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Seasonal acoustic environments of beluga and bowhead whale core-use regions in the Pacific Arctic

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ABSTRACT

The acoustic environment of two focal Arctic species, bowhead (*Balaena mysticetus*) and beluga (*Delphinapterus leucas*) whales, varied among the three core-use regions of the Pacific Arctic examined during the months in which both species occur: (1) January-March in the St. Lawrence Island/Anadyr Strait region, (2) November-January in the Bering Strait region, and (3) August-October in the Barrow Canyon region. Biological noise (consisting of the signals of bowhead whales, walrus and bearded seals) dominated the acoustic environment for the focal species in the St. Lawrence Island/Anadyr Strait region, which was covered with ice throughout the months studied. In the Bering Strait region whales were exposed primarily to environmental noise (in the form of wind noise) during November, before the region was ice-covered in December, and biological noise (from bowhead and walrus) again was prevalent. Anthropogenic noise dominated the Barrow Canyon region for the focal species in late summer and fall (August through October); this was also the only region in which the two species did not overlap with sea ice. Under open water conditions both near Barrow Canyon and in Bering Strait, noise levels were tightly correlated with wind. However, with climate-change driven increases in open water leading to rising noise levels across multiple fronts (atmospheric, biological, anthropogenic), the relatively pristine acoustic environment of Arctic cetaceans is changing rapidly. Characterizing the acoustic habitat of these regions before they are further altered should be considered a management and conservation priority in the Arctic.

1. Introduction

The acoustic ecology of a species can be described by how an animal uses, and is influenced by, sound in its environment (Pijanowski et al., 2011; van Opzeeland, 2010). Marine animals evolved in varying underwater acoustic environments over millions of years, which certainly influenced their acoustic ecology. However, the rapid rise of anthropogenic noise over the past ~150 years, and its subsequent modification of the acoustic environment, may be presenting some challenges to these animals that rely primarily on sound to communicate, navigate, find food, avoid predators, and maintain contact with each other. Anthropogenic signals produced at frequencies overlapping those used by marine animals are candidates for disrupting the acoustic ecology of those species (Clark et al., 2009). This is of concern in rapidly developing regions like the Arctic (Gervaise et al., 2012; Reeves et al., 2014). An understanding of the variability of noise levels to which Arctic cetaceans are exposed throughout their migratory route can be used to study underwater acoustic environments and establish baseline levels of noise exposure to address noise disturbance by human activities (Moore et al., 2012; Reeves et al., 2014). There is a growing body of research documenting the impacts of noise on the acoustic ecology of marine mammals among which include changes in frequency or amplitude of signals used by animals (Parks et al., 2007, 2011), changes in call rate (Blackwell et al., 2015), increases in stress hormones (Rolland et al., 2012), decreased foraging (Blair et al., 2016), and spatial displacement (Castellote et al., 2012a).

Van Opzeeland (2010) categorized the acoustic ecology of polar marine mammals as driven by anthropogenic, biotic, and abiotic factors each of which may influence the behavioral ecology of each species. In her example, the seasonal and temporally varying sound production by animals (in the context of distribution, migration, or reproductive behavior) is influenced by variations of the natural acoustic environment (ice, wind, waves, predators, and prey) and, more recently, anthropogenic inputs (increases in noise, climate change). Depending upon the species, season, and location, the local underwater acoustic environment can play a role in shaping the acoustic ecology of Arctic

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species. Changes in the physical environment, whether sustained (climate change) or short-lived (anthropogenic activity), are likely to cause changes in this acoustic environment. The bellwether of change in the Arctic is the decrease in seasonal sea-ice extent or, conversely, the expansion of the open water season. Not only does this shortened sea-ice season permit increased human activities in the Arctic and the occurrence of seasonal subarctic species over longer periods and into previously unoccupied areas, but increased open water makes it likely that the contribution of wind to ambient noise levels in the Arctic will also increase (Menze et al., 2017). These elements (industrial use, subarctic species, meteorological inputs) have the potential to increase ambient noise levels in frequency bands that are most used by Arctic marine mammals.

