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Megan F. McKenna ; Brandon L. Southall; Emily Chou; Martin Robards; Howard C. Rosenbaum

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An integrated underwater soundscape analysis in the Bering Strait region[a)]

Megan F. McKenna,[1,b)] Brandon L. Southall,[1] Emily Chou,[2] Martin Robards,[3] and Howard C. Rosenbaum[2]
[1]*California Ocean Alliance, Aptos, California 95003, USA*
[2]*Ocean Giants Program, Wildlife Conservation Society, Bronx, New York 10460, USA*
[3]*Arctic Beringia Program, Wildlife Conservation Society, Fairbanks, Alaska 99709, USA*

ABSTRACT:
Rapid changes in the Arctic from shifting climate and human use patterns are affecting previously reported distributions and movements of marine mammals. The underwater soundscape, a key component of marine mammal habitats, is also changing. This study integrates acoustic data, collected at a site in the northern Bering Sea, with information on sound sources to quantify their occurrence throughout the year and identify deviations in conditions and dominant soundscape components. Predictive models are applied to explain variation in sound levels and to compare the relative contributions of various soundscape components. Levels across all octave bands were influenced most strongly by the variation in abiotic environment across seasons. The presence of commercial ships did not have a discernible effect on sound levels at this location and period of time. The occurrence of sources was compared to a second site, where we documented how higher levels of shipping changed that soundscape. This study demonstrated the value of acoustic monitoring to characterize the dominant acoustic features in a soundscape and the importance of preserving soundscapes based on dominant features rather than level of sound. Using a soundscape approach has relevance for protecting marine mammals and for the food security of Alaska Native communities that depend upon them.
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I. INTRODUCTION

Understanding natural and human influences on underwater soundscapes and how they vary can inform effective resource management (Duarte *et al.*, 2021), particularly in biologically and culturally important areas and for protected and endangered species. The Arctic is experiencing substantial climatic changes, with greater and more rapid warming than other regions across the globe (Baker *et al.*, 2020; Wood *et al.*, 2015; Zhang, 2005). Warmer temperatures are reducing sea ice coverage and transforming the Arctic sea ice system from perennial to seasonal (Baker *et al.*, 2020). The consequences of these changes for life in the Arctic are significant. Species reliant on the sea ice are shifting distributions (Davidson *et al.*, 2020; Falardeau and Bennett, 2020; Overland and Stabeno, 2004; Xavier *et al.*, 2018), Indigenous communities' access to food and resources are altered (Krupnik, 2018), and the industrialized world is discovering a new frontier for trade (Ng *et al.*, 2018). These changes are all interrelated and influenced by a variety of broadscale environmental and anthropogenic forces. Finding integrated ways to study the changes is key to building a resilient future for marine mammals and people in the Arctic (Dankel *et al.*, 2020; Prip, 2019).

The marine acoustic environment encapsulates and conveys numerous aspects of an ecosystem. Biological sounds reveal presence, distribution, behavior, and in some cases population estimates and migration (Chou *et al.*, 2020; Marques *et al.*, 2013; Oestreich *et al.*, 2020; Seger and Miksis-Olds, 2020). Sounds from wind and ice indicate conditions of the shifting abiotic environment (Halliday *et al.*, 2020; Kinda *et al.*, 2015; Menze *et al.*, 2017; Roth *et al.*, 2012; Southall *et al.*, 2020). Human activity often produces noise, either as a by-product of the activity, such as vessel operations, or directly from the activity, such as seismic survey explorations (Hildebrand, 2009). All these sounds together at a location and the variation over time are considered the *underwater soundscape* (Miksis-Olds *et al.*, 2018) and hold vital information for many marine species for which acoustic perception is a primary sensory modality. Soundscapes are highly dynamic, varying in both space and time, and changes in one component of a soundscape can influence the presence of other sounds [see Fig. 2 in Miksis-Olds *et al.* (2018)].

Soundscapes play an important role in ecological systems (Duarte *et al.*, 2021; McKenna, 2020; Merchant *et al.*, 2015; Mooney *et al.*, 2020). Extraneous noise from abiotic, biotic, and anthropogenic sources contributes to the ambient sound field against which animals must detect and decipher

[a)]This paper is part of a special issue on Ocean Acoustics in the Changing Arctic.
[b)]Electronic mail: megan.mckenna@gmail.com, ORCID: 0000-0003-3475-0785.

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signals from conspecifics, predators, and prey. In addition to communication-specific signals, sounds can also offer important cues on the conditions of the environment (Popper and Hawkins, 2019). The concept of using ambient sounds as cues to direct movement or identify appropriate habitats is referred to as soundscape orientation (Slabbekoorn and Bouton, 2008) and is thought to be important for many marine species. Ice seals, for example, may be using ambient sound fields as a cue for open water and solid ice conditions in addition to conspecific acoustic cues (Miksis-Olds and Madden, 2014). To capture these interrelated features of soundscapes, a holistic approach is needed when quantifying them. Measuring a soundscape as a single physical parameter, such as ambient noise level within a specified frequency band, in some cases limits the interpretation of how and why a soundscape varies (Miksis-Olds *et al.*, 2018) or how taxa interpret and respond (Francis and Barber, 2013). Quantifying the dominant features of a soundscape, in terms of occurrence and contribution to sound energy, can reveal what cues are available to animals as well as how noise from human activity interferes with vital acoustic information.

Here, we integrate acoustic data, collected for an entire year at a site near St. Lawrence Island in the northern Bering Sea, with information on a suite of potential acoustic sources (including biotic sources from marine mammals, abiotic sources from ice and wind, and anthropogenic sources from commercial shipping) to quantify their occurrence throughout the year and deviations in conditions and to identify dominant features of the soundscape. For comparative purposes, we analyzed the occurrence of sound sources at a second site in the Bering Strait region within an overlapping 13-day period to understand effects of commercial shipping on the soundscape. The site in the Bering Strait is exposed to more ships transiting, as multiple lanes coverage in this region (Marine Exchange of Alaska, 2019). We applied predictive models to explain variation in measured sound pressure levels (SPLs) within different frequency bands and to compare the relative contributions of each soundscape component. This study builds on recent efforts to quantify ambient noise (Southall *et al.*, 2020) and seasonal habitat utilization patterns for protected and culturally important Arctic marine mammal species (Chou *et al.*, 2020). By integrating the different soundscape components with measured ambient noise levels, we both enhance our understanding of the conditions of the soundscape and advance our ability to track changes in soundscapes over space and time.

II. METHODS

A. Acoustic monitoring data

Passive acoustic underwater recordings from two deployments at a site near St. Lawrence Island in the northern Bering Sea were analyzed in this study (Gambell site, Fig. 1). These deployments were part of a larger effort to characterize seasonal patterns in animal sounds and ambient noise in this region (Chou *et al.*, 2020; Southall *et al.*, 2020). One deployment at a second site (Bering Strait site, Fig. 1) was analyzed to compare conditions in an overlapping time period with the Gambell site.

FIG. 1. Locations of acoustic monitoring sites. Data collected at the Gambell site (63.8227° N, 171.6758° W) near St. Lawrence Island were used for year-long study of acoustic conditions (2014–2015), and data collected at the Bering Strait site (65.6998° N 168.3886° W) were used for comparison of conditions in October 2015. All recorders were deployed within several meters of the bottom in 20–30 m water depth.

