the foreseeable future (Koetse and Rietveld, 2009; Khon et al., 2010; Stephenson et al., 2011).

Only a few studies have documented ocean ambient noise in the Arctic (Diachok and Winokur, 1974; Lewis and Denner, 1987; Roth et al., 2012; Kinda et al., 2013; Clark et al., 2015). We present trends in ocean ambient noise determined over 15 months by using passive acoustic monitoring near Sachs Harbour, Northwest Territories, Canada, a small community on Banks Island in the eastern Beaufort Sea (Fig. 1). The patterns that we document can be a useful baseline of current conditions for forecasting and monitoring changes in the Arctic marine acoustic environment, especially when compared to patterns observed in other studies of ocean ambient noise in the Arctic. Our study site at Sachs Harbour is located at the western entrance of the Northwest Passage southern shipping route and is therefore likely to be affected by increased shipping traffic in the Arctic. Our data provide an acoustic baseline for the area prior to a significant increase in shipping activity.

METHODS

Data Collection

We used Wildlife Acoustics (Maynard, Maryland, USA) SM3M bioacoustics recorders fitted with a low-noise HTI 92-WB hydrophone (High Tech, Inc., Gulfport, Mississippi, USA) for all acoustic recordings. Sensitivity for these hydrophones changes with frequency: sensitivity starts at −175 dB re 1 V/μPa at 25 Hz, increases to −166.5 dB by 100 Hz, and levels off around −165.6 dB between 200 Hz and 6 kHz, after which it decreases to −167.5 dB by 8 kHz and stays at that level until 16 kHz. The noise floor for these units also varies with frequency: the noise floor is at ~63 dB re 1 $\mu Pa^2/Hz$ at 25 Hz, decreases steadily to ~40 dB by 200 Hz, and decreases to ~35 dB between 1 and 5 kHz. Background levels below this noise floor cannot be reliably detected because they are largely masked by electronic self-noise.