1.1. Abiotic, biotic and anthropogenic sound sources in the Pacific Arctic

The abiotic acoustic environment in the Pacific Arctic presents contributions of both natural and anthropogenic origin (Moore et al., 2012; Roth et al., 2012). Many of these sources overlap in frequency with the signals of marine mammals. Natural sources of noise include wind, waves and sea-ice (Farmer and Xie, 1989; Langley, 1989; Lewis and Denner, 1987; Waddell and Farmer, 1988). Wind produces noise in the ocean through the development and breaking of waves on the surface of the water. There is a direct correlation between wind speed and noise levels under ice-free conditions (Carey and Evans, 2011; Menze et al., 2017; Wenz, 1962) over the frequency range of roughly 200 Hz to 30 kHz; noise levels are often higher in shallow water than deep water (Ramji et al., 2008; Wenz, 1962). Winds, and their contribution to the acoustic environment in the Pacific Arctic, have been increasing over the past 25 years due to changes in the relative strengths and positions of the Beaufort High and the Aleutian Low (Pickart et al., 2013). Although under-ice ambient noise levels can be very quiet when there is little wind, current or drift, large-scale ice motion and deformation forced by meteorological events generates ice cracking, fracturing, shearing, and ridging producing broadband impulses, frequency modulated tones, and high-frequency broadband noise (Kinda et al., 2015). Low frequency bands (< 100 Hz) tend to be influenced by wind and ice drift while changes in atmospheric temperature that cause ice fractures contribute more to mid- and high frequencies (500 Hz to 5 kHz, Makris and Dyer, 1986; Xie and Farmer, 1991).

Biotic sources of sound in the Arctic are primarily from marine mammals. Bowhead whales (*Balaena mysticetus*) sing from November to late April, occasionally into May (Stafford et al., 2012). This encompasses both the fall (southbound) and spring (northbound) migrations. Bowhead songs are complex, broad-band (~30 Hz to 5 kHz), acoustic displays that are thought to be a reproductive strategy, likely of males, and which vary within and between years (Johnson et al., 2015; Delarue et al., 2009; Stafford et al., 2008). During the summer and fall, bowheads produce much simpler, lower-frequency (< 500 Hz), sounds that are likely used to maintain contact among migrating animals, navigate in ice, and to socialize (Blackwell et al., 2015; George et al., 1989; Würsig and Clark, 1993). These signals are primarily low-frequency amplitude- and frequency-modulated signals. Songs, however, are much longer and broader-band than the simpler signals used at other times of the year. Because bowhead sounds are relatively low frequency, they can be reliably detected as far as 30 km away, depending on their source level as well as levels of ambient noise (Bonnel et al., 2014)

Beluga whales (*Delphinapterus leucas*) echolocate to find and capture food and navigate but also have a highly variable repertoire of social signals that can be pulsed, tonal or mixed in nature (Bel'kovich and Sh'ektov, 1990; Chmelnitsky and Ferguson, 2012; Sjare and Smith, 1986). These two types of sounds are produced at very different time and frequency scales. Echolocation in belugas ranges from 20 kHz to 160 kHz with clicks produced every 30–200 ms in long click trains with highly variable inter-click intervals, that can be shorter than 2 ms when emitted in buzzes (Roy et al., 2010). Beluga whales have been shown to adapt the peak frequency of their echolocation clicks under different sources of ambient noise (Au et al., 1985). 'Social' calls of belugas are lower in frequency (400 Hz to 20 kHz) and longer (0.1–3 s, Sjare and Smith, 1986) and can be detected farther than echolocation signals (1–3 km versus < 1 km, Castellote et al., 2015; Simard et al., 2010).

Other biotic signals that typically dominate the Pacific Arctic acoustic environment include the trills of bearded seals (*Erignathus barbatus*), which are relatively broadband long signals from 50 Hz to 6 kHz (Cleator et al., 1989; Ray et al., 1969), and walrus (*Odobenus rosmarus*) knocks, which are broad band pulsive signals from about 0.2 to 8 kHz (Stirling et al., 1987; Sjare et al., 2003). There are other Arctic and subarctic marine mammals seasonally visiting the Pacific Arctic, but their vocal behavior is not typically prevalent (e.g. ringed seals, *Pusa hispida*, ribbon seals, *Histriophoca fasciata,* spotted seals, killer whales, *Orcinus orca*, fin, *Balaenoptera physalus*, minke, *B. acutorostrata,* and humpback whales, *Megaptera novaeangliae*, and porpoises, Phocoenidae spp). As the sea-ice-free season continues to increase (Laidre et al., 2015), the sounds of subarctic species may become a more important contributor to the acoustic environment (Woodgate et al., 2015).

