



The summer soundscape of a shallow-water estuary used by beluga whales in the western Canadian Arctic¹

William D. Halliday, Kevin Scharffenberg, Dustin Whalen, Shannon A. MacPhee, Lisa L. Loseto, and Stephen J. Insley

Abstract: The soundscape is an important habitat component for marine animals. In the Arctic, marine conditions are changing rapidly due to sea ice loss and increased anthropogenic activities such as shipping, which will influence the soundscape. Here, we assess the contributors to the summer soundscape in the shallow waters of the Mackenzie River estuary within the Tarium Niryutait Marine Protected Area in the western Canadian Arctic, a core summering habitat for beluga whales (*Delphinapterus leucas* Pallas, 1776). We collected passive acoustic data during the summer over four years, and assessed the influence of physical variables, beluga whale vocalizations, and boat noise on sound pressure levels in three frequency bands (low: 0.2–1 kHz; medium: 1–10 kHz; high: 10–48 kHz) to quantify the soundscape. Wind speed, wave height, beluga vocalizations, and boat noise were all large contributors to the soundscape in various frequency bands. The soundscape varied to a lesser degree between sites, time of day, and with tide height, but remained relatively constant between years. This study is the first detailed description of a shallow summer soundscape in the western Canadian Arctic, an important habitat for beluga whales, and can be used as a baseline to monitor future changes during this season.

Key words: ambient sound levels, Delphinapterus leucas, passive acoustic monitoring, vocalizations.

Résumé : Le paysage sonore est un élément important de l'habitat des animaux marins. Dans l'Arctique, les conditions marines changent rapidement en raison de la perte de glace de mer et de l'augmentation des activités anthropiques comme la navigation, ce qui aura une incidence sur le paysage sonore. Nous évaluons ici les facteurs qui contribuent au paysage sonore estival dans les eaux peu profondes de l'estuaire du fleuve Mackenzie, dans l'aire marine protégée de Tarium Niryutait, dans l'ouest de l'Arctique canadien, un habitat d'été central pour les bélugas (*Delphinapterus leucas* Pallas, 1776). Nous avons recueilli des données acoustiques passives pendant l'été sur une période de quatre ans et évalué

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l'incidence des variables physiques, de la vocalisation des bélugas et du bruit des embarcations sur les niveaux de pression acoustique dans trois bandes de fréquence (basse : 0,2–1 kHz; moyenne : 1–10 kHz; haute : 10–48 kHz) pour quantifier le paysage sonore. La vitesse du vent, la hauteur des vagues, les vocalisations des bélugas et le bruit des bateaux ont tous grandement contribué au paysage sonore dans diverses bandes de fréquences. Le paysage sonore variait dans une moindre mesure entre les sites, le moment de la journée et la hauteur de la marée, mais il restait relativement constant d'une année à l'autre. Cette étude est la première description détaillée d'un paysage sonore estival en eau peu profonde dans l'ouest de l'Arctique canadien, un habitat important pour les bélugas, et elle peut servir de référence pour surveiller les changements futurs au cours de la saison. [Traduit par la Rédaction]

Mots-clés : niveaux sonores ambiants, *Delphinapterus leucas*, surveillance acoustique passive, vocalisations.

Introduction

The underwater soundscape is a key habitat feature for marine mammals and many other marine animals (e.g., Ellison et al. 2012; Williams et al. 2014; Clark et al. 2015). Marine mammals rely on the underwater acoustic environment for a variety of life functions, including basic communication, mating, finding food, and avoiding predators (Richardson et al. 1995). The soundscape is shaped by three main categories of sound: the geophony (natural physical processes that create sound), the biophony (sounds made by living organisms), and the anthropophony (sounds made by anthropogenic activities) (Pijanowski et al. 2011). The relative importance of these three soundscape components will vary greatly both spatially and temporally. For example, the biophony will only be a large component of the soundscape if soniferous animals live in that area and actively make sounds (e.g., Ahonen et al. 2017; Halliday et al. 2018b; Pine et al. 2018b). Anthropophony will only influence the soundscape if noisy anthropogenic activities occur in that area (Gervaise et al. 2012; Martin et al. 2017). Although the relative contribution of the geophony will vary among soundscapes, noise from wind and waves will likely be a large contributor to the soundscape at all locations (Wenz 1962; Roth et al. 2012; Insley et al. 2017). The soundscape will also vary greatly between seasons as all three components vary differentially between seasons. For example, in the Arctic, bearded seal (Erignathus barbatus Erxleben, 1777) and bowhead whale (Balaena mysticetus Linnaeus, 1758) vocalizations can be major contributors to the soundscape during their breeding seasons (Clark et al. 2015; Ahonen et al. 2017; Stafford et al. 2018), but bearded seals are generally much less vocal during the summer and autumn (MacIntyre et al. 2013; Jones et al. 2014; Halliday et al. 2018a), and bowhead whales switch from singing during the winter to moaning for the rest of the year (Clark et al. 2015; Ahonen et al. 2017; Halliday et al. 2018a).

Beluga whales (*Delphinapterus leucas* Pallas, 1776) are a wide-spread species of Arctic odontocetes (with a few sub-Arctic populations). Like other odontocetes, they actively use echolocation for navigation and foraging (Lammers and Castellote 2009); however, belugas are an exceptionally vocal species with a very large repertoire of calls (Chmelnitsky and Ferguson 2012; Blevins-Manhard et al. 2016), and are often called the "canaries of the sea". Belugas produce echolocation clicks (Au et al. 1985), a very wide range of whistles and pulsed calls (Chmelnitsky and Ferguson 2012), and also use contact calls to maintain contact between mothers and calves (Vergara et al. 2010; Vergara and Mikus 2019). Belugas rely on acoustics in all aspects of their lives, and therefore the soundscape is a key habitat feature for this species. Throughout the Arctic, belugas have adapted to a complex soundscape. The Arctic is one of the quietest places on earth under solid sea ice (Diachok and Winokur 1974; Roth et al. 2012; Insley et al. 2017), but it can be extremely noisy when ice is forming and breaking

up (Diachok and Winokur 1974; Roth et al. 2012; Kinda et al. 2013, 2015; Insley et al. 2017), during storm events (Roth et al. 2012; Insley et al. 2017), or around calving glaciers (Deane et al. 2014). In contrast to other cetaceans that occur in temperate or tropical latitudes, belugas in the Arctic currently deal with very low levels of anthropogenic noise; however, climate change will likely result in a changing soundscape (Moore et al. 2012). A reduction in sea ice could result in increased ambient sound levels through the loss of the quieting effect of solid sea ice (Stroeve et al. 2007; Markus et al. 2009), and increased access for noisy anthropogenic activities (Stephenson et al. 2011; Reeves et al. 2014; Dawson et al. 2018). Indeed, increases in vessel traffic have already been documented throughout the Arctic (Dawson et al. 2018), and are forecasted to continue increasing (Stephenson et al. 2011), resulting in increased underwater noise (Aulanier et al. 2017; Halliday et al. 2017; Pine et al. 2018a). Given the importance of soundscapes to beluga whales and other Arctic marine animals, it is imperative to understand Arctic soundscapes before they drastically change (Stafford et al. 2018).