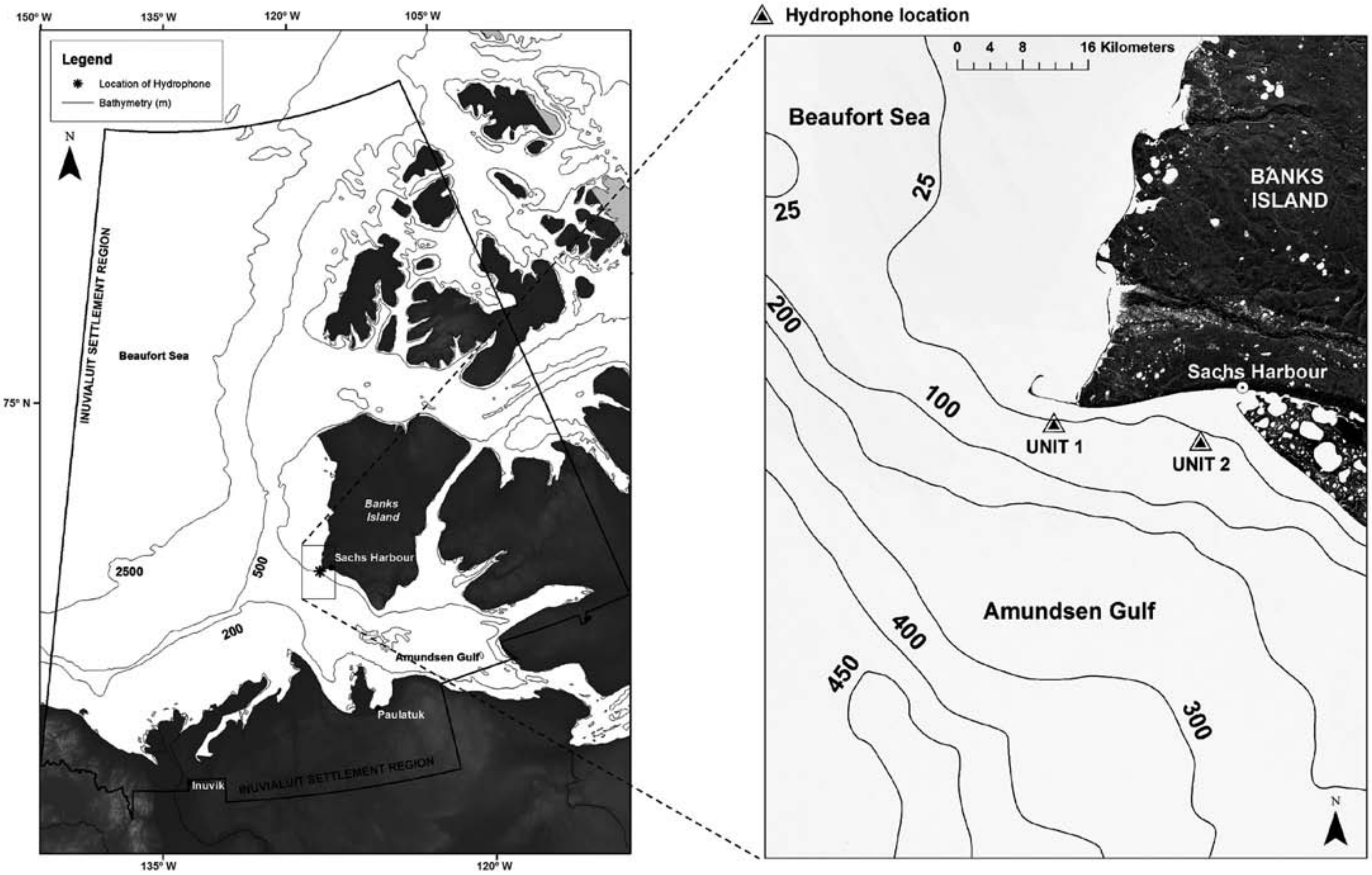

FIG. 1. Location of hydrophones deployed near Sachs Harbour, Northwest Territories, Canada. Unit 1 was deployed from 18 May to 22 August 2015, and Unit 2, from 20 August 2015 to 8 July 2016.

We deployed two recorders west of Sachs Harbour, Northwest Territories, Canada (Unit 1, 22 km W of Sachs Harbour: 71˚56.373′ N, 125˚54.622′ W; Unit 2, 8 km SW of Sachs Harbour: 71˚55.621′ N, 125˚23.447′ W; Fig. 1) for two different deployment periods. Unit 1, deployed from 18 May to 22 August 2015, was anchored at a depth of 23.5 m (water depth = 26.5 m) with the recorder set to record continuously with a 16-bit resolution, a 32 kHz sampling rate, and +12 dB of gain. Unit 2, deployed from 20 August 2015 to 8 July 2016, was anchored at a depth of 23.5 m (water depth = 28.5 m), with a duty cycle of 5 min recording followed by 30 minutes off, with a 16-bit resolution, a 48 kHz sampling rate, and +18 dB of gain. Both units were deployed by attaching the unit to an anchor using 3 – 5 m of 9 mm rope with soft connections (i.e., no metal on metal) in order to minimize noise; the positively buoyant unit then floated above the anchor. Because the line securing the unit was short, soft, and not very taut (very little pull from marginal positive buoyancy and minimal current), no "strumming" noise (often associated with oceanographic moorings) was experienced (e.g., Kinda et al., 2013). We occasionally found "bump" noises in the recordings, which were likely caused by fish hitting our recorder. However, these noise events were rare and would have little effect on overall noise levels.

Sound Processing

We processed all recordings using PAMGuide software in Matlab (Merchant et al., 2015) to describe the existing underwater soundscape quantitatively. We measured power spectral densities (PSDs) between 10 Hz and 16 kHz based on one-minute averages of the data computed from fast Fourier transforms (FFTs) using a Hanning window of 1 s of data in 1 Hz bins that overlapped by 0.5 s (120 averages/min). We used exceedance percentiles to quantify the distribution of recorded sound levels. From these PSDs, we calculated in-band SPLs.

Throughout the majority of our recordings, levels below 50 Hz had very little variation and were very close to the noise floor of the units. Above 1000 Hz, all recordings had many spikes in sound level caused by electronic self-noise from the units. We therefore restricted all analyses to levels between 50 and 1000 Hz to avoid confusing self-noise from the units with actual ambient noise.