As in other regions of the global ocean, the predominant local anthropogenic sound sources in the Pacific Arctic are mainly comprised of shipping and geophysical exploration. In the Arctic, these sources have been historically limited to the open water season, between July and early October. Distant and mid-range ship noise consists primarily of low-frequency (< 1 kHz) continuous tones caused by propeller cavitation and blade harmonics, but higher frequency sounds (up to several kHz) from the main engine firing rate, auxiliary engines (e.g. diesel generators) or other reciprocating machinery can be detected within a few kilometers of the ship (Arveson and Vendittis, 2000; Veirs et al., 2016; Wales and Heitmeyer, 2002). Distance, but also ship speed, size, and load influence the frequency and amplitude of received shipping noise (McKenna et al., 2012). Seismic exploration exercises profile the bottom composition by repeatedly discharging impulses from towed airgun arrays (normally fired at intervals of 10–20 s) that create broadband signals in a frequency range of 1 Hz to > 1 kHz if recorded at long range, but much higher frequencies at closer distances (DeRuiter et al., 2006; Goold and Fish, 1998; Madsen et al., 2006), even though airgun arrays are designed to produce a low frequency peak signal centered around 50 Hz (Greene and Moore, 1995). Recent studies in shallow waters of the Pacific Arctic have shown that environmental reverberation can elevate ambient noise levels during the inter-impulse period by as much as 9 dB re 1 μPa (Guerra et al., 2011; Guan et al., 2015).

1.2. Beluga and bowhead whale core-use areas

In the Pacific Arctic, there are two endemic cetaceans, the bowhead whale (*Balaena mysticetus*), the only Arctic mysticete, and the beluga whale (*Delphinapterus leucas*), one of two species of toothed whale that live year-round in the Arctic. Although both species have largely circum-Arctic distributions, they occur in discrete populations around the Arctic. Bowhead whales in the Pacific Arctic are known as the 'western Arctic' or 'Bering-Chukchi-Beaufort' population of whales and migrate annually, as might be ascertained from their name, between the Bering and Beaufort Seas via the Chukchi Sea (Citta et al., 2012; Moore and Reeves, 1993; Quakenbush et al., 2010). The annual movements of this population include transits among five core-use areas (regions of extended residency by animals used annually, as defined by probability density kernels derived from locations of satellite-tagged individuals, e.g. Citta et al., 2012, 2015; Hauser et al., 2014) in the Pacific Arctic: the Amundsen Gulf in May through September, the western Beaufort off Barrow, Alaska in August through October, along Chukotka, Russia in November and December, the Bering Strait in November through

February and then again in April-May and the northwestern Bering Sea near St Lawrence Island in January through March (Citta et al., 2015).

At least two populations of beluga whales also migrate annually between the Bering and Beaufort Seas, the Eastern Chukchi Sea and the Beaufort Sea populations (Stafford et al., this issue). The Beaufort population of belugas migrates north earlier in the year than the Chukchi population and each population appears to have distinct core-use areas that vary over time (Hauser et al., 2014; Stafford et al., this issue). Beaufort Sea belugas have core-use areas in July through September in the Amundsen Gulf region, specifically the MacKenzie River Delta region and Viscount Melville Sound; in October and November, they occur near Barrow Canyon, towards Chukotka and in Bering Strait, and in Anadyr Strait and near Saint Lawrence Island in January-March (Citta et al., 2017; Hauser et al., 2014; Luque and Ferguson, 2009). Chukchi beluga whales spend July through October in the Alaskan Beaufort Sea with a core-use area around Barrow Canyon before moving southwards to the Bering Strait region in November and spend December through March north of St Lawrence Island (Citta et al., 2017; Hauser et al., 2014).

Migratory populations of beluga and bowhead whales are exposed to different acoustic environments during migration and residency in different core-use areas and thus their acoustic ecology may be seasonally and spatially dependent. For this reason, it is important to consider the ambient noise characteristics of all key habitat areas for each species.

To examine the spatial and temporal variability of the acoustic environment in the Pacific Arctic, Clark et al. (2015) used passive acoustic data collected contemporaneously at 20 sites grouped into 5 regions from the Bering Sea through the Chukchi Sea and eastward towards the Canadian Beaufort Sea. This unprecedented synthesis of acoustic data provided a “year in the acoustic world of bowhead whales” that examined the time-varying noise levels across the entire migratory pathway of western Arctic bowheads (Clark et al., 2015). Migrating bowheads (and belugas) experience a range of ambient noise levels during their annual movements from the Bering Sea through the Chukchi Sea into the Beaufort Sea and back again. These levels are influenced by transient events such as storms or ship passages, but also more persistent signals such as open water season air gun surveys, and winter and spring chorusing of marine mammals (Clark et al., 2015).