In this study, we examine the summer soundscape in the shallow Mackenzie River estuary that is a key aggregating habitat used by belugas in the western Canadian Arctic (Fig. 1). The Eastern Beaufort Sea beluga population spends its summers in the eastern Beaufort Sea and Amundsen Gulf in the western Canadian Arctic, and an important core area used by this population is the Mackenzie River estuary (Norton and Harwood 1986; Loseto et al 2006; Hauser et al. 2014). It is thought that all belugas migrating to this region in the spring stop in the estuary for a period of several days (Richard et al. 2001; Hornby et al. 2016). Once the whales leave the estuary, size and sexual segregation is observed whereby female belugas and calves spend time in shallow ice-free waters, whereas adult males and sub-adults travel much more broadly within the region throughout the summer (Richard et al. 2001; Loseto et al. 2006; Hauser et al. 2014, 2017). In an effort to protect this critical beluga habitat, the Tarium Niryutait Marine Protected Area (TNMPA) was established within the Mackenzie River estuary in 2010 (Fisheries and Oceans Canada and Fisheries Joint Management Committee 2013). Here, we specifically examine the influence of geophony (wind, waves, water depth, and tides), biophony (beluga vocalizations), and anthropophony (boat noise) on ambient sound levels at up to four sites within the TNMPA between 2015 and 2018 to characterize this soundscape. This is the first detailed assessment of the soundscape in this area. An earlier report (Simard et al. 2014) conducted a preliminary assessment of beluga whale vocalizations at this site in 2011 and 2012, with only a cursory assessment of ambient sound levels.

Methods

Acoustic data collection

We deployed acoustic recorders equipped with factory-calibrated ultrasonic hydrophones (Wildlife Acoustics model SM2M, Maynard, Maryland, USA) in Kugmallit Bay at the mouth of the Mackenzie River close to the community of Tuktoyaktuk, Northwest Territories between 2015 and 2018, with between 1 and 4 of these recorders deployed per year (Fig. 1; Table 1). We deployed three of these recorders at the same sites over three years (Channel and Mid Hendrickson from 2015 to 2017, and East Whitefish from 2016 to 2018; Table 1), making up our long-term data sets (see analysis section below). These ultrasonic hydrophones have a flat frequency response around -165 dB re 1 V/µPa between 0.2 and >50 kHz. All moorings were set in relatively shallow waters (1–9 m depth). At all locations except East Whitefish, moorings consisted of a four-post metal frame with the acoustic recording device fixed vertically in the center (using a plastic collar and hose clamps) allowing for the hydrophone to sit 1 m above the seabed. Each mooring was fixed with up to 33 kg of weight and had a 15 m ground line attached to a 14 kg weight, which was **Fig. 1.** Study area map for the Mackenzie River estuary in the western Canadian Arctic, including the location of four acoustic recorders deployed in 2017 and the location of the main pathway for marine navigation. Recorder locations for 2015, 2016, and 2018 were similar to those in 2017. Information for base map was digitized from the Canadian Hydrographic Service chart 766301 Beaufort Sea Kugmallit Bay (1:150 000 scale). This map was created in ArcGIS 10.1. Permission is not required to use the information from the chart as presented here. The map inset was made with Natural Earth. Free vector and raster map data at naturalearthdata.com.



attached to a buoy at the surface. At the East Whitefish site where depth was 1 m, the acoustic recorder was attached horizontally to a metal plate using two plastic collars and no surface buoy, and the hydrophone was 0.3 m above the seabed. Recorders were either set at a lower sampling rate (96 kHz) with a higher duty cycle (recording 15 min every half hour), or a higher sampling rate (384 kHz) with a lower duty cycle (recording 15 min every hour; Table 1). Gain was set to 16.5 dB on all recorders. All recorders were set with a high pass filter at 180 Hz to target beluga vocalizations, and because lower frequency sounds do not effectively propagate at the shallow depths where these recorders were placed, and all sounds recorded in these lower frequencies would likely be from sources very close to the recorder, possibly from the mooring itself (Simard et al. 2014). All moorings were deployed in June and recovered in August of each year. Other oceanographic instruments were also included on the moorings (Table 1): all moorings had either a conductivity, temperature, and depth (CTD) logger (RBR concerto CTD: 5 s sample period; RBR Ltd., Ottawa, Ontario, Canada) or a time depth recorder (TDR) (TDR-2050: 5 s sample period; RBR Ltd., Ottawa, Ontario, Canada); some moorings also had a wave recorder (RBR virtuoso D|wave: 6 Hz burst rate, 512 burst length, 5 min burst sample period; RBR Ltd., Ottawa, Ontario,

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| Location | Latitude (°N) | Longitude (°W) | Depth (m) | Sensitivity (dB re 1 vµ/µPa mA) | Sample rate (kHz) | Gain (dB) | Duty cycle (min on/off) | Days recording | Instruments | |
|------------------|------------------|-------------------|--------------|------------------------------------|----------------------|--------------|----------------------------|-------------------|-------------|--|
| 2015 | | | | | | | | | | |
| Channel | 69.3940 | 133.8674 | 9 | -164.4 | 96 | 16.5 | 15/15 | 31 | Т | |
| Mid Hendrickson | 69.4465 | 133.6123 | 2.5 | -165.2 | 96 | 16.5 | 15/15 | 67 | С | |
| 2016 | | | | | | | | | | |
| Channel | 69.3981 | 133.8560 | 9.1 | -165.1 | 96 | 16.5 | 15/15 | 60 | Т | |
| East Whitefish | 69.3804 | 133.6344 | 1.4 | -164.1 | 384 | 16.5 | 15/45 | 71 | T, W | |
| Mid Hendrickson | 69.4591 | 133.5650 | 2.5 | -165.2 | 96 | 16.5 | 15/15 | 60 | C, W | |
| 2017 | | | | | | | | | | |
| Channel | 69.3947 | 133.8620 | 8 | -165.1 | 96 | 16.5 | 15/15 | 62 | Т | |
| East Whitefish | 69.3804 | 133.6344 | 1 | -164.1 | 384 | 16.5 | 15/45 | 63 | Т | |
| Mid Hendrickson | 69.4448 | 133.6113 | 1.6 | -164.2 | 384 | 16.5 | 15/45 | 63 | С | |
| West Hendrickson | 69.5077 | 133.6980 | 1.6 | -165.2 | 96 | 16.5 | 15/15 | 54 | A, C, W | |
| 2018 | | | | | | | | | | |
| East Whitefish | 69.3804 | 133.6344 | 1.4 | -164.1 | 384 | 16.5 | 15/45 | 50 | Т | |

Note: A, acoustic Doppler current profiler; C, conductivity, temperature, and depth recorder; T, time-depth recorder; W, wave height recorders.