Seasonal Patterns

We examined hourly averages of in-band SPLs at 50 – 1000 Hz by month, season, and throughout the day. These averages were based on all 60 min of each hour for our first deployment, and normally 10 min of each hour for our second deployment (because of duty cycling). We define the seasons as in Clark et al. (2015): spring is from 1 April to 31 July, summer-fall is from 1 August to 30 November, and winter is from 1 December to 31 March. We split hourly levels into quarter days (0000 to 0600, 0600 to 1200, 1200 to 1800, and 1800 to 2400) for diurnal level comparisons. We compared levels by month, season, and time of day using analysis of variance in R version 3.3.0 (package: stats; function: aov; R Core Team, 2016). We specifically built models with each factor (month, season, and time of day) on its own, as well as models with main effects for month + time of day and season + time of day. We also included the deployment (first or second unit) as a factor in all models to control for differences between the deployment locations and the timing of deployments. We compared models using Akaike's information criterion (package: stats; functions: AIC), and selected the model with the lowest AIC value as the best model. We examined differences between factor levels for the best model using a post-hoc Tukey's Honest Significant Difference test (package: stats; function: TukeyHSD). We assessed all assumptions for the analysis (e.g., normality of distribution, homoscedasticity of variance), and models met all assumptions.

We examined median PSD levels in each month using analysis of covariance in R (package: stats; function: lm). We used month rather than season because month explained more variance in the previous analysis. We used a $\log_{10}$ transformation on the frequency data for this analysis. We also visually compared PSD exceedance percentiles to curves by Wenz (1962), which describe the PSD levels of marine ambient sound from weather, wind, geologic activity, and commercial shipping.

Effects of Wind and Ice

We examined the effect of wind and ice concentration on ambient noise levels. First, we obtained hourly wind speed data at Sachs Harbour for each hour between 18 May 2015 and 8 July 2016 from Environment Canada's Historic Climate Database (Environment Canada, 2016). We then used remote sensing data on daily sea ice concentrations above our recorders throughout the study. Specifically, we used sea ice concentration data derived from the Advanced Microwave Scanning Radiometer 2 (AMSR2) instrument onboard the Japan Aerospace Exploration Agency's GCOM-W satellite, which we 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 above each recorder for each day of their deployment. We also extracted daily sea ice concentrations at multiple scales (width = 18.75, 31.25, and 106.25 km; area = 351.56, 976.56, and 11 289.06 km^2) centered directly above the recorder locations, while masking out land areas, in order to capture ice dynamics at multiple scales around the recorder. Given that sound can be propagated over great distances in water, we wanted to identify an appropriate scale at which ice concentration most affects noise levels.

We conducted linear regression on hourly median SPLs at 250 Hz and on in-band median SPLs at 50 – 1000 Hz. We examined 250 Hz in order to compare our results with patterns from other studies that specifically examined the effect of wind speed on noise levels at 250 Hz (Ross, 1976; McDonald et al., 2006; Roth et al., 2012). For each regression, we included hourly wind speed, daily ice concentration, and their interaction as independent variables. Finally, we created four different models for each analysis and included the different scales used for ice concentration in each model. We compared models using AIC.

RESULTS

Seasonal Patterns

Sound pressure levels were lower in January through April than in all other months. SPLs were highest between May and October and were intermediate in November and December (Fig. 2). Levels recorded in January through March, and possibly also in April, seemed to bottom out at the noise floor of the units (SPL = 70.68 dB re 1 μPa in the 50 – 1000 Hz band), so although levels from these months were already significantly lower than in all other months, the levels that we recorded might actually be higher than the true SPLs. Levels recorded from Unit 1 (deployed May to August 2015) were higher than those recorded from Unit 2 (deployed August 2015 to July 2016). The models containing month as a variable were better than models with season or time of day for each in-band comparison according to AIC (Fig. 2; online Appendix 1: Table S1).