The data presented here are a follow-on to that recent study and are used to examine the sources of ambient noise during times and locations that are considered core-use areas for bowhead, as well as for beluga whales (Citta et al., 2015; Kuletz et al., 2015; Citta et al., 2017). For this synthesis, we focus on: Anadyr Strait/St Lawrence Island (Clark et al., 2015 Region 1), Bering Strait (Clark et al., 2015 Region 2), and Point Barrow (Clark et al., 2015 Region 4, Fig. 1). Acoustic data from the Canadian Beaufort, which is a core-use area for both bowhead and beluga whales were not used in Clark et al. (2015) ambient noise analysis (and were not available for the current analysis). Recent publications from this region over the same bandwidth, however, now exist for November to June (Kinda et al., 2013). In the Pacific Arctic, the open water season (August-October) is when bowhead and beluga core-use areas overlap spatially with oil and gas industry activities, primarily in the near shore Canadian and Alaskan Beaufort Sea (Reeves et al., 2014). During winter and spring (December through May), they overlap primarily with other biotic sources of noise – both the signals they produce, and those produced by other marine mammals and from conspecifics (Hannay et al., 2013; MacIntyre et al., 2015).

Here we examine bowhead and beluga core-use areas to examine the different biotic and abiotic contributors to the ambient noise environment to which these species are exposed. For the three regions, and broad seasons presented here, the Anadyr Strait/St. Lawrence Island area (Region1) is a core-use area only in winter (December through March), the Bering Strait (Region 2) is a core-use area for bowhead and/or beluga whales in fall and winter (November through January) and Point Barrow (Region 4) is a core-use area for both species late summer through fall (August through October, Fig. 1, Table 1). First, we present the temporal occurrence of the natural and anthropogenic sound sources in hours detected per day for each region, to display the seasonality of contributors to the acoustic environment. This is followed by long-term spectral averages and concurrent sea ice concentration and wind speeds over each three-month period, which highlights the broadband, time-varying acoustic environments. Power spectral densities and empirical probability density functions are shown by month to illustrate the frequency-dependent variability in the acoustic environment. Finally, correlations between wind speed and mean broadband noise levels examine the relationship between wind, ice, and noise at each location.

2. Methods

Three underwater acoustic recorders (Aural-M2, multi-electronique.com) were moored in the Bering, Chukchi, and Beaufort Seas (Fig. 1) to record ambient noise in each region. The instruments sampled acoustic data for an entire year beginning in August or September on a duty cycle of 9 min/20 min for Region 1 and 9 min/30 min for Regions 2 and 4 at a sample rate of 8192 Hz (with 16-bit resolution) and effective bandwidth 10–4096 Hz (Clark et al., 2015), and gain of 16 dB. Per the manufacturer's specifications, this results in a signal saturation level of 154 dB re 1 μPa. The instrument noise floor has been reported as ~ 52 dB re 1 $\mu Pa^2\ Hz^{-1}$ for 0–4096 Hz (Kinda et al., 2013).

These data were previously used for a 14-month study of the acoustic environment of bowhead whales (Clark et al., 2015). That study examined the presence of bowhead whale signals at 20 sites in the Pacific Arctic and presented overall ambient noise levels from 10 of these sites but did not examine the specific sources of noise. Here we re-examine data from three of the sites in more detail to investigate how the physical and biological environment influences noise levels in the frequency range 10–4096 Hz during the months when Arctic species occupy these core-use areas. Each site was chosen because it was defined by satellite telemetry studies as a shared core-use area for both bowhead and beluga whales (Citta et al., 2012; Hauser et al., 2014; Kuletz et al., 2015; Citta et al., 2017). The data were limited to just those months considered core-use months for both species (Table 1).

For each of the three sites during its respective core-use period, the daily occurrence of vocal animals and anthropogenic noise sources (ships, airguns), was determined by manually viewing spectrograms (1 s window, 50% overlap, Hanning window) of all individual acoustic data files from each location and month examined, and noting the presence (or absence) of sources per hour.