Canada) and an acoustic Doppler current profiler (ADCP) (Aquadopp Profiler 2 MHz, Nortek, USA). The oceanographic instruments were attached to the four posts of the mooring frame using electrical tape and hose clamps. The upward-looking ADCP was placed at the base of the metal frame in a secure bracket extending out over the side of the frame to ensure an unobstructed view of the water column that did not overlap with the hydrophone. None of these instruments created acoustic signals that were recorded by the acoustic recorders.

Processing acoustic data

We processed all acoustic data using the PAMGuide package (Merchant et al. 2015) in Matlab (version R2016b). For each recorder, we calculated the average (root mean squared) sound pressure level (SPL) for each file (15 min) in three bandwidths: low (200–1000 Hz), medium (1–10 kHz), and high (10–48 kHz). Data were processed using a Hann window with averages taken every second with a 50% overlap. We did not examine any frequencies below 200 Hz because the high pass filter cut-off was set to 180 Hz on each recorder. We similarly did not examine data above 48 kHz because this was the upper limit for the data recorded by many of the four recorders (Table 1).

All files were visually and aurally examined for the presence of beluga whale vocal activity, including whistles, contact calls, and echolocation clicks, as well as for the presence of boat noise by a single analyst for all data sets, except for East Whitefish 2018, which was analyzed by a second analyst. The second analyst first trained on the earlier data sets to ensure that results were identical to those of the first analyst before analyzing the final data set. Spectrograms were made using the software Raven (version 1.5; Cornell Lab of Ornithology), with a 512 or 2048-point (for files with a 96 or 384 kHz sample rate respectively) Hann window (3 dB bandwidth = 270 Hz), with 50% overlap, and a 1024 or 4096-point discrete Fourier transform (for files with a 96 or 384 kHz sample rate respectively), yielding time and frequency measurement precision of 2.67 ms and 93.8 Hz. Files were examined in the 200 Hz to 48 kHz range, 1 min at a time until a beluga vocalization and boat noise was identified (or vocalizations and boat noise were determined to be absent) within each file. For files with a 384 kHz sample rate, we also examined data above 48 kHz to assess if we missed any beluga vocalizations, particularly echolocation clicks, by focusing on data below 48 kHz, and found that assessing data between 200 Hz and 48 kHz was sufficient for detecting the presence of beluga vocalizations within the 15 min files.

Statistical analyses

We examined the influence of geophony (weather data and oceanographic parameters), biophony (presence of beluga vocalizations), and anthropophony (presence of boat noise) on SPL. We only examined the first 15 min file per hour for the recorders that recorded two files per hour to have a similar sample size to the recorders that had a lower duty cycle. All recorders were paired with an oceanographic device that recorded depth (either CTD or TDR), and with these data, we were able to measure the absolute depth of the recorder, the relative depth of the recorder, and the change in depth (due to tidal cycles). We used relative depth rather than absolute depth in the statistical analyses to standardize this variable across all recorders; absolute depth is strongly biased by the different sites because the four sites were at different water depths (see Table 1 for recorder depths). Change in depth allowed us to examine the directionality of tidal flows. One recorder from 2017 also had a wave logger and an ADCP to measure wave height and current speed, respectively. Hourly wind speed measurements were downloaded from the Environment and Climate Change Canada weather station at the Tuktoyaktuk Airport (Environment and Climate Change Canada 2018), roughly 30 km east of the recorders. Wind speed is considered to be a very important predictor of ambient sound levels (Wenz 1962), mainly due to the associated increase in wave size with increased wind speed. We, therefore, expect that wave height will be a stronger predictor of SPL than wind speed, but that wind speed and wave height will have a strong, positive correlation. As wave height data were not available for all recorders, we used wind speed as a proxy for wave height for our analysis of the 2017 data set and long-term data sets (see below). Current speed is often correlated with flow noise over the hydrophone, which is an artificial source of noise not associated with ambient sound levels (Haxel et al. 2013). We examined the influence of current speed on SPL to determine if there was significant flow noise created by current. We used linear models in R (package: stats; function: lm; R Core Team 2016) to examine the relationship between SPL in each frequency bandwidth and both wave height and current speed for the single recorder in 2017 that measured both wave height and current speed.

After we examined the influence of wave height and current speed on SPL at one recorder in 2017, as well as the relationship between wave height and wind speed, we then analyzed the full 2017 data set from all four recorders, including wind speed, relative depth and change in depth, and the presence of beluga vocalizations (all call types pooled together) and boat noise as independent variables. We included the interaction term between wind speed and both presence of beluga vocalizations and boat noise because these are the three main sources of strong signals in our data set, and both beluga vocalizations and boat noise could be affected by increased ambient sound levels, which are driven by increased wind speed. We also included site and time of day (categorized as quarters of the day: quarter 1 = 0000 to 0559, quarter 2 = 0600 to 1159, quarter 3 = 1200 to 1759, and quarter 4 = 1800 to 2359) as independent variables. We used Akaike's information criterion (AIC; package = stats; function = AIC) for model selection, and considered the model with the lowest AIC to be the best model, and models within 2 AIC units to be competing models.

We also conducted an analysis of all three of our long-term data sets (Channel, East Whitefish, and Mid Hendrickson), each of which recorded at the same location over three separate summers. Similar to the previous analysis, we included wind speed, presence of beluga vocalizations and boat noise, site, year, and the interactions between wind speed and the presence of beluga vocalizations and boat noise.

Results

General patterns in acoustic data and acoustic indicators

Beluga vocalizations were detected on all recorders in all years (Fig. 2), and the majority of vocalizations were in July, although there was high variability between recorders, with a minimum of 24 and a maximum of 1083 files with vocalizations present for a single recorder within a summer. Boat noise was very rare throughout the data set, with the highest occurrence at the East Whitefish and Mid Hendrickson sites (Fig. 2), with a minimum of 0 and a maximum of 74 files with boat noise present for a single recorder within a summer. Sound pressure level varied widely, both within and between recorders (Fig. 2), depending on weather, beluga activity, and boat noise (see below).

The acoustic occurrence of belugas or boat noise can also be a useful indicator for the managers of the MPA, and we present these acoustic indicators here in Table 2. The earliest date that belugas were recorded in the MPA was 16 June 2015, and latest date that belugas were recorded in the MPA was 19 August 2018. Belugas were detected a maximum of 58 days in the MPA during the summer of 2015. The earliest date that boats were detected in the MPA was 22 June 2017, and the latest date was 19 August 2018. Boats were detected over a maximum of 39 days in the MPA during the summer of 2017. Note that some boat noise is missed with this analysis because a boat was used to both deploy and recover these acoustic recorders, and those boats were not recorded in the acoustic data. Also, both belugas and boats may have gone through the MPA earlier and later than the acoustic recording periods.