Median PSD increased between 50 and 1000 Hz in May, July, August, September, and October of 2015, and also in May and June of 2016. In all other months, median PSD decreased between 50 and 1000 Hz. Generally, in the noisier months (May to October), median PSD was between 53 and 63 dB re 1 μPa^2/Hz at 50 Hz and increased to between 60 and 70 dB re 1 μPa^2/Hz at 1000 Hz. June 2015 was an outlier in this analysis because levels were higher at 50 Hz (73 dB re 1 μPa^2/Hz) than at 1000 Hz (68 dB re 1 μPa^2/Hz). Levels in July 2016 were also lower than expected, with median PSD at 57 dB re 1 μPa^2/Hz at 50 Hz and 46 dB re 1 μPa^2/Hz at 1000 Hz. In the quietest months (November to April), median PSD was between 48 and 56 dB re 1 μPa^2/Hz at 50 Hz, and decreased to between 37 and 43 dB re 1 μPa^2/Hz at 1000 Hz. In the noisier months, levels were mostly centered within the Wenz curves, whereas in the quieter months, levels were much closer to the lower levels suggested by Wenz (Figs. 3, 4). Levels in January through March were skewed towards the lower edge of the Wenz curves, which suggests that levels in those

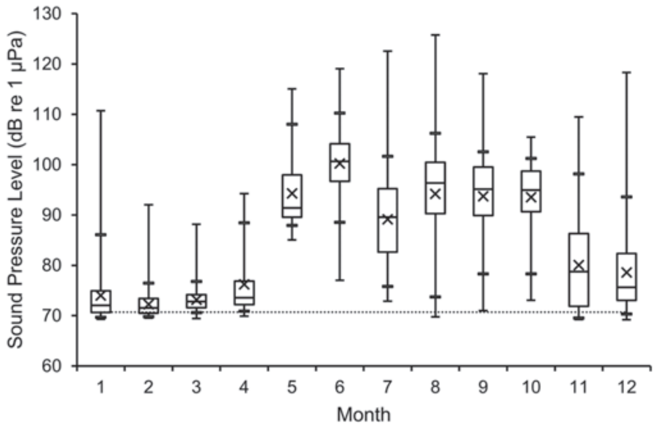

FIG. 2. Sound pressure levels by month between 50 and 1000 Hz for hydrophones recording from May 2015 to July 2016 near Sachs Harbour, Northwest Territories. The line within the boxes is the median value, the box represents the 25% and 75% exceedance levels, whiskers represent the minimum and maximum SPLs, and dark lines on the whiskers represent 5% and 95% exceedance levels. The "x" within the box represents the linear mean value. The dotted horizontal line spanning all months at 71 dB re 1 μPa is the noise floor of the recorders, which significantly overlaps with the values for January through March.

months were limited by the noise floor of the recorders rather than by ambient noise levels. Self-noise created by the recorders (i.e., electronic noise) is apparent on most PSD plots (Figs. 3, 4), but is most evident in the winter months, when ambient noise is lowest. Self-noise shows up on these plots as major peaks in PSD at 43, 131, 375, and 750 Hz. In noisier months, such as September (Fig. 4), this self-noise is mostly masked by actual ambient noise, except at the lowest exceedance percentile.

Effects of Wind and Ice

Wind speed, ice concentration, and their interaction had significant effects on SPLs at 50–1000 Hz and at 250 Hz, and accounted for a large proportion of the variance in SPL ($R^2 = 0.66$ at 50–1000 Hz, $R^2 = 0.65$ at 250 Hz). The 106.25 km scale for ice concentration had the largest effect on SPL both across the 50–1000 Hz band and at 250 Hz (online Appendix 1: Tables S2 and S3). An increase in wind speed led to increased SPLs, an increase in ice concentration led to a decrease in SPL, and increased ice concentration also dampened the effect of increased wind speed (Table 1).