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Acoustic recordings were obtained from archival recorders [Loggerhead Instruments (Sarasota, FL) DSG] suspended from sub-surface floats to anchored moorings to isolate recorders from deployment-related movement near the seafloor or sea surface. Calibrated HTI-96-Min hydrophones (High Tech, Inc., Long Beach, MS; flat response between 2 Hz and 30 kHz) were used with each recorder. The gain settings were set to ensure sufficient dynamic range for the 16-bit analog-to-digital (A/D) converter (~96 dB dynamic range). Sound pressure levels that exceeded 155 dB re 1 μPa were considered clipped and were excluded from further analysis. If an object made direct contact with the recorder likely to only occur during high tidal flow events, these samples were removed as well (Southall *et al.*, 2020). For context, the loudest ice cracking event at the surface (source level 180 dB re 1 μPa; Greening and Zakarauskas, 1992) would saturate the hydrophone at ranges less than ~30 m, assuming spherical spreading loss. Since the hydrophone was in 30 m of water, this dynamic range was sufficient for the sources of interest and only 0.2% of the samples were clipped.

Acoustic recordings, sampled at 20 kHz, were made for either 5- or 10-min durations in each hour of every day. The 20 kHz sample rate extended sampling through the ice-covered periods when recorders could not be accessed. Timing of the samples varied throughout the hour for the first deployment and occurred at the top of the hour in the second deployment at the Gambell site and the deployment at the Bering Strait site. Previous studies using this same data set reported different sampling parameters for some of the deployments (Chou *et al.*, 2020; Southall *et al.*, 2020), and we confirmed that the parameters presented in here are the correct values for these data (Table I).

B. Presence of biological sounds

Selection of marine mammal sounds in the acoustic records was detailed in a previous study (Chou *et al.*, 2020). Briefly, the sound recordings were manually inspected by visualizing spectrograms [fast Fourier transform (FFT) size 2048 samples, Hann window, 90% overlap] using RAVEN PRO (Center for Conservation Bioacoustics, 2019) or ISHMAEL (Mellinger, 2001) by an experienced analyst. Species identified included bowhead whale (*Balaena mysticetus*), Pacific walrus (*Odobenus rosmarus divergens*), bearded seal (*Erignathus barbatus*), ribbon seal (*Histriophoca fasciata*), beluga whales (*Delphinapterus leucas*), and sounds from other baleen whales. Unknown biologic sounds were also recorded as present, and these sounds could have been unknown calls from any of the above species, calls too faint to identify, or in the case of the Bering Strait site, croaks and drumming sounds likely from fish (e.g., Pine *et al.*, 2020). Sounds from unknown anthropogenic sources, potentially from small outboard motors and skiffs, and ice cracking were recorded as well. If these sounds were present in an hourly sample, the sample was coded as 1 for each type of sound present and 0 if a sound type was not present. The hourly presence/absence data were then used for further analysis.

C. Conditions of abiotic environment

The abiotic environment, including wind, ice coverage, and tidal flow, influence received sound levels (Avgar *et al.*, 2016; Halliday *et al.*, 2017; Roth *et al.*, 2012; Southall *et al.*, 2020; Wenz, 1962); therefore, we paired the hourly acoustic samples with a measure of wind speed from a nearby weather station (NOAA, 2021a). Wind speed is reported four times every hour, and for each hourly acoustic sample, we calculated the average wind speed within 30 min and matched the average with the acoustic sample. For the Gambell site, missing data for wind speed resulted in removing 54% of the data, as the statistical models do not handle missing data sufficiently. To reduce missing data, we interpolated wind speed data [R package zoo v1.8–8, na.approx (R Core Team, 2017)] to fill gaps within 2 h of a missing sample and thereby reduced data removal to only 34% of the data in the statistical models (Fig. S1 of the supplementary material[1]). A large gap in wind speed data occurred in May 2016 for unidentified reasons, and therefore the model predictions in this study do not include May.

We estimated sea ice concentration from the Advanced Microwave Scanning Radiometer 2 instrument aboard the Global Change Observation Mission 1st-Water "SHIZUKU" satellite (Spreen *et al.*, 2008). We averaged daily sea ice coverage from all cells within 20 km from the acoustic monitoring station and paired it with each acoustic sample, resulting in the same value for all hourly samples in a given day. Based on simple spherical spreading loss calculations and known ambient noise levels (Southall *et al.*, 2020), the 20 km sampling area would acoustically capture most ice cracking events (Greening and Zakarauskas, 1992).

Tidal flow can introduce both sounds from moving sediment and artificial sound as water moves past the

TABLE I. Summary of acoustic recording stations.

Site	Deployment ID	Latitude	Longitude	Depth (m)	Sample rate (kHz)	Recording schedule	Recording dates	
Gambell	2015.2	63.823°	171.676°	~30	20	Sampled 10 min every hour with rotating start time in the hour (0, 10, 20, 30, 40, 50)	21-Jun-2015	14-Oct-2015
Gambell	2015.11	63.832°	171.641°	~30	20	Sampled 5 min every hour, always at the top of the hour (0 min)	15-Oct-2015	1-Jul-2016
Bering Strait	2015.14	65.7°	168.389°	~30	48	Sampled 5 min every hour, always at the top of the hour (0 min)	19-Oct-2015	13-Jun-2016

hydrophone. Some biological sounds change depending on tide. We included a novel metric to describe both the magnitude and direction of the tide by calculating the difference in the height above sea level from the previous hour. We downloaded hourly tidal data from a nearby NOAA tides and currents station in Nome Sound, AK (station 9468756; 64° 29.7′ N, 165° 26.4′ W) (NOAA, 2021b).

D. Presence of anthropogenic sources

To capture broad ship traffic patterns in the Bering Sea, we used satellite-based automatic information system (AIS) data. Data were provided by exactEarth (Cambridge, Canada) and processed to find all ship locations within 50 km of the acoustic stations. For each acoustic sample, the number of ships in the area (<50 km), average speeds, and minimum and maximum distances were extracted from the AIS data. The sampling area for AIS data of 50 km was chosen based on known and predicted traffic patterns in the area; most of the larger ships transited >20 km away. The larger sampling area ensured that both distant ship passages creating chronic low-frequency energy and individual passages were included in the analysis. Further, since large commercial ships have higher source levels (McKenna *et al.*, 2012) compared to cracking ice (Greening and Zakarauskas, 1992), the larger spatial sampling accounts for larger detection ranges.

AIS data only capture a portion of the vessel traffic (i.e., vessels equipped with AIS transponders that can communicate with satellite receivers) and do not typically capture smaller vessels or non-commercial vessels carrying AIS class B transponders. These smaller vessels can have significant impact on the soundscape (Cope *et al.*, 2020; Erbe *et al.*, 2019; Hermannsen *et al.*, 2019). To try to account for a portion of this activity in the statistical models, we know that small vessel activity, particularly from hunting and fishing skiffs, is present more often in daytime hours in this region and therefore calculated sun inclination for each acoustic sample using the latitude and longitude and time stamp [getSunlightPosition, suncalc package v1.8–33 in R version 3.4.1 (R Core Team, 2017)]. Increased daytime activity in small vessel traffic has been observed in other nearby regions, and the activity influenced the daytime sound levels (McKenna *et al.*, 2017).

E. Sound level measurements and statistics

For each hourly acoustic sample, either 5 or 10 min in duration, an unweighted time-averaged equivalent sound pressure level (LZeq) in each one-third octave band was calculated. Standard center frequencies from 0.02 to 8 kHz were used for the one-third octave band calculations (ANSI/ASA, 2013). Sound levels were calculated as dB re 1 μPa (see Southall *et al.*, 2020). These ambient noise measurements were matched with hourly data on presence of animal sounds, wind speed, and ship tracking data to compare sound levels with different sounds present in the environment. Sound levels when specific sources are present were summarized as percentiles (10th, 50th, 90th) to quantify variation in levels related to the presence of specific sound sources.