Fig. 2. Daily patterns in detections of beluga whales (*Delphinapterus leucas*; blue bars) and boat noise (orange bars), as well as daily mean (root mean squared; RMS) sound pressure level (SPL; black line) for each acoustic recorder deployed during the summer at up to four sites between 2015 and 2018 in the Mackenzie River estuary. The y-axis on the left is the number of files per day with either beluga vocalizations or boat noise present, up to a maximum of 24 files per day. The y-axis on the right is the daily mean SPL between 200 Hz and 48 kHz (dB re 1 μ Pa). Days within a year that do not have data for SPL are days when the acoustic recorder was not deployed.



Assessing wave height and current speed

Wave height had a strong, positive relationship with wind speed at the one site where we recorded wave height (intercept = -0.02 ± 0.003 , $t_{1213} = 5.90$, p < 0.01; slope = 0.007 ± 0.0002 , $t_{1213} = 43.30$, p < 0.01; $R^2 = 0.61$; Fig. 3C). Wave height had a strong, positive relationship with SPL in the low frequency (200–1000 Hz) band (slope = 61.15 ± 2.12 dB/m, $t_{1213} = 28.80$, p < 0.01, $R^2 = 0.41$) (Fig. 3A) and in the mid frequency (1–10 kHz) band (slope = 48.04 ± 2.01 dB/m, $t_{1213} = 23.93$, p < 0.01, $R^2 = 0.32$), but a weak, negative relationship in the

| | Belugas | | | Boats | | | | | |
|------|--------------|----------------|------|--------------|----------------|------|--|--|--|
| Year | Earliest | Latest | Days | Earliest | Latest | Days | | | |
| 2015 | 19 June 2015 | 17 August 2015 | 58 | 10 July 2015 | 10 August 2015 | 7 | | | |
| 2016 | 17 June 2016 | 17 August 2016 | 53 | 9 July 2016 | 12 August 2016 | 3 | | | |
| 2017 | 22 June 2017 | 18 August 2017 | 56 | 22 June 2017 | 19 August 2017 | 39 | | | |
| 2018 | 30 June 2018 | 19 August 2018 | 49 | 1 July 2018 | 19 August 2018 | 24 | | | |

Table 2. Acoustic indicators of belugas and boat noise within Kugmallit Bay, where "Earliest" and "Latest" are the earliest and latest dates that either a beluga or boat were acoustically detected in the system.

Note: The category "Days" is the total number of days with sounds from belugas or boats present.

high frequency (10–48 kHz) band (slope = -7.46 ± 3.15 dB/m, $t_{1213} = 2.37$, p = 0.02, $R^2 = 0.005$). However, beluga whale vocalizations added significant energy to the high frequency band (see Analysis of the 2017 data set below), which confounded the effect of wave height on SPL. When we included the presence of beluga whale vocalizations as an independent variable in the high frequency model to control for this confounding effect, wave height had a positive relationship with SPL (wave height: slope = 8.56 ± 2.59 dB/m, $t_{1211} = 3.30$, p < 0.001; beluga vocalizations: slope = 10.28 ± 0.39 dB, $t_{1211} = 26.06$, p < 0.0001; model $R^2 = 0.36$). Wave height is, therefore, a good predictor of SPL in all frequency bands, and wind speed is a good predictor of wave height. Wind speed also had a strong, positive effect on SPL at this same site (low frequency: slope = 0.49 ± 0.03 dB/(km·h), $t_{1276} = 19.43$, p < 0.01, $R^2 = 0.23$; Fig. 3B), but the model with wave height was better at predicting SPL than the model with wind speed (Δ AIC > 1000).

Current speed (mean \pm SE = 0.24 \pm 0.004 m/s; range = 0.04–0.82 m/s) had very little effect on SPL in any of the frequency bands (p > 0.05 and $R^2 < 0.01$ in all bands). We therefore assume that there was very little flow noise due to current speed over the hydrophone at that location.

Analysis of the 2017 data set

Wind speed was positively related to SPL in all frequency bands at all sites (p < 0.0001). In the low frequency band, the slope of this relationship was 0.64 dB/(km ·h) (SE = 0.01, $t_{5412} = 56.09$, p < 0.0001, Fig. 3D), in the mid frequency band, slope was 0.51 dB/(km ·h) (SE = 0.01, $t_{5412} = 51.04$, p < 0.0001, Fig. 3E), and in the high frequency band, slope was 0.21 dB/(km ·h) (SE = 0.01, $t_{5412} = 19.47$, p < 0.0001, Fig. 3F). Wind speed varied between 2 and 54 km/h, so at its maximum, wind speed could increase SPL by 35 dB in the low frequency band, 28 dB in the mid frequency band, and 11 dB in the high frequency band. Model fit was generally good for all bandwidths. The model for the low frequency band had $R^2 = 0.56$, the mid frequency model had $R^2 = 0.41$. Full power spectral density (PSD) percentiles for each of the four sites recorded in 2017 are presented in Fig. 4.

We examined two variables for water depth and tide: relative depth (depth of a recorder relative to the minimum depth of that recorder) and change in depth (change since previous recording period). In both the low and mid frequency bands, neither relative depth (range: 0-1.53 m; mean: 0.5 m) nor change in depth (range: -0.49 m to 0.31 m/h; mean: 2.1×10^{-5} m/h) had a statistically significant relationship with SPL (p > 0.05). In the high frequency band, relative depth was negatively related to SPL (slope = -0.81 ± 0.36 dB/m, $t_{5412} = 2.24$, p = 0.03) and change in depth was positively related with SPL (slope = 2.56 ± 1.07 dB/m, $t_{5412} = 2.38$, p < 0.02).

Fig. 3. The relationship between sound pressure level (SPL) and wave height (A) and wind speed (B, D–F), and the relationship between wave height and wind speed (C). Panels (A)–(C) were measured at a single site (West Hendrickson) in 2017, whereas panels (D)–(F) combine all four sites from 2017. SPL is measured in three frequency bands: 0.2–1 kHz (A, B, D), 1–10 kHz (E), and 10–48 kHz (F).





Fig. 4. Power spectral density (PSD) plots for the four recording sites in Kugmallit Bay in 2017. RMS (orange line) is the root mean squared PSD. The other lines are the 1st, 5th, 50th, 95th, and 99th percentiles. Top left: Channel; top right: East Whitefish; bottom left: Mid Hendrickson; bottom right: West Hendrickson.

Fig. 5. The influence of the presence of beluga whale (*Delphinapterus leucas*) vocalizations on sound pressure level (SPL). The box is the interquartile range, the line within the box is the median, the "x" is the linear mean, and the whiskers are minimum and maximum values.



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Fig. 6. Spectrograms (A–D) and median power spectral densities (PSDs) (E) for four example files with no beluga whale (*Delphinapterus leucas*) vocalizations or boat noise and low wind speed (A), beluga vocalizations, no boat noise, and low wind speed (B), boat noise, no beluga vocalizations, and low wind (C), and no beluga vocalizations or boat noise and high wind speed (D). The colour scale in the spectrograms ranges from low PSD (blue) to high PSD (red), and the actual median PSD values can be seen in (E). The boat noise in (C) is likely from a small boat with an outboard engine.