DISCUSSION

Ocean ambient noise near Sachs Harbour generally followed expected trends in ambient noise levels. Levels varied between months and seasons; these differences were due to the effects of wind speed and ice concentration, which both varied between months. Ambient noise was lower than the noise floor of our recorders below 50 Hz in all months, with very little variance compared to higher frequencies. For this reason, we were unable to analyze these lower frequencies. This pattern is likely due to the shallow depth of our deployment locations (water depth = 26.5 and 28.5 m), since low frequencies do not propagate effectively in shallow waters (Au and Hastings, 2008). The sandy silt sediment at our site has a cut-off frequency of roughly 50 Hz at the depth of our recorders (Au and Hastings, 2008), which means that sound at frequencies below 50 Hz will not propagate effectively at this depth. These shallow water effects make it difficult to compare our results for frequencies below 50 Hz with results from deeper water. The patterns in ocean ambient noise that we documented are comparable to patterns from another study done in Amundsen Gulf, roughly 100 km south of our study area (Kinda et al., 2013). That study recorded ambient noise under ice at a depth of 50 m from November 2005 to June 2006 and found that median PSD at 50 Hz was 65 dB re 1 μPa^2/Hz, and decreased to 55 dB by 1 kHz. This trend is similar to the pattern that we documented, except that our data were 5 to 15 dB lower throughout the frequency range, and patterns in May and June were 5 to 10 dB higher from 100 to 1000 Hz. Patterns in PSD were very different at the site of the next closest study (Roth et al., 2012). In this study, which was conducted in the Chukchi Sea north of Barrow, Alaska, median PSD started much higher (85–95 dB), but steadily decreased to ~50 dB by 1 kHz. However, Roth et al. (2012) anchored their hydrophone at a depth of 235 m, which is much deeper than our hydrophone at 23.5 m. The same study also documented the effect on ambient noise levels of air gun surveys, which typically increased levels in the 10 to 100 Hz range during the open-water season and likely contributed to the increased levels that Roth et al. (2012) found at lower frequencies (but not to those found by our study or by Kinda et al., 2013). In comparison, ambient noise levels at our site in the Arctic were much lower than those in southern latitudes. For example, at a shallow site near Oregon, PSDs were between 75 and 80 dB from 10 to 840 Hz (Haxel et al., 2013), whereas median PSD in this frequency range at our site was typically below 70 dB and reached 73 dB only in June 2015.

We found that month was a better predictor of ambient noise levels than season and that time of day had little effect on noise levels. Although some obvious seasonal trends appeared (i.e., quieter SPLs in winter, high SPLs in summer), there was variability from month to month that season alone did not account for. For example, spring included March through July, yet ice break-up occurs primarily in June, and varying concentrations of ice are moving (which makes a lot of noise) throughout the rest of the spring and summer. The lack of diel patterns in noise levels might be caused by the relatively weak effect of solar radiation in the Arctic, or even by weaker tides. Winter months, for example, have 24 h of darkness, whereas summer months have 24 h of light. It is likely that temperatures rarely get warm enough to cause thermal winds, and other factors causing noise would not necessarily change throughout the day.