F. Co-occurrence of acoustic sources through data integration

Data were combined using time stamps for the different data sets. All time stamps were converted to local Alaska time. For each acoustic sample (5- or 10-min hourly samples) in the species presence analysis, we first found the corresponding LZeq for the same time. We then matched the wind speed data by taking the average of wind speed for the hour around the sample, 30 min before and 30 min after. If no match was found due to missing weather data, these samples were excluded from statistical analyses (see Sec. II C for data interpolation methods). We matched tidal data by finding the corresponding hour on a given day. Ship tracking data were matched by finding nearby (<50 km) ships within the exact time period of the sample, and total number of ships, distances, and speeds were recorded. Time periods without ships were simply marked as no ships and remained in the analysis.

G. Predicting the influence of soundscape components on sound levels

We used a predictive modeling approach to understand how the presence of different sound sources as well as environmental conditions influence the hourly sound levels at the site near St. Lawrence Island. Predictive variables representing different sound sources included known presence of biological sounds, abiotic (wind, ice, tide) sources, anthropogenic sources (AIS-transmitting vessels), and Julian day to capture seasonal variation (Table II). Vessel traffic in the region includes other non-AIS-transmitting motorized vessels (for example, local hunting skiffs) that can contribute to the measured sound levels. Activity from these vessels typically occurs in daytime hours, so to try to account for this activity, we included sun inclination as a predictor variable in the models. Further, previous studies have also shown daytime levels are elevated compared to nighttime at this site and may be related to small boat activity near the site (Southall *et al.*, 2020).

We used a general additive modeling approach (GAM, mgcv package v1.8–33 in R version 3.4.1 (R Core Team, 2017; Wood, 2017) to understand what variables influenced hourly measured sound levels. Given that different sound sources contribute to different frequencies, statistical models for each octave band were built (125, 250, 500, 1000, 2000, and 8000 Hz). GAMs use smoothing terms to represent non-linear contributions by predictor variables ("s" in Table III). For each octave band model, we assumed Gaussian errors in fitting the dependent variable (an identity link function was used), controlled for autocorrelation, and minimized overfitting the smooth terms (Table III, global model structure for each octave band, includes all predictor variables). Smooth terms ("bs" in Table III) varied depending on type

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TABLE II. Acoustic source descriptions.

Variable	Soundscape category	Description	Source	Model code
Julian day	Seasonal	Numerical value for day of the year	Calculated using lubridate package in R	jul
hour of the day	Seasonal	Numerical value for hour of the day	Extracted from time stamp	hr
Wind speed (knots)	Physical	Average wind speed within 30 min of the audio sample	Nearby NOAA weather station, WBAN:26703	ws
Ice concentration	Physical	Daily sea ice concentration 20 km around site	Advanced microwave scanning Radiometer 2 instrument	ice
Tide change	Physical/Artificial	Change in water level from the previous hour	Nearby NOAA weather buoy, 9468756	tide
Bowhead whale calls	Biological	Presence of call within acoustic sample (5 or 10 min window)	Chou *et al.* (2020)	Bmy
Other baleen whale calls	Biological	Same as bowhead	Chou *et al.* (2020)	Bal
Bearded seal sound	Biological	Same as bowhead	Chou *et al.* (2020)	Eba
Walrus sound	Biological	Same as bowhead	Chou *et al.* (2020)	Oro
Unidentified biological sound	Biological	Same as bowhead	Chou *et al.* (2020)	Ubi
Ribbon seal sound	Biological	Same as bowhead	Chou *et al.* (2020)	Hfa
Beluga whale sound	Biological	Same as bowhead	Chou *et al.* (2020)	Dle
Sun altitude	Anthropogenic	Height of the sun above the horizon	Calculated using suncalc in R	sunAlt
AIS ships	Anthropogenic	Number of ships within 50 km of the stations	exactEarth	nShips

of predictor variable, for example, for hour variable, a cyclic cubic regression (cc) spline was used, and all other variables used cubic regression spline (cr). All octave band models included a correlation term to account for the temporally dependent hourly acoustic data samples. We used an autoregressive process for a continuous time variable within the GAM modeling structure ("corARI," Table III) with a correlation value derived from the Pearson correlation estimate between measured sound levels with sound levels in the next hour (value = 0.81). We did not optimize the global models using Akaike's information criterion (AICc) or perform model averaging because we were interested in how all the possible sources influenced SPLs to be able to compare how soundscape components influence measured levels. To interpret how different soundscape variables contributed to models, we used significance terms for each variable. For the parametric variables, significant influence was deemed at a *p*-value of <0.05, and for smoothed terms, we looked for very small *p*-values <0.001, to ensure variables contributed to explaining sound level and acknowledge the issues with using *p*-values for smoothed terms. From previous studies, we know the biological sounds are highly correlated with the abiotic environment (Chou *et al.*, 2020), and our models likely have multicollinearity or correlated explanatory variables. Instead of removing all correlated variables, we accepted unstable parameter estimates or changes in sign of parameter estimates because we were ultimately interested in understanding how different components of the soundscape affect sound levels in each of the six octave bands. These six models are the "global models" that include all predictor variables shown in Table III.

To compare how each soundscape category [(1) abiotic, (2) seasonal, (3) biotic, and (4) anthropogenic] predicted measured sound levels, we explored the proportion of variance explained by each octave band model when only variables in a specific soundscape category were included (Table II). We built a total of 24 additional models with only terms specific to each of the four soundscape categories for all octave bands and calculated the deviance explained by each model. We used the same smoothing parameters from the global models to ensure fit did not change with the presence or absence of correlated variables (Table III).

We used the program R version 3.4.1 for all quantitative analyses (R Core Team, 2017). All data and code are available online (McKenna, 2021).

III. RESULTS

A. Temporal occurrence of sound sources

The occurrence of sound sources varies spatially, depending on biological and human use patterns near the site as well as the acoustic propagation conditions. A variety of sound sources are present in this coastal marine environment with occurrence varying by time of year and time of day (Fig. 2). Bowhead whale sounds occurred on the greatest number of days (157 days) and, when present, occurred throughout the day, especially in December. Similarly, walrus sounds (155 days) and bearded seal sounds (136 days) also occurred consistently through the winter months. Bearded seal calls became more common throughout the day later in the spring (April and May). Unknown biologic sounds occurred throughout the years and usually only in a few samples on a given day. Sounds from ice cracking occurred throughout the winter months when wind speeds were also higher (Fig. 2). Anthropogenic sources, specifically, the presence of commercial ships equipped with AIS transponders, were, as expected, most common in ice-free periods in summer and fall, with only a few AIS ships present per day. A total of 73 days had

TABLE III. Summary of model performance and variable importance for the six-octave band global models that included all predictor variables. Significant predictors are in bold; "Not included" indicates species that were not included in global models because their calls do not fall within that frequency band. The predictor variables for the models are colored by soundscape category: red = anthropogenic sources, blue = biological sources, gray = abiotic sources, and green = seasonal. The colors match with the color coding in Fig. 5.

gam(SPL_OTBHz ~ s(jul, bs="cr") + s(ice, bs="cr") + s(WS, bs="cr") + s(tide) + s(sunAlt, bs="cr") + (nShips) + (Bmy) + (Bal) + (Eba) + (Oro) + (Ubi) + (Hfa) + (Dle), correlation=corCAR1(value=corACI, form=~dataTime), data=dataModel, method="REML", select=TRUE, gamma=1.4, na.rm = TRUE)