Mean sound pressure levels increased in the presence of beluga vocalizations by 2.9 dB in the low frequency band (SE = 0.43, t_{5412} = 6.75, p < 0.0001), 6.7 dB in the mid frequency band (SE = 0.38, t_{5412} = 17.87, p < 0.0001), and 14.13 dB in the high frequency band (SE = 0.41, t_{5412} = 34.65, p < 0.0001; Fig. 5). In the high frequency band, beluga vocalizations regularly caused increases in SPL well above those caused by increased wind speed (Figs. 6 and 7). For example, increased wind speed primarily caused low and mid frequency sounds (0.2–10 kHz; Table 3, Figs. 6A, 6C, and 6D), whereas many beluga vocalizations, especially clicks, buzzes, and contact calls, were mid and high frequency sounds (Figs. 6B and 6D). Predictably, the relationship between wind speed and SPL in the high frequency band



Fig. 7. The influence of wind speed on sound pressure level (SPL) in the 10–48 kHz band when beluga whale (*Delphinapterus leucas*) vocalizations are absent (top panel) and present (bottom panel). Beluga vocalizations obscure the wind speed by SPL relationship.

Table 3. Sound pressure levels (dB re 1μ Pa) in four frequency bands and wind speed (km/h) for four example files, two with no beluga vocalizations or boat noise present and either low or high wind speed, one with beluga vocalizations present, no boat noise, and low wind speed, and one with boat noise present, no beluga vocalizations, and low wind speed.

| | 0.2–1 kHz | 1–10 kHz | 10–48 kHz | 0.2–48 kHz | Wind speed |
|------------------------------|-----------|----------|-----------|------------|------------|
| No beluga or boat, low wind | 75.5 | 79.7 | 82.8 | 85.1 | 4 |
| No beluga or boat, high wind | 97.9 | 97.0 | 88.1 | 100.7 | 48 |
| Beluga, no boat, low wind | 85.4 | 90.0 | 103.5 | 103.7 | 8 |
| Boat, no beluga, low wind | 67.8 | 98.7 | 92.5 | 99.6 | 17 |

Note: These are the same files used in Fig. 6.

drastically changed based on the presence or absence of beluga vocalizations; in the absence of beluga vocalizations, a tight relationship existed ($R^2 = 0.45$), but in the presence of beluga vocalizations, the relationship disappeared and SPL varied over a much wider range ($R^2 = 0.01$; Fig. 7). In all frequency bands, the interaction between wind speed and the presence of beluga vocalizations was statistically significant (p < 0.01) and had a negative slope between -0.06 and -0.31.

We detected boat noise in 5.2% (74/1414) of files from East Whitefish, 0.8% (11/1414) of files from Mid Hendrickson, 0.3% (4/1387) of files from Channel, and 0% of files from West Hendrickson. The presence of boat noise added 8.4 dB in the mid frequency band (SE = 1.39, t_{5412} = 6.05, p < 0.0001) and 3.1 dB in the high frequency band (SE = 1.50, t_{5412} = 2.04, p = 0.04); however, in the low frequency band, the relationship was negative (slope = -3.2 dB, SE = 1.58, t_{5412} = 2.02, p = 0.04) because boat noise was almost never detected below 1 kHz, but boats primarily traveled on calm days when ambient sound levels were lower. This is further demonstrated by the interaction between wind speed and the presence of boat noise, which was significant and negative in the mid frequency band (slope = -0.18 ± 0.08 , t_{5412} = 2.16, p = 0.03), but not in the other bands (p > 0.20). The lack of boat noise in low frequencies is caused by the shallow bathymetry of our study site, where low frequency sounds do not propagate effectively.

Table 4. Comparisons of sound pressure levels (dB re 1 µPa) in three frequency bands at four sites during the summer of 2017 in the Mackenzie River estuary, Northwest Territories, Canada.

| | 200–1000 Hz | | | 1–10 kHz | | | | 10–48 kHz | | | | | | | |
|------------------|---------------|--------------------------|--------|--------------------------|-------------------|--------------------------|--------|--------------------------|--------------------|--------------------------|--------|--------------------------|----------------|--------|------|
| Recorder | Mean ± SE | 1 st quartile | Median | 3 rd quartile | Mean ± SE | 1 st quartile | Median | 3 rd quartile | Mean ± SE | 1 st quartile | Median | 3 rd quartile | Wind | Beluga | Boat |
| Channel | 89.1 ± 0.2(A) | 81.0 | 87.1 | 90.4 | $95.4 \pm 0.2(A)$ | 87.7 | 93.6 | 96.7 | 88.7 ± 0.1(A) | 83.1 | 86.5 | 89.0 | 19.2 ± 0.2 | 56 | 4 |
| East Whitefish | 85.2 ± 0.2(B) | 69.8 | 76.6 | 83.2 | 90.4 ± 0.1(B) | 79.7 | 83.7 | 88.9 | 89.5 ± 0.1(A) | 83.5 | 85.5 | 88.7 | 19.1 ± 0.2 | 503 | 74 |
| Mid Hendrickson | 93.7 ± 0.2(A) | 80.5 | 86.7 | 91.3 | 97.8 ± 0.2(C) | 84.6 | 89.2 | 93.6 | 103.5 ± 0.2(B) | 84.0 | 86.7 | 95.9 | 19.1 ± 0.2 | 809 | 11 |
| West Hendrickson | 91.8 ± 0.2(A) | 79.5 | 84.6 | 89.0 | 91.1 ± 0.2(D) | 86.8 | 91.2 | 94.9 | $100.0 \pm 0.2(B)$ | 84.6 | 88.1 | 97.0 | 19.3 ± 0.2 | 756 | 0 |

Note: Additional columns show the mean ± SE wind speed (km/h) and the number of files with beluga vocalizations and boat noise present. Statistical comparisons are shown when comparing the mean \pm SE between recorders within one frequency band by the uppercase letters in parentheses, where values with the same letter are not significantly different according to $\alpha = 0.05$.