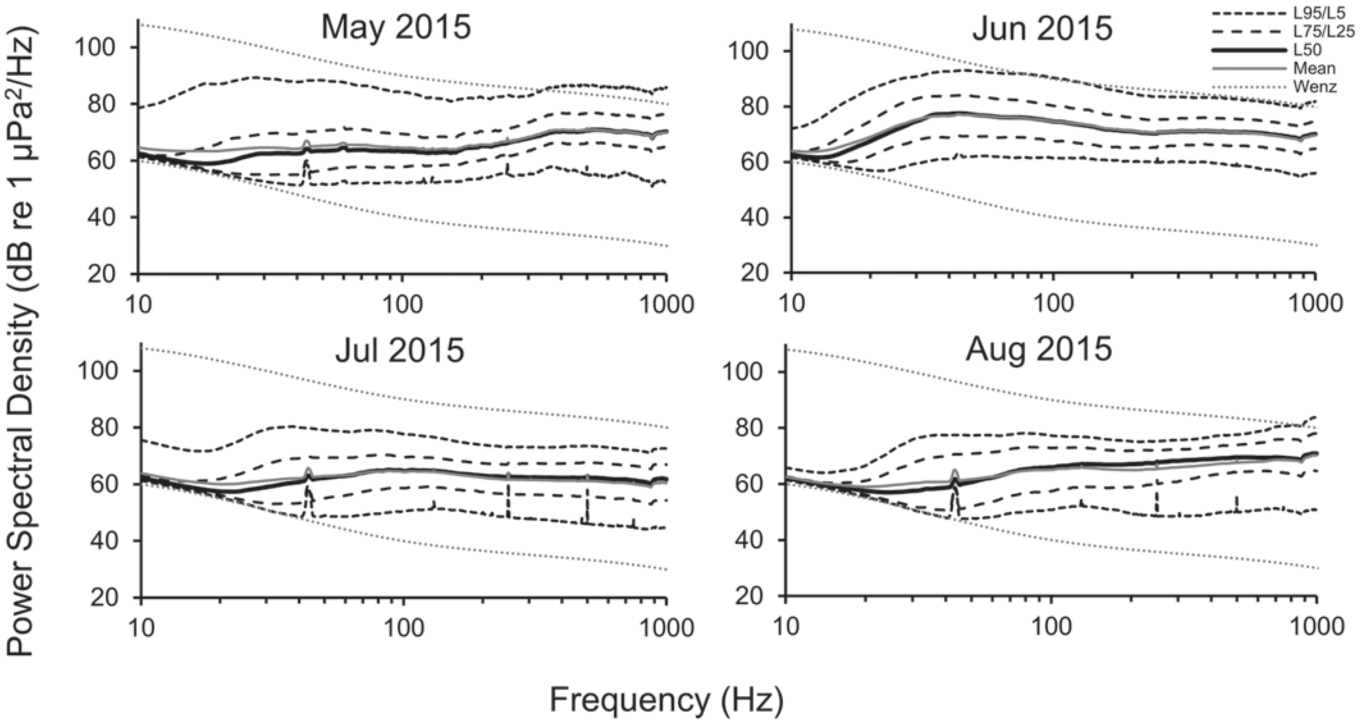

FIG. 3. Power spectral density by month for the Unit 1 hydrophone, which recorded continuously from 18 May to 22 August 2015 near Sachs Harbour, Northwest Territories. The panels represent successive months during the recording period. Dotted gray lines are adapted from Wenz (1962) and represent a range of normal levels caused by wind. Analyses focused on frequencies of 50 – 1000 Hz.

Wind is known to be a major contributing factor to ocean ambient noise levels (Wenz, 1962; Ross, 1976; McDonald et al., 2006; Roth et al., 2012), and our results confirm that wind had a strong effect on the noise levels that we detected, although its impact was strongly modulated by ice conditions. The effect of wind and its resulting wave action on sound levels ranged from 0.40 to 0.43 dB re 1 μPa/km/h in our study and was similar at 50 – 1000 Hz and at 250 Hz (Table 1). Ross (1976) found that the relationship between SPL at 250 Hz and wind speed was 0.23 dB re 1 μPa/km/h, whereas McDonald et al. (2006) found that the effect of wind speed was lower when wind speed was below 20 km/h (0.18 dB/km/h) and much higher when wind speed was above 20 km/h (0.56 dB/km/h). In our study, the mean effect of wind at 250 Hz was 0.43 dB re 1 μPa/km/h (Table 1), which is near the upper end of the values from McDonald et al. (2006). Finally, Roth et al. (2012) found that the effect of wind speed on sound levels was 0.14 and 0.28 dB re 1 μPa/km/h for times of high and low ice concentration, respectively. These levels are much lower than those that we report in this study. However, when we take the interaction term for ice concentration and wind speed into account, the effect of wind speed on SPLs could be as low as 0.14 dB re 1 μPa/km/h at 100% ice concentration, which is identical to the lower value presented by Roth et al. (2012).

Ice is a unique factor affecting noise in the Arctic, and our study demonstrated a strong effect of ice concentration on ambient noise levels. Roth et al. (2012) found a significant interaction between wind speed and ice concentration at 250 Hz, where wind speed had a greater effect (steeper slope, high intercept) on SPLs when ice cover was between 0% and 25% and a much smaller effect (lower intercept, shallower slope) when ice cover was between 75% and 100%. Our results confirm that increased ice concentration generally dampens the effect of wind.

We also found that the scale used to examine ice concentration has important implications for ambient noise. The largest scale that we examined (106.25 km) was most important to noise levels both at 50 – 1000 Hz and at 250 Hz. Ice events (cracking, colliding pack ice) that occurred farther away could still affect noise levels at lower frequencies than we examined in this study. Future work could track these ice events in order to examine their impact on ambient noise levels and specifically examine the distances over which these events propagate.

Implications for Marine Mammals

Ocean ambient noise is a crucial habitat feature for marine mammals because it represents the noise threshold below which their vocalizations will be masked (Erbe and Farmer, 2000). As a result, it directly determines a vocalizing animal's acoustically active space (Clark et al., 2009; Hatch et al., 2012) or the effective distance at which an animal can passively monitor the surrounding acoustic environment. The importance of an animal's active space, in turn, is largely determined by the importance of acoustic communication for basic survival functions such as foraging, mating, and predator detection.