Global model structure	125 Hz model		250 Hz model		500 Hz model		1000 Hz model		2000 Hz model		8000 Hz model	
Parametric variables	Parameter estimates	Significance (*p*-value)	Parameter estimates	Significance (*p*-value)	Parameter estimates	Significance (*p*-value)	Parameter estimates	Significance (*p*-value)	Parameter estimates	Significance (*p*-value)	Parameter estimates	Significance (*p*-value)
Intercept	95.49	**<2e−16**	97.41	**<2e−16**	94.99	**<2e−16**	95.32	**<2e−16**	97.99	**<2e−16**	91.44	**<2e−16**
AIS ships	0.05	0.93	0.03	0.94	0.10	0.77	0.17	0.54	0.26	0.37	−0.29	0.23
Bowhead	−1.63	**0.00**	0.01	0.99	0.70	**0.01**	Not included		Not included		Not included	
Other baleen whale	4.77	**0.00**	4.49	**0.00**	3.93	**0.00**	2.35	**0.00**	1.57	**0.02**	0.79	0.14
Bearded seal	−3.29	**0.00**	−2.74	**0.00**	−0.96	**0.02**	−1.56	**0.00**	−2.85	**0.00**	−2.15	**0.00**
Walrus	−1.96	**0.00**	−0.69	0.08	−0.24	0.45	−0.53	0.05	Not included		Not included	
Unknown bio	4.64	**<2e−16**	1.45	**0.00**	0.64	**0.02**	0.03	0.91	−0.37	0.11	−0.02	0.92
Ribbon seal	No detections		No detections		No detections		No detections		No detections		No detections	
Beluga whale	Not included		Not included		−0.61	0.08	0.16	0.58	0.45	0.11	0.84	**0.00**
Smooth variables	Smooth terms	Significance (*p*-value)	Smooth terms	Significance (*p*-value)	Smooth terms	Significance (*p*-value)	Smooth terms	Significance (*p*-value)	Smooth terms	Significance (*p*-value)	Smooth terms	Significance (*p*-value)
Julian day	7.86	**<2e−16**	8.63	**<2e−16**	8.71	**<2e−16**	8.67	**<2e−16**	8.12	**<2e−16**	8.55	**<2e−16**
Ice coverage	2.28	**<2e−16**	4.95	**<2e−16**	5.57	**<2e−16**	5.09	**<2e−16**	6.45	**<2e−16**	6.86	**<2e−16**
Wind speed	3.77	**<2e−16**	5.25	**<2e−16**	6.10	**<2e−16**	5.43	**<2e−16**	4.22	**<2e−16**	5.81	**<2e−16**
Tide	4.79	**<2e−16**	4.15	**<2e−16**	2.99	**<2e−16**	2.00	**0.00**	1.45	**0.00**	1.43	**0.00**
Sun Altitude	5.23	**<2e−16**	4.83	**<2e−16**	4.07	**0.00**	3.20	**0.00**	1.62	**0.00**	3.59	**0.00**
R-sq	0.31		0.49		0.50		0.59		0.63		0.77	
Deviance explained	31%		50%		51%		59%		63%		77%	
Hourly samples (*N*)	5554		5554		5554		5554		5554		5554	

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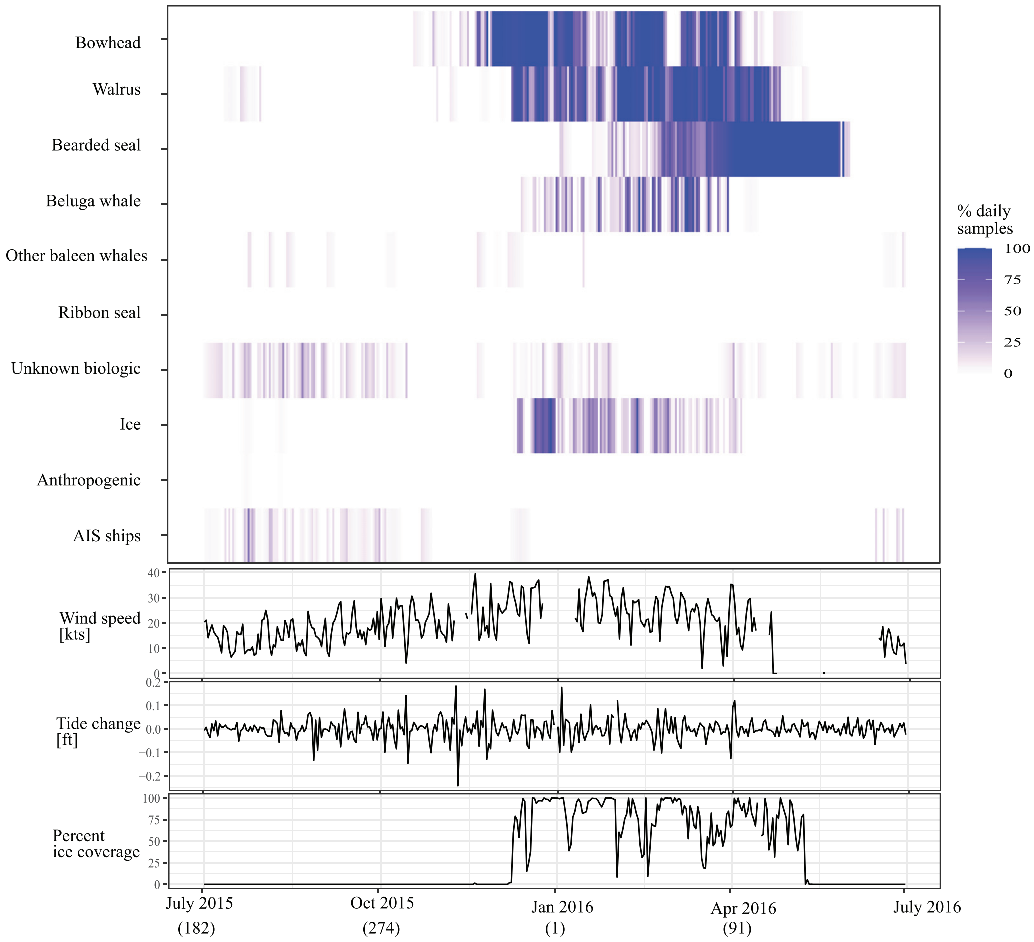

FIG. 2. (Color online) The occurrence of sound sources during an entire year of acoustic recording at the Gambell site, ordered by days of occurrence (bowhead whale, 175 days; walrus, 155 days; bearded seal, 136 days; beluga whale, 88 days; other baleen whales, 24 days; ribbon seal, 1 day; unknown biologic, 149 days; ice, 110 days; anthropogenic, 4 days; and AIS-transmitting ships, 73 days). The bottom three panels are conditions of the abiotic environment known to influence sound levels: wind speed (mph), tidal change (difference in height from previous hour), and ice coverage (percent of surface in 20 km buffer). Numbers under the dates are Julian days. Acoustic data were collected hourly, and color shading represents the percent of the daily samples with a specific source present.

AIS ships present within the 50 km range, and most ships were transiting >20 km away (83%) and traveling at speeds <10 knots (5 m s^{-1}).

B. Received SPLs for different sources

A comparison of LZeqs when only specific sources or conditions occurred revealed variation in received sound levels (Fig. 3). As expected, wind speed influenced received median sound levels at frequencies below 8 kHz. Sound levels were ∼15–20 dB higher in 40 knot compared to 0 knot wind conditions [Fig. 3(A)]. This range of conditions provided an estimate of sound levels when no identifiable sources are present to understand the natural conditions animals are communicating under. The 0 knot median curve is a useful metric of the lowest ambient conditions and can be used to understand how much a specific source increases the ambient conditions at the site [Fig. 3(B)] and how it changes over time.