Table 5. The impacts of wind speed, presence of beluga vocalizations, presence of boat noise, and their two-way interactions on sound pressure levels in three frequency bands based on three summers of recordings in each of three different recording sites in the Mackenzie River estuary, Northwest Territories, Canada.

| Parameter | Slope ± SE | t | р |
|----------------------------|------------------|-------|----------|
| Low frequency band (20 | 00–1000 Hz) | | |
| Wind speed (dB/(km·h)) | 0.55 ± 0.01 | 66.12 | < 0.0001 |
| Beluga | 0.02 ± 0.30 | 0.05 | 0.96 |
| Boat | -3.34 ± 1.30 | 2.58 | 0.01 |
| Wind speed × beluga | 0.06 ± 0.01 | 3.99 | < 0.0001 |
| Wind speed × boat | 0.18 ± 0.07 | 2.48 | 0.01 |
| Mid frequency band (1- | 10 kHz) | | |
| Wind speed (dB/(km·h)) | 0.43 ± 0.01 | 58.05 | < 0.0001 |
| Beluga | 3.58 ± 0.27 | 13.46 | < 0.0001 |
| Boat | 6.26 ± 1.15 | 5.42 | < 0.0001 |
| Wind speed × beluga | -0.08 ± 0.01 | 6.51 | < 0.0001 |
| Wind speed × boat | -0.19 ± 0.06 | 3.04 | < 0.01 |
| High frequency band (1 | 0–48 kHz) | | |
| Wind speed (dB/(km·h)) | 0.15 ± 0.01 | 19.85 | < 0.0001 |
| Beluga | 11.45 ± 0.28 | 40.20 | < 0.0001 |
| Boat | 1.60 ± 1.24 | 1.29 | 0.20 |
| Wind speed \times beluga | -0.26 ± 0.01 | 18.86 | < 0.0001 |
| Wind speed × boat | -0.01 ± 0.07 | 0.12 | 0.90 |

Sound pressure level varied between recording sites (Table 4). In the low frequency band, East Whitefish was significantly lower than all other sites (p < 0.01) by between 3.9 and 8.5 dB. In the mid frequency band, SPLs were significantly different at all sites (p < 0.01), where East Whitefish was lowest, followed by West Hendrickson, Channel, and Mid Hendrickson. In the high frequency band, SPL at East Whitefish was not significantly different from Channel (p = 0.35) and West and Mid Hendrickson were not significantly different (p = 0.62), and SPL at West and Mid Hendrickson were more than 10 dB higher than Channel and East Whitefish.

Sound pressure levels varied by time of day, but this relationship was weak. In the low frequency band, SPL did not differ significantly between the first (midnight to 0559) and second (0600–1159) quarters (p = 1.00), or between the third and fourth quarters (p = 0.33), but SPL in the third (noon to 1759) and fourth (1800–2359) quarters were significantly higher than in the first and second quarters (p < 0.0001). The third quarter was 1.5 dB higher than both the first and second quarters, and the fourth quarter was 2.0 dB higher than the first and second quarters. In the mid frequency band, SPL followed the same diurnal pattern, but the third quarter was 1.2 and 1.1 dB higher than the first and second quarters, respectively, and the fourth quarter was 1.2 and 1.0 dB higher than the first and second quarters, respectively. In the high frequency band, SPL in the first and fourth quarters were not significantly different (p = 1.00) and the second and third quarters were not significantly different (p = 0.78). The first and fourth quarters were both lower than the second quarter by 0.9 dB.

Analysis of the long-term data sets

Within the long-term data sets, similar patterns around geophony, biophony, and anthropophony emerged as in the previous analysis. SPL in all bands increased as wind speed increased, and SPL in the mid and high frequency bands was higher in the presence of beluga vocalizations (Table 5). Different sites also had high variation in the amount of

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Table 6. Long-term trends in sound pressure levels (dB re 1 µPa) in three frequency bands at three sites over three summers in the Mackenzie River estuary, Northwest Territories, Canada.

| Recorder/year | 200–1000 Hz | | | | 1–10 kHz | | | 1048 kHz | | | | | | | |
|----------------------|---------------|--------------------------|--------|--------------------------|--------------------|--------------------------|--------|--------------------------|--------------------|--------------------------|--------|--------------------------|----------------|--------|------|
| | Mean ± SE | 1 st quartile | Median | 3 rd quartile | Mean ± SE | 1 st quartile | Median | 3 rd quartile | Mean ± SE | 1 st quartile | Median | 3 rd quartile | Wind | Beluga | Boat |
| Channel 2015 | 84.4±0.4(A) | 71.4 | 82.6 | 85.8 | 92.8 ± 0.4(A) | 81.6 | 90.6 | 93.5 | 89.9 ± 0.3(A) | 82.6 | 85.6 | 87.7 | 14.7 ± 0.3 | 197 | 0 |
| Channel 2016 | 84.7 ± 0.2(A) | 75.1 | 81.3 | 85.8 | 91.6 ± 0.2(A) | 82.2 | 88.6 | 92.9 | 85.9 ± 0.1(B) | 81.6 | 84.1 | 87.0 | 18.2 ± 0.2 | 24 | 0 |
| Channel 2017 | 89.8 ± 0.2(B) | 80.1 | 86.9 | 90.4 | 95.7 ± 0.2(B) | 87.0 | 93.4 | 96.6 | 88.6 ± 0.2(Å) | 82.8 | 86.4 | 88.9 | 19.2 ± 0.2 | 56 | 4 |
| East Whitefish 2016 | 80.3 ± 0.2(A) | 67.3 | 72.5 | 79.2 | 89.3 ± 0.2(A) | 79.0 | 82.5 | 87.3 | 89.9 ± 0.1(A) | 83.4 | 85.1 | 88.4 | 17.7 ± 0.2 | 453 | 0 |
| East Whitefish 2017 | 85.1±0.2(B) | 69.6 | 76.6 | 83.1 | 90.4 ± 0.2(B) | 79.7 | 83.7 | 88.9 | 89.4 ± 0.2(A) | 83.5 | 85.4 | 88.6 | 19.1 ± 0.2 | 503 | 74 |
| East Whitefish 2018 | 85.5 ± 0.3(B) | 70.5 | 77.9 | 84.2 | 89.5 ± 0.2(A) | 81.5 | 86.0 | 89.6 | 92.6 ± 0.2(B) | 85.3 | 87.6 | 90.2 | 19.0 ± 0.3 | 770 | 41 |
| Mid Hendrickson 2015 | 93.9 ± 0.2(A) | 81.1 | 86.7 | 91.6 | $100.3 \pm 0.2(A)$ | 87.9 | 92.8 | 96.7 | 104.5 ± 0.3(A) | 84.8 | 90.4 | 102.7 | 16.9 ± 0.2 | 1083 | 7 |
| Mid Hendrickson 2016 | 93.8 ± 0.2(A) | 78.3 | 85.0 | 89.3 | 99.7 ± 0.2(A) | 87.8 | 93.1 | 96.9 | 103.5 ± 0.3(A) | 85.1 | 90.5 | 102.4 | 18.2 ± 0.2 | 838 | 5 |
| Mid Hendrickson 2017 | 93.6 ± 0.2(A) | 80.5 | 86.7 | 91.3 | 97.8 ± 0.2(B) | 84.6 | 89.2 | 93.6 | $103.5 \pm 0.2(A)$ | 84.0 | 86.7 | 95.9 | 19.1 ± 0.2 | 809 | 11 |

Note: Additional columns show the mean \pm SE wind speed (km/h) and the number of files with beluga vocalizations and boat noise present. When comparing one mean \pm SE recorder within one frequency band, statistical comparisons are shown between years by the uppercase letters in parentheses, where values with the same letter are not significantly different according to $\alpha = 0.05$.

beluga vocalizations between years, which has implications for SPL. For example, the number of files per year with beluga vocalizations at the East Whitefish site ranged between 453 (27.8%) and 770 (64.1%). SPL was significantly higher in the mid frequency band in the presence of boat noise, but not in the other frequency bands (Table 5). In both the mid and high frequency bands, the interactions between wind speed and both the presence of beluga vocalizations and the presence of boat noise had statistically significant negative relationships (Table 5), suggesting that the relationship between SPL and wind speed weakens in the presence of both beluga vocalizations and boat noise.