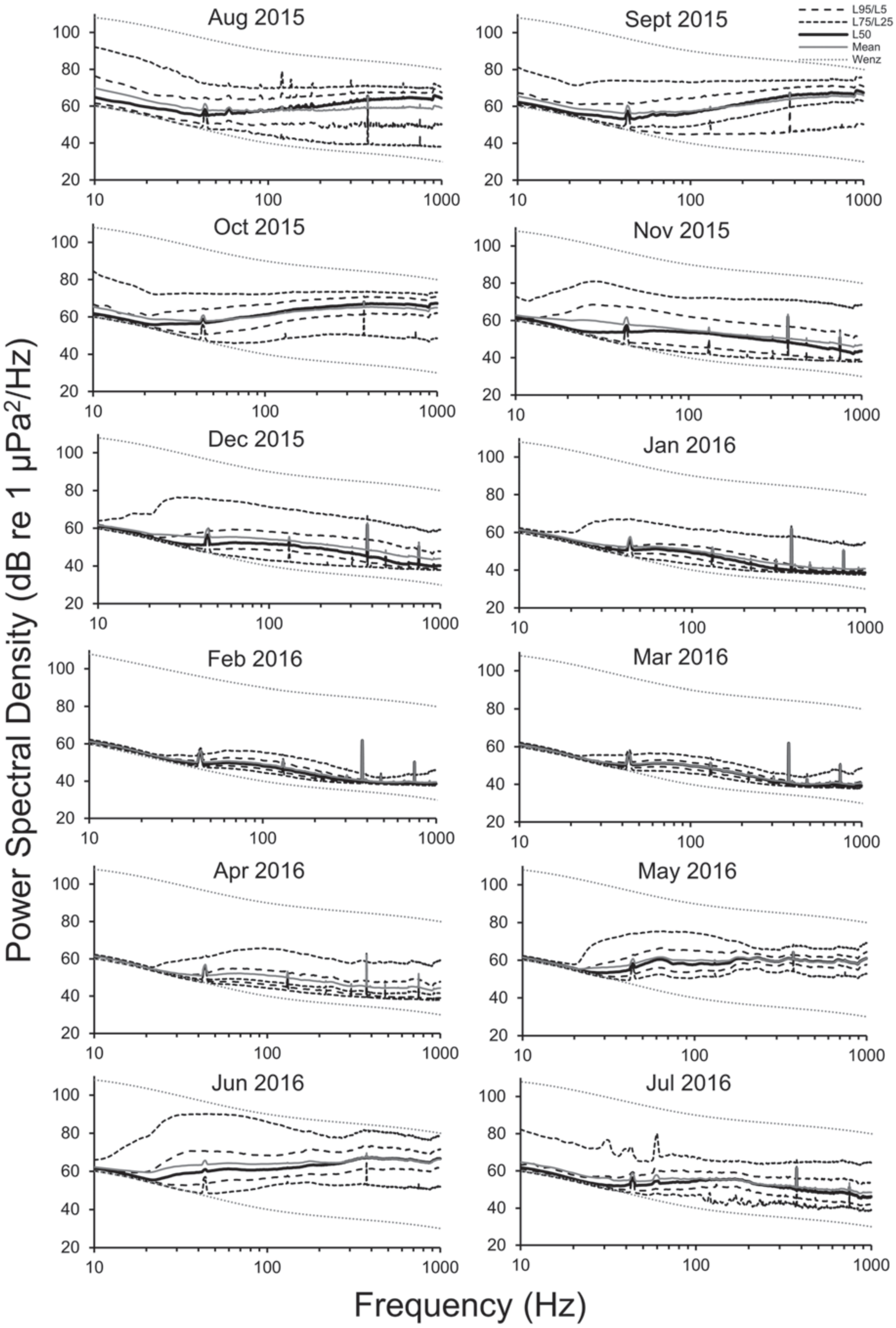

FIG. 4. Power spectral density by month for the Unit 2 hydrophone, which recorded on a 5 min on, 30 min off duty cycle from 19 August 2015 to 8 July 2016 near Sachs Harbour, Northwest Territories. Details as in Figure 3.