Received sound levels for different source categories are a function of the sound level of the source, the distance between the source and the hydrophone, and propagation conditions; therefore, these comparisons are simplistic and an average view of how conditions can vary when a source is present under the current biological and human use patterns. Acoustic samples with only AIS-transmitting ships within 10 km of the hydrophone and traveling at more than 5 knots showed no discernible increase in median received sound levels [<1 dB change between 100 and 1000 Hz; Fig. 3(B)]. Despite no change in median values, these samples with AIS-transmitting ships showed a large variation in sound levels [represented by the 10th and 90th percentiles; Fig. 3(C)], and lower frequencies (<100 Hz) exceeded median sound levels for 40 knot wind conditions. Acoustic samples with only biological sources present raised median sound levels by ∼5 dB between 31.5 and 100 Hz [Fig. 3(B)]; however, there was a large variation in received levels (represented by the 10th and 90th percentiles) when biological sources were present, >20 dB in some frequencies [Fig. 3(D)]. The 90th percentile levels in lower frequencies when biological sounds were present were greater than median levels when wind speeds were 40 knots [Fig. 3(D)].

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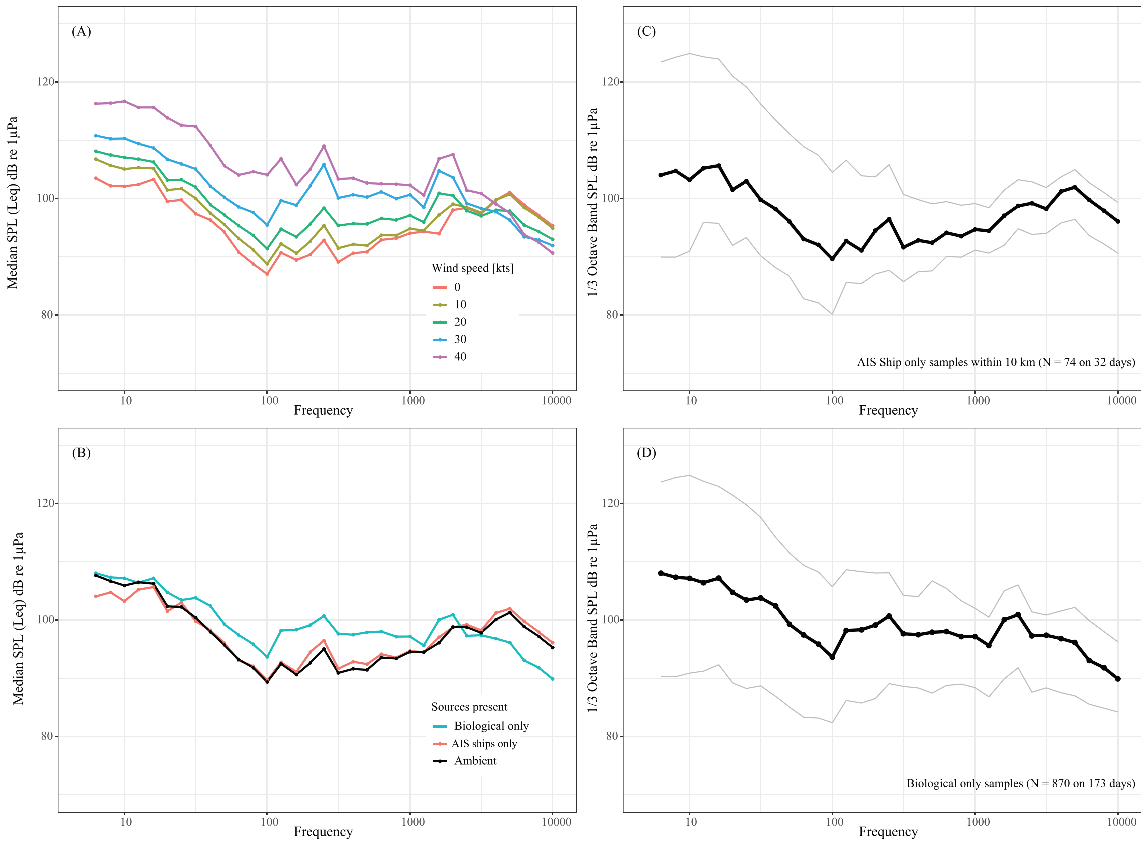

FIG. 3. Received one-third octave band SPLs when only specific sound sources are present. These values are received sound levels since the distance to the source(s) is unknown. (A) conditions when no specific sources were identified at different wind speeds, represented as median received sound levels (4020 samples on 205 days: 1083 samples with 0 knot wind, 1964 samples at 10 knots, 2391 samples at 20 knots, 1501 samples at 30 knots, and 1076 samples at 40 knots). (B) Comparison of median sound levels for different sources present in the soundscape. (C) Only acoustic samples when AIS-transmitting ships are traveling within 10 km of the station, traveling at 5 knots or greater, and wind was less than 15 knots. (D) Only samples with baleen whale (excluding bowhead) sounds present (870 samples on 173 days). Solid black line = median, light gray lines = 10th and 90th percentiles.

C. Influence of soundscape components

Received sound levels across all octave bands at the Gambell recording site were influenced strongly by conditions in the abiotic environment and how these conditions vary across seasons (Table III, Fig. 4, and Fig. S3[1]). All models also included significant biological variables, and the specific biological source varied by octave band model. For example, the 125 Hz model included other baleen whales and unknown biologic sounds as significant positive predictors of sound levels. Baleen whales, including bowhead whales, were a significant positive predictor in the 500 Hz model, and presence of beluga whale calls was significant positive predictor in the 8000 Hz model. Some of the biological terms had negative coefficients (Fig. S3[1]), likely due to the correlation with abiotic features. Presence of AIS-transmitting ships at 50 km was not included as a significant predictor of sound level in any octave band; however, sun altitude was a significant term in all models. Overall model fit varied across octave bands, with increased fit in higher-frequency models (Table III and Fig. 5). We also evaluated significance of AIS vessel presence at a spatial range of 20 km to see if the spatial resolution changed model results for any of the octave band models (Table S11). The presence of AIS-transmitting ships at 20 km was not a significant predictor of sound level in any of the models.

Our comparison of different soundscape category models revealed what component of the soundscape explains the most variation in sound levels within each octave band (Fig. 5), in other words, what soundscape component (abiotic, seasonal, biotic, or anthropogenic) had the greatest influence on the received sound levels. The abiotic environment (wind and ice) explained most of the deviance in all octave band models except 1000 Hz, where seasonal conditions dominated. Biological components explained a similar amount across all octave band models (∼15%). Anthropogenic components (AIS-transmitting ships and sun altitude) explained very little of the deviations in sound levels at the site, with only a slight increase in influence within the higher-frequency models (8000 Hz).