The three sites had different patterns in SPL in each of the frequency bands between years (Table 6). Channel had a significantly higher SPL in the low and mid frequency bands in 2017 compared with both 2015 and 2016, but higher SPL in the high frequency band in 2016 compared with 2015 and 2017. East Whitefish had variable patterns in SPL in all frequency bands across all years, although SPL in 2016 was lower than at least one of the other years in each band. Mid Hendrickson was relatively consistent through time, although SPL in the mid frequency band was higher in 2017 than in 2015 and 2016.

Discussion

The soundscape in the shallow Mackenzie River estuary is dominated by wind and wave sounds and by beluga whale vocalizations, but boat noise adds significant energy when it is present. In all frequency bands at all sites, there was a strong relationship between wind speed and SPL. Beluga vocalizations also had strong effects on SPLs, especially in the highest bandwidth. Boat noise had a strong influence on the mid frequency band, but less on the other bands.

Geophony

The geophony had a large influence on the shallow summer soundscape in the Mackenzie River estuary. Wind speed had a strong, positive relationship with SPL. We also demonstrated the strong correlation between wave height and wind speed at one site, and although wave height is a better predictor of SPL than wind speed, wind speed serves as a close proxy of this relationship between SPL and wave height. The dependency of SPL on both wind speed and wave height is well known (Wenz 1962) and has been found in other shallow water systems (Haxel et al. 2013). Wind speed is often used in SPL analyses rather than wave height because wind speed is measured automatically by many weather stations, and is, therefore, easier to obtain (McDonald et al. 2006; Roth et al. 2012; Insley et al. 2017).

Water depth (relative water depth at a site) and tide also influenced SPL, but only in the high frequency band, and to a much lesser degree than wind speed did. As water depth increased, SPL decreased in the high frequency band. However, the overall effect size of this trend was relatively low, and the influence of water depth would only add a maximum of 1.4 dB to SPL in this study. This general trend has been shown in other shallow water studies (Halliday et al. 2018b), but at this time, we are uncertain of what might be causing this relationship between water depth and SPL. Change in water depth, which is related to the direction of tidal flow (i.e., tide ebbing and flowing), also influenced SPL in the high frequency band, where a positive change in depth was related to increased SPL. This could be related to flow noise from water movement or from movement of sediment. However, as with the relative water depth, effect size was low (slope = 2.89 dB/m) and change in depth varied between -0.5 and 0.3 m, leading to a maximum addition of 2.3 dB onto SPL in this frequency band. We, therefore, suggest that changes in water depth in this system had very little influence on SPL, and contribute minimally to the soundscape. Similarly, we found that current speed, as measured by the ADCP, was not related to SPL. In this case, the current speed seemed to follow the tidal cycle quite closely, given the low tidal range (±0.5 m), and we suspect that the flow of water over the hydrophone was limited. In other systems, current can be correlated with the noise of water running over a hydrophone (flow noise) (Haxel et al. 2013; Bassett et al. 2014). Although not measured for this study, we suspect that increased SPL at one of our sites (Channel) could be related to increased flow because this site was deeper than all other sites and appeared to have a faster current. Given that we did not find a direct relationship between current speed and SPL, we suggest that there was very little flow noise in our acoustic data outside of this single deeper site.

Biophony

Beluga whale vocalizations were a significant driver of SPL in all bandwidths, especially in the high frequency band. These frequency-dependent effects are due to the frequency characteristics of their different vocalizations. Whistles range from <0.5 to 22 kHz (Chmelnitsky and Ferguson 2012), contact calls cover large bandwidths from <1 to 100 kHz (Vergara and Mikus 2019), and echolocation clicks range between 20 and 120 kHz (Au et al. 1985). These values were consistent with our observations, so contact calls contributed to all bandwidths that we assessed, whistles had the strongest effects on the low and mid frequency bands, and echolocation clicks only affected the high frequency band. Future work could further define this relationship by quantifying the number, type, duration, and characteristics of calls, and relating this information to SPL.

Wind speed is often considered a dominant natural factor of ambient sound levels in marine systems (Wenz 1962), yet in this system, beluga vocalizations seem to be the dominant factor in higher frequencies. In the high frequency band, wind-driven noise had a relatively tight relationship with SPL in the absence of beluga vocalizations, causing variation in SPL between ~85 and 105 dB, yet in the presence of beluga vocalizations, this relationship between wind speed and SPL essentially disappeared, and SPL ranged between ~85 and 125 dB (Fig. 7). Beluga vocalizations caused SPL to rise up to 20 dB above the levels caused by wind speed. In this system, belugas are the only animals that we are aware of that vocalize in these high frequencies.

Anthropophony

Anthropophony at these sites was limited to noise from boats, both small boats with outboard engines and tugboats or barges traveling between Inuvik and Tuktoyaktuk, but these boats were not very common. These boats also likely have much lower source levels than the large ships that typically have the greatest impact on soundscapes, such as container ships and ferries (Veirs et al. 2016). We occasionally detected boat noise at East Whitefish, but rarely at any other mooring. When boat noise was present, it could add significant energy to the soundscape, but boats were so rare in this system that, overall, anthropophony has little influence. However, if ship traffic does continue to increase in the Arctic, boats may also become more common in the Mackenzie River estuary and may have more of an influence on the soundscape (see Ecological relevance section below). This data set, therefore, serves as a baseline for levels of boat traffic and boat noise in this system.

The shallow bathymetry in this system did significantly limit the propagation of boat noise. Most boat noise that we detected was restricted to above 1 kHz, yet it is very well known that the majority of noise generated by boats is below 1 kHz (Erbe et al. 2016; Simard et al. 2016; Veirs et al. 2016). In deeper water, boat noise would have added significantly to our lower frequency band, but this did not happen in this system. The shallow waters of this MPA do limit boat noise, and this MPA might be considered a quiet area for belugas compared with offshore areas where belugas typically forage. Any boats that we

detected were likely very close to the recorders, given that we only detected most boats for very short periods of time, and the signal almost always included the closest point of approach. We confirmed this point in a recent analysis where we found that vessel tracks derived from Automatic Identification System data did not correlate well with boat noise detected at these recorders (Halliday et al. 2019).