TABLE 1. Effect size and standard error for linear regression of wind speed (dB re 1 μPa/km/hour), ice concentration (dB re 1 μPa/concentration), and their interaction on sound pressure levels at 50–1000 Hz and at 250 Hz. Note that ice concentration was calculated at a scale of 106.25 km for both 50–1000 Hz and 250 Hz.

	50–1000 Hz	250 Hz
Wind speed	0.40 ± 0.01	0.43 ± 0.01
Ice concentration	−0.16 ± 0.003	−0.13 ± 0.003
Interaction	−0.003 ± 0.0002	−0.003 ± 0.0001

Our study region has four main marine mammal species that are vocally active underwater: bowhead whales (*Balaena mysticetus*), beluga whales (*Delphinapterus leucas*), bearded seals (*Erignathus barbatus*), and ringed seals (*Pusa hispida*). Bowhead whales vocalize at lower frequencies than the other marine mammals at our site (50 to 600 Hz; Clark et al., 1996), although some studies have reported bowhead vocalizations as high as 3 kHz (Delarue et al., 2009; Tervo et al., 2012). Beluga calls typically cover a much wider frequency spectrum (2 to 12 kHz) and are more variable (Sjare and Smith, 1986). Bearded seal vocalizations are typically between 100 Hz and 4 kHz (Cleator et al., 1989), and ringed seal vocalizations are typically between 100 Hz and 1 kHz (Jones et al., 2014), although Stirling et al. (1983) recorded ringed seal calls up to 6 kHz. Our site near Sachs Harbour was fairly quiet compared to most marine environments, and these low ambient sound levels would potentially allow for very effective acoustic communication among marine mammals. Given the relatively quiet marine soundscape, however, Arctic marine mammals may be more susceptible to adverse effects of anthropogenic underwater noises (although there is no direct evidence to support this possibility). Shipping traffic generally increases noise levels in the 10–1000 Hz range, which would overlap with the range of vocalization for all these species except beluga whales and would completely overlap the bowhead whale vocalizations (Moore et al., 2012). This impact could be important since bowhead whales are currently listed as of special concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2009).

Anthropogenic noise is likely to increase in the near future as the ice-free season lengthens in the Arctic, enabling activities such as shipping through the Northwest Passage. In 2016, the first major cruise liner attempted to transit the Northwest Passage (Migdal, 2016), a clear indication of increased ship traffic in Amundsen Gulf and throughout the Canadian Arctic. It is therefore imperative to understand the relationship between ocean ambient noise and Arctic marine mammals in order to predict and avoid negative impacts on these species.

As sea ice decreases, the effect of wind on ambient noise levels is expected to increase while the dampening and quieting effect of sea ice is expected to decrease. The result will likely be a net increase in ambient noise levels. Such an increase will be additional to any increase resulting from anthropogenic factors such as shipping and may in itself impact acoustically sensitive marine animals. Acoustic baselines in the Arctic are important to understand this process.

Our study provides a useful baseline for noise levels in the eastern Beaufort Sea before the anticipated increase in commercial ship traffic. We need to establish other comparable baselines elsewhere in the Arctic and continue monitoring baseline areas into the future in order to capture changes in ambient noise levels.

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APPENDIX 1

The following tables are available in a supplementary file to the online version of this article at:
https://arctic.journalhosting.ucalgary.ca/arctic/index.php/arctic/rt/suppFiles/4662/0

TABLE S1. Model selection (above) and final model output (below) for models examining patterns in sound pressure level (SPL) at 50–1000 Hz recorded by hydrophones near Sachs Harbour, Northwest Territories, during May 2015–July 2016.

TABLE S2. Model selection (above) and final model output (below) for models examining patterns in sound pressure level (SPL) × wind speed and ice concentration between 50 and 1000 Hz recorded by hydrophones near Sachs Harbour, Northwest Territories, during May 2015–July 2016.

TABLE S3. Model selection (above) and final model output (below) for models examining patterns in sound pressure level (SPL) × wind speed and ice concentration at 250 Hz recorded by hydrophones near Sachs Harbour, Northwest Territories, during May 2015–July 2016.

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