D. Spatial comparison of sound source occurrence

When we compared the occurrence of sound sources at the two sites in the northern Bering Sea region, we found marked differences in sound source occurrence during an

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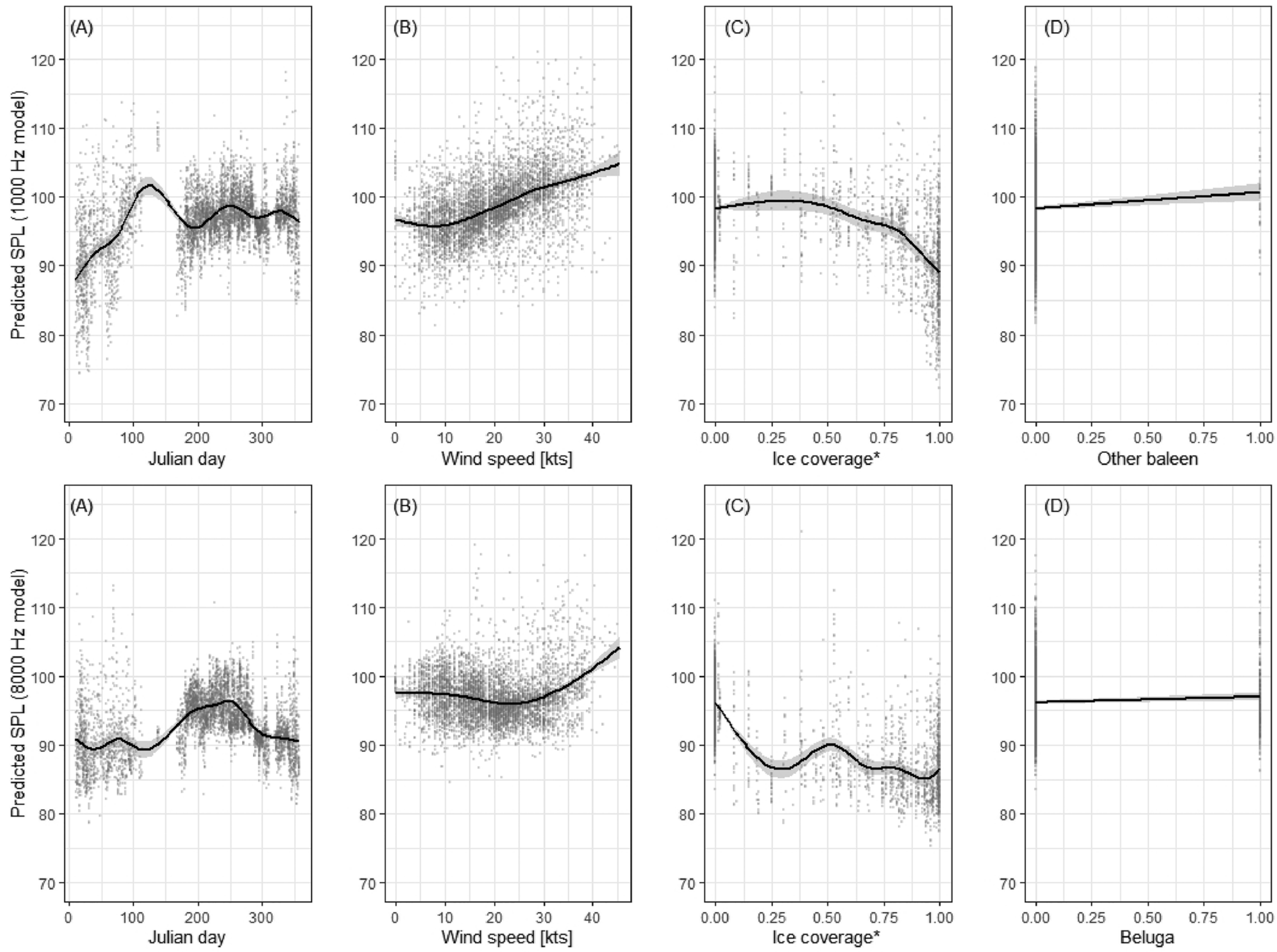

FIG. 4. Summary of relationships between predictor variables and SPLs for the two top performing models [1000 Hz (top panels) and 8000 Hz (bottom panels)]. (A) Julian day; (B) wind speed; (C) ice coverage (*, proportion of 20 km radius around site with ice); (D) most influential biological variable, other baleen whale presence for 500 Hz and beluga whale presence for 8000 Hz model. Median values are used for all other predictor variables to visualize the predictions by individual predictor variables. See Table III for summary of models and Figs. S3.1–S3.6[1] for other frequency band model results.

overlapping 13-day period in October 2015 (Fig. 6). Compared to the Gambell site (near St. Lawrence Island), the Bering Strait site to the north had more anthropogenic activity in proximity to the recorder—shown in both the anthropogenic source and presence of AIS-transmitting ships within 50 km [Fig. 6(B)]. Only three days at Gambell site had nearby AIS-transmitting ships, with the closest ship approximately 16 km away and traveling at <10 knots; these passages were not detected by the analyst [see Anthropogenic row in Fig. 6(A)]. All 13 days at the more constrained Bering Strait site had AIS-transmitting ships in the region (ranging from 8 to 50 km at closest approaches); however, the ships were only acoustically detected on three of the days [see Anthropogenic row in Fig. 6(B)] when AIS-transmitting ships were at 15–40 km away at closest approaches. When ships were detected at this site, sound levels were 3–5 dB (100–1000 Hz) above levels when no other sound sources were present and wind speed was below 10 knots (Fig. S2[1]). The biological activity also differed with more baleen whale calls (excluding bowhead whales) and unknown biologic sounds (likely fish) in the Bering Strait and more bowhead whale sounds at the Gambell site.

IV. DISCUSSION

This study uses an established soundscape paradigm to build on previous research and document important habitat features, both natural and anthropogenic, at a biological and culturally important region in the northern Bering Sea. This research advances the study of marine soundscapes in this important region by integrating different sound source contributions to quantify ambient conditions as well as variability and to characterize the most influential contributing sources. The results demonstrate the value of using passive acoustic monitoring with integrated analysis methods to characterize and compare the interrelated and rapid environmental and industrial changes occurring in the Arctic. Further, we highlight the value of characterizing the dominant acoustic features in a soundscape, rather than absolute sound level, as a method to understand and ultimately preserve natural sounds as the predominant feature in biologically rich underwater habitats.

Understanding the contribution of sources to overall sound energy in the environment complements occurrence metrics by providing a method to understand how different

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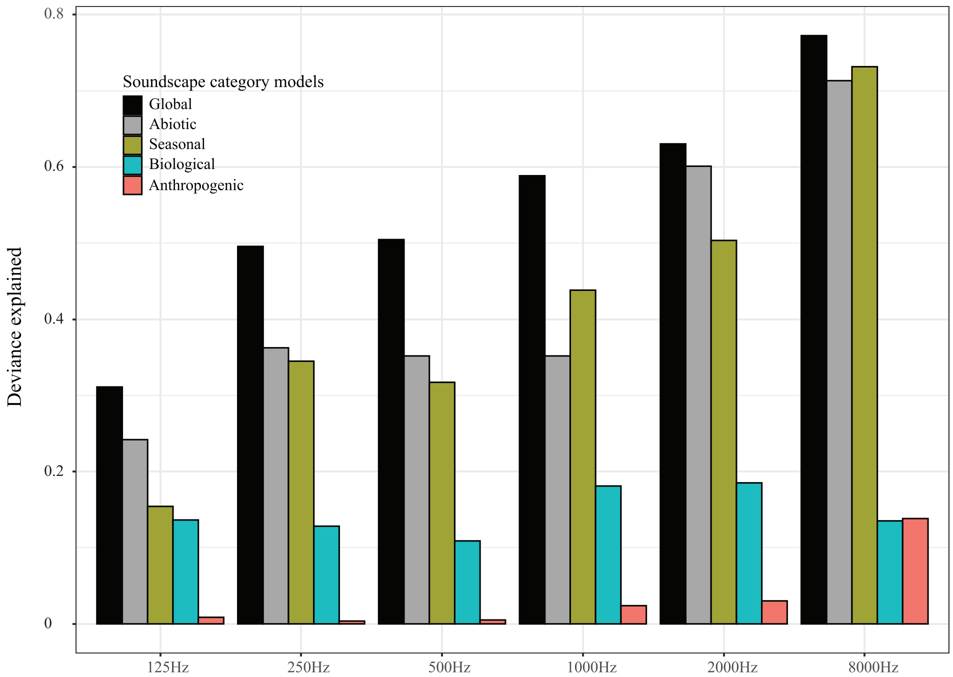