Differences between sites and time of day

We found site-specific and time-specific differences in SPL, but these were relatively minor, especially for time of day. Both wind speed and SPL followed a similar diurnal pattern, on average, with higher wind speed and SPL in the afternoon and evening, and lower wind speed and SPL overnight and in the morning. However, this relationship is generally overshadowed by much larger variations in wind speed that are not dependent on the time of day, which have a greater influence on SPL. One significant difference between sites is the number of files with beluga whale vocalizations at each site. Channel had relatively few files with beluga vocalizations (56), whereas Mid and West Hendrickson had the highest levels (809 and 756 files, respectively), and these patterns matched well with patterns in the high frequency band. Conversely, Channel had the highest SPLs of any site in the low and mid frequency bands, and this was likely related to the strong current that has been observed at the site during deployment and retrieval. The Channel site is at the main extension and conduit of riverine flow into the estuary. Subsequently, the depth of this site may also affect SPL levels, where Channel was 8 m deep and the other sites were 1 and 1.6 m deep. Deeper water allows for greater propagation of lower frequency signals, which might cause higher low frequency ambient sound levels at Channel relative to the other sites, as long as the signal source originated within the deeper channel, as this channel is surrounded by shallow water. Indeed, Channel did have high levels of low frequency sounds compared with the other sites (Fig. 4).

Long-term comparisons

Sound pressure levels were relatively consistent within a site over multiple summers, and any significant differences in average SPL between years was only by few decibels. Moreover, no obvious patterns emerged when comparing changes through time between sites. We can, therefore, assume that the soundscape is relatively stable through time. As with the differences that we found between sites in 2017, any differences between years are likely driven by varying contributions of the geophony, biophony, and anthropophony. For example, the number of files per year with beluga vocalizations at the East Whitefish site ranged between 453 (27.8%) and 770 (64.1%), which had a large impact on the variation in SPL at this site.

Detection ranges

An important consideration in studies using passive acoustic monitoring is the detection range of different acoustic signals. At shallow sites such as those used in this study, the shape of the local bathymetry is going to be one of the most important environmental predictors of detection range, simply because low frequency sounds will not propagate through the shallowest water. In a previous analysis, we estimated that beluga vocalizations might be detectable above low ambient sound conditions out to 2 km (Halliday et al. 2019). This detection range was confirmed by another recent study in the same system that paired visual observations of belugas with acoustic detections and found that belugas as far away as 2 km were detected acoustically (Scharffenberg et al. 2019). This study took place at our shallowest site, so we can assume that this range would be similar for deeper sites in this system. Unlike beluga vocalizations, boat noise is strongest in the low frequencies, although it does have a higher frequency component that does not propagate far. In this

shallow system, the low frequency component of boat noise does not propagate well, and we did not find any examples of boat noise with a signal below 1 kHz. We did, however, detect higher frequency signals from boats, but likely only from boats within roughly 2 km from the recording site. Detection ranges for all signals would also decrease as ambient sound levels increase, so these 2 km estimates only apply under low ambient sound levels. At this time, we cannot provide estimates of detection distance specific to each of our recording sites because either local playback experiments or acoustic propagation modeling are required to make these estimates. Acoustic propagation modeling would require high resolution bathymetry data for each of these sites, which, to the best of our knowledge, does not exist.

Ecological relevance of the soundscape to beluga

The soundscape is one aspect of the habitats used by beluga whales. Belugas vocalize for communication and use echolocation for foraging and navigation. The soundscape, therefore, defines the background sound levels that belugas must overcome to communicate, forage, and navigate. Our study demonstrates that beluga echolocation clicks and contact calls dominate the high frequency bands, which suggests that even under the noisiest natural soundscapes at these sites, belugas can effectively use these call types. However, the most complex components of beluga communication (e.g., whistles and signature components of contact calls, see Vergara and Mikus 2019) occur in the lower frequency bands. These bands are full of noise from wind and waves, as well as from boat noise when boats are present. Belugas must, therefore, carefully consider ambient sound levels in the lower frequency bands when selecting habitat so that they can effectively communicate, which may be especially important in habitats used for large social gatherings. In addition, although belugas evolved around naturally varying ambient sound levels driven by wind and waves, boat noise is a much more recent addition to the soundscape that belugas may have difficulty adequately adapting to. Indeed, belugas have been shown to react to the presence of boats and boat noise at this site (Halliday et al. 2019) and at other sites in the Arctic (LGL 1986; Finley et al. 1990), often by leaving the area where the noisy activity is occurring (LGL 1986; Finley et al. 1990). At this site, specifically, belugas have been shown to react to boats, and likely leave the area when boats are around (Halliday et al. 2019). However, this reaction was not correlated with detection of boat noise at the acoustic recorder because the shallow water limits the propagation of boat noise; belugas may have been reacting to boat noise that they could hear, but that we were unable to detect. Such a situation might occur if a boat was out of the detection range for the acoustic recorder, but belugas were between the acoustic recorder and the boat, or belugas may simply be better at detecting boats than we are. It is, therefore, imperative to understand the soundscape in which belugas live to determine how often anthropogenic noise influences the soundscape, and whether anthropogenic noise is increasing. This study is a first step in understanding the soundscape at an important site for this beluga population. However, further monitoring is needed to track any changes in both how belugas use this site through time and any changes in anthropogenic noise using acoustic indicators (Table 2) consistently from year to year is imperative. An additional useful indicator would be to track boats using Automatic Identification System data. We examined this data set in a previous study that also used this same acoustic data set (Halliday et al. 2019), and found that boat traffic over the four years of data collection remained relatively stable at these recording sites, with between three and nine Automatic Identification System vessels coming within 10 km of a recording site each year during the recording period. However, Automatic Identification System data should continue to be monitored to track ship traffic in this system.

Conclusions

This work serves as a baseline for assessing changes to this soundscape as climate change causes shifts in the ecosystem. We documented the summer soundscape, but the soundscape is expected to be highly seasonal. Beluga whales only occupy the estuary between June and August, and much of this ecosystem is frozen down to the sediment in the winter, making it uninhabitable for most marine vertebrates. However, climate change is causing ice to break up earlier in the spring and form later into the autumn (Markus et al. 2009; Loseto et al. 2018), which could mean that the summer soundscape described here may occur for longer periods of the year in the future. The changing climate may also lead to shifts in species composition. Beluga whales may change their habitat preference, or other species may begin to use this ecosystem. Changes in the composition of soniferous species could lead to substantial soundscape changes, as evidenced by the large influence of beluga vocalizations on the current soundscape. Finally, noise from vessel traffic may increase throughout this region, especially in areas closer to the transportation routes and in deeper water where lower frequency sounds propagate more effectively. Continued monitoring is essential to track changes in this soundscape and changes in how species like the beluga whale, which rely on the soundscape, use this environment. Moreover, acoustic monitoring specifically will continue to be an excellent way to track changes in this ecosystem, including monitoring the presence of soniferous species and underwater noise from boats.

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