	125Hz	250Hz	500Hz	1000Hz	2000Hz	8000Hz
Global	0.31	0.50	0.50	0.59	0.63	0.77
Abiotic	0.24	0.36	0.35	0.35	0.60	0.71
Seasonal	0.15	0.35	0.32	0.44	0.50	0.73
Biological	0.14	0.13	0.11	0.18	0.19	0.14
Anthropogenic	0.01	0.00	0.01	0.02	0.03	0.14

FIG. 5. Comparison of different soundscape category models (global, abiotic, seasonal, biological, anthropogenic) and the variation in SPLs explained (measured as deviance explained) within different octave bands (*x* axis). Global models are shown in black, and variables included in the models are summarized in Table III. In soundscape category models, smoothing parameters from the global models were used to ensure fit did not change with presence or absence of correlated variables. The table reports the values for deviance explained in each model.

sources influence the soundscape. At a site near St. Lawrence Island (Gambell), our statistical modeling approach revealed that the abiotic environment (wind, ice coverage, tide) was the main driver of received sound levels across all octave band models (Fig. 5). Even with the abiotic features dominating the soundscape, both biological and anthropogenic sources were present (Fig. 2) and had some contribution to levels in different frequency bands. Bowhead whales, the source identified on the greatest number of days (Fig. 2), only positively influenced the 500 Hz octave band model (Table III). The presence of other baleen whales influenced all octave band models, although more so in the lower-frequency models (<500 Hz) where most baleen whale calls are more common (Stafford, 2013). Presence of beluga whale calls was only significant in the 8000 Hz octave band model, as expected given the frequency range of their calls. Unknown biologic sounds, which occur throughout the year (Fig. 2), had a significant influence on sound levels in the lower-frequency octave bands (Table III). This category included sounds that could not be identified because of overlap as well as faint or simply unknown sounds. Identifying these sounds may provide key insight into biological drivers in the soundscape. At a second site in the Bering Strait, there was an almost constant presence of unknown biologic sounds [Fig. 6(B)]; most of the sounds in this category were low-frequency (<100 Hz) drumming and knocking sounds consistent with unknown species of fish (e.g., Pine *et al.*, 2020). Fish sounds were also likely a source present at the Gambell site but not a focus of the initial analysis to extract biological sounds. Although pinnipeds (bearded seals and walrus) were commonly identified in the acoustic data (Fig. 2), the sign of the coefficient was negative in all statistical models, meaning presence had a negative effect on sound levels (Table III and Fig. S3[1]). This is likely an artifact of the high correlation of the presence of these species with abiotic features (Chou *et al.*, 2020), making it difficult to isolate the influence on sound levels in the global model.

With the predicted increase in shipping in this region, this year of recording can serve as a baseline to compare how vessel noise contributes to the soundscape change if commercial shipping continues to expand in this region as predicted (CMTS, 2013; Ng *et al.*, 2018). The presence of known ships within 50 and 20 km identified through their AIS-transmission signatures did not have a discernible effect on sound levels in any octave band model. AIS-transmitting ships only occurred during a 2–3-month period (73 days) during the year (Fig. 2) and represented a relatively small number of ships traveling at slower speeds (<10 knots, 5 m s^{-1}), especially when compared to activity near the Bering Strait site (Fig. 6). At this low level of ship traffic, while the influence of ship noise on soundscapes (or even detections) is relatively low at this point in time, this does not preclude other impacts such as through collisions or physical disruption of animal movements. As shipping continues to increase in the region, evaluating different spatial scales on which AIS-transmitting vessels influence the soundscape as both identifiable ship passages and more chronic low-frequency energy remains an important factor to consider.

Sun altitude, used as a proxy for the presence of smaller (non-AIS-transmitting) vessel presence, was a predictor of sound levels, with slightly higher predicted sound levels

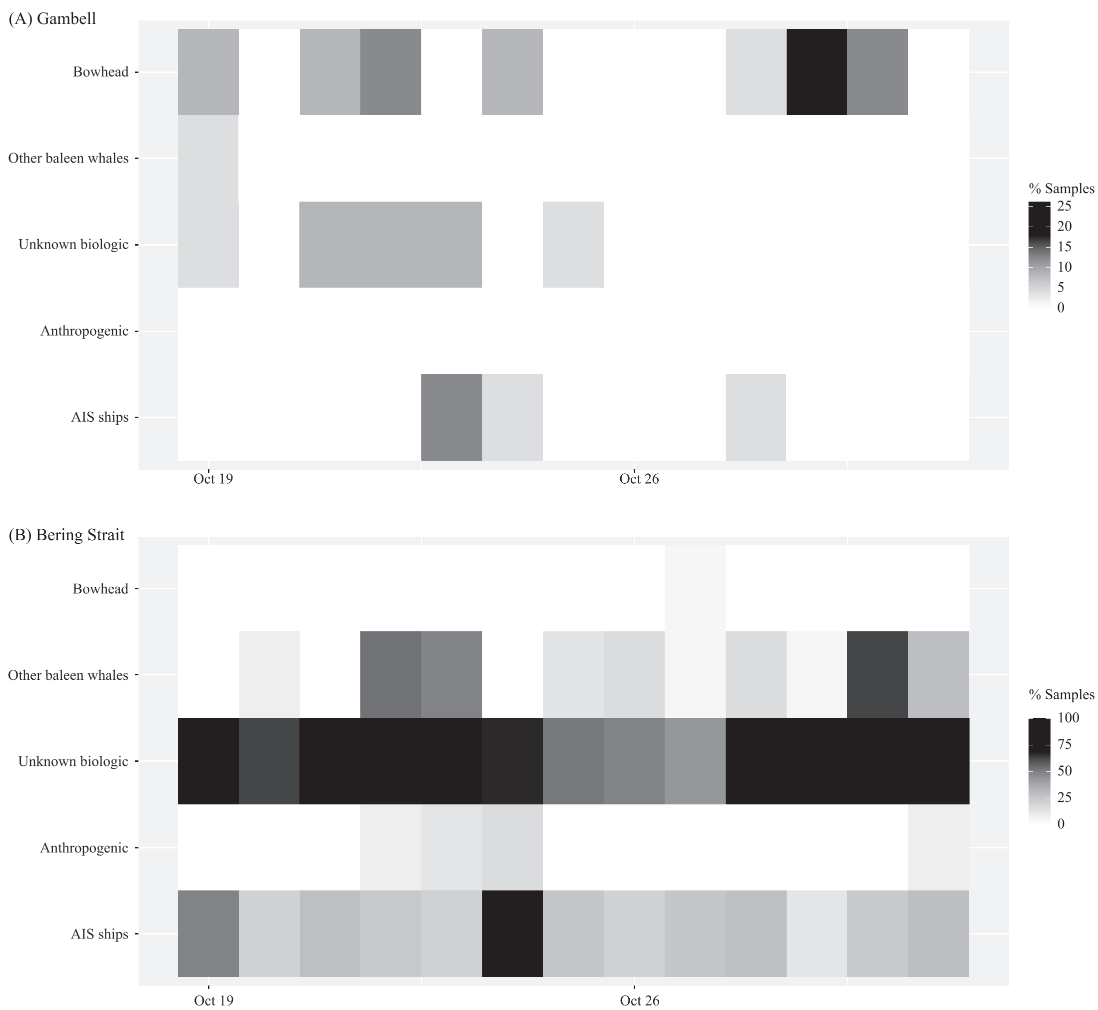

FIG. 6. The occurrence of acoustic sources for a 13-day period in October 2015 at the Gambell site (A) and Bering Strait site (B). Acoustic data were collected hourly, and color shading represents the percent of the daily samples with a specific source present.

when the sun was higher in the sky. Previous studies also showed slightly elevated daytime ambient noise levels (Southall *et al.*, 2020), and our modeling approach allowed us to control for other variation in the data to understand this contribution to the soundscape. While these results might indicate increased human daytime activity and effects on the soundscape, it is possible the sun altitude metric also represents other soundscape components, like fish calling, and therefore interpretation of this relationship is limited. More precise metrics of human activity from small vessel traffic such as hunting skiffs and fishing vessels are needed and recommended for future studies, possibly using vessel detection methods (Solsona-Berga *et al.*, 2020); these vessels are known to alter underwater soundscapes, especially in nearshore environments. Further, other environmental conditions from both wind and fog might also predict small boat activity, especially from hunting skiffs (Huntington *et al.*, 2013).

Each octave band model differed in terms of the relative contribution of each soundscape component (abiotic, seasonal, biotic, and anthropogenic), and performance of the global models increased with frequency (Fig. 5). The 125 Hz octave band model explained the least amount of variance in the received sound levels (31%) with abiotic environment as the dominant soundscape component and similar explained deviance for seasonal and biological components (∼15%). At these low frequencies, shear currents can induce strumming or flow noise into acoustic recordings from fixed recorders, especially in relatively shallow waters, where wave and tidal activity may be present. We included a metric to account for this effect—the difference in height above sea level from the previous hour (tide)—and including it improved the model fit. Another possible source contributing to low frequencies is fish sounds; however, identifying these sounds was not a focus of the initial analysis and therefore not accounted for in the models. Evidence for this possibility is the almost constant fish sounds present at the Bering Strait site, coded as unknown biologic (Fig. 6).

The 250 and 500 Hz global model both explained 50% of the variation in received sound levels, and the seasonal and abiotic components explained similar amounts of deviance, indicating that both these features dominate the soundscape. The 1000 Hz model showed a stronger influence of seasonal and biological components and, unlike the other octave bands, is less influenced by the abiotic environment (Fig. 5). This shift likely indicates that the presence of marine mammals in the winter months (Chou *et al.*, 2020) is the dominant soundscape component in this frequency band. The 1000 and 2000 Hz models performed similarly (~60% explained deviance), but the abiotic environment was the dominant soundscape component in the 2000 Hz model. The 8000 Hz global model had the highest explained deviance (77%), and the seasonal component of the soundscape explained slightly higher deviance than the abiotic features. Explained deviance for anthropogenic sources was highest in this model (15%), likely from the sun altitude variable. Including additional variables on human activity and quantifying additional biological sounds present would likely improve model performance. We show that the 500 and 8000 Hz octave band models hold promise for making comparisons across years to understand how shifts in the presence of sources influence the dominant components of this soundscape.

We provide an annual prediction of the main acoustic contributors to the local soundscape and enable future comparisons given environmental changes and increasing human use of the Bering Sea. We explored monthly predictions of the dominant soundscape components. However, using these divisions in the data set will likely mask the rapid seasonal shift occurring in the Arctic (Baker *et al.*, 2020) when comparing conditions across years; therefore, we only presented the annual models. Currently, anthropogenic sources do not contribute significantly to the measured sound levels and therefore are not a dominant feature of the soundscape in this region. The sound levels are high from multiple biological sources (baleen whales, odontocetes, and pinnipeds) and abiotic conditions (Fig. 3), and these natural sources of sounds are the predominant feature of the soundscape. Unique to this study is incorporating multiple species to understand the biological component of the soundscape. Within a global context, soundscapes are rapidly changing, and many studies have documented the intrusion of human-generated noise and the consequences of a shift from naturally dominated to human-dominated (Duarte *et al.*, 2021). There is an opportunity in this region for more sustainable development to protect this unique and valuable soundscape.

Where local and regional shipping traffic increases, both the occurrence and dominance of ship noise in the coincident soundscape is expected, perhaps most notably in the Bering Strait location, where there is a notable difference in shipping activity (Fig. 6) as well as a concentration of that activity due to the relatively constrained nature of the shipping lanes in this region. Using both ship traffic metrics and acoustic metrics of vessel presence will be key in understanding the spatial extent of vessel contribution to the soundscape. A shift to a more anthropogenically dominated soundscape will alter the availability of cues from conspecifics through reduced communication ranges (Frankel and Gabriele, 2017; Hatch *et al.*, 2012; Fournet *et al.*, 2018), masking of important biological cues (Fournet *et al.*, 2021), and loss of information from the abiotic environment (Miksis-Olds and Madden, 2014). In addition to tracking changes in the soundscape from human use patterns, the soundscape will also show changes related to reduced ice coverage and perhaps shifts in biological use. Monitoring shifts in soundscapes can inform conditions at which species respond and is therefore useful for developing strategies for reducing impacts on marine mammals, upon which Alaska Native communities critically depend. In the context of this project, local communities were involved in project logistics and data collection (Buckiewicz, 2020; Robards *et al.*, 2017), and we provided accessible data interpretation for communities to include the information in marine mammal co-management strategies. Co-production models that involve extensive local engagement in various stages of the project are a key strategy for building this information into policy (Chou *et al.*, 2021; Robards *et al.*, 2018).

Scaling up soundscape analysis to broader spatial and temporal scales using the methods in this research holds important implications for monitoring and effectively managing the rapidly changing Arctic. Perhaps most importantly, strategic and regular monitoring must be maintained, including over-winter moorings in locations with previous measurements to replicate animal presence, sound levels, and similar and enhanced measurements of environmental factors and human industrial activity. Higher sampling rates would capture other biological sources (e.g., odontocetes), and improved storage and battery capacity would allow for similar deployment durations at these sampling rates. Further, future applications would benefit from applying automated methods for feature extraction and classification. There are numerous algorithms and tools to extract different sources in an acoustic recording (Kvsn *et al.*, 2020). These tools range from manual extraction by a trained analyst (Chou *et al.*, 2020) to fully automated techniques (Seger *et al.*, 2018). Fully automated feature extraction methods for acoustic data are a rapidly increasing field of research and have the potential to open many opportunities to then integrate the occurrence of the sounds to better understand how soundscapes are changing. Pairing acoustic sensors with other marine observation platforms would improve metrics on the conditions of the abiotic environment to better understand how these features influence the soundscape. Integrating other sources for monitoring human activity in coastal environments will also likely improve predictions. Last, systematic and strategic spatial sampling is needed to capture the variation in conditions in both biological and culturally important habitats and possible shifts in habitat use.

V. CONCLUSION

By integrating the occurrence of biological and anthropogenic sources and conditions of the abiotic environment with measured sound levels, we characterize the dominant acoustic features at a biologically and culturally important site in the northern Bering Sea. We also compare occurrence of sources with a second site and show how increased shipping changes the soundscape. Our results using a soundscape framework show that, at least for the year sampled, the abiotic environment is the main feature in this soundscape and driver of sound levels across all octave bands, with seasonal biological sources as other dominant features. Currently, anthropogenic sources do not contribute significantly to the measured sound levels and therefore are not a dominant feature of the soundscape. Although sound levels are high from biological and abiotic sources, maintaining and protecting natural sounds as the predominant feature of the soundscape is of key importance from a conservation perspective, especially given the number of marine mammal sounds in the soundscape. The methods applied in this study offer a robust framework, applied to a relatively recent acoustic data set, to track how a soundscape changes by identifying the most influential predictors of sound levels with changes in both the abiotic environment and patterns of human activity.

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[1]See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0006099 for a series of figures with descriptions showing results from various analytical methods.

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