To check the frequency distribution of overall ambient noise levels, a long-term spectral average (LTSA, window size 120 s, 50% overlap, Hanning window) was produced for each core-use region and its associated 3-month core-use period. Sound pressure levels (SPL in dB re 1 μPa) and power spectral density (PSD, in dB re $\mu Pa^2\ Hz^{-1}$, window size 1 s, 50% overlap, Hanning window) were calculated over 60 s windows for the effective frequency range of recordings used (10–4096 Hz). Monthly average values for PSD, 5th, 50th and 95th noise percentiles were obtained, as well as the empirical spectral probability density (SPD) for each month, following Merchant et al. (2013, 2015). Every file for which the mean SPL exceeded 72 dB re 1 μPa was manually scanned as an individual spectrogram and the source of noise identified. This dB threshold corresponded with the 95th percentile of the mean monthly SPL. Monthly arithmetic means for broadband SPL values were calculated to compare overall sound pressure across core-use areas.

Wind speed and ice coverage were obtained for the core-use regions and seasons. High resolution wind speed measurements were obtained from the North American Regional Reanalysis (NARR) database, which grids zonal (u) and meridional (v) wind components in 3-h time intervals and a ~ 32 km spatial resolution (Mesinger et al., 2006). The NARR project re-analyzes historical data (1978-onwards) from the

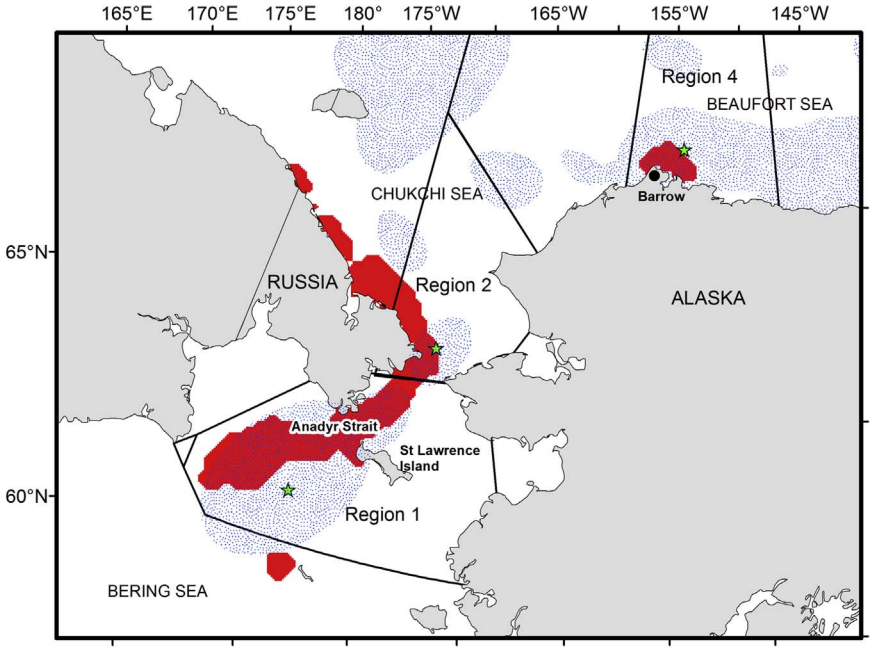

Fig. 1. Map of the Pacific Arctic showing hydrophone locations (green stars) in regions defined by Clark et al. (2015); bowhead (red) and beluga (blue stippled) core-use areas (adapted from Citta et al. (2015), Hauser et al. (2014) and Citta et al. (2017)) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Table 1
Core-use areas of bowhead and beluga whales and sources of biotic and abiotic sound by season and region, as defined in Clark et al. (2015) and Reeves et al. (2014). Shaded boxes are locations/seasons where whales generally do not occur.

Region (from Clark et al. (2015))	Spring-Summer (April- July)	Summer-Fall (August-November)	Winter (December-March)
1: Anadyr Strait/St Lawrence I			Beluga (Dec-Mar) Bowhead (Jan-Mar) Wind/Ice
2: Bering Strait		Beluga (Nov) Bowhead (Nov) Shipping Wind	Beluga (Dec) Bowhead (Dec, Jan) Walrus Wind/Ice
4: Point Barrow	Beluga (Jul) Bearded seal Shipping Wind/Ice	Beluga (Aug-Nov) Bowhead (Sep, Oct) Seismic surveys (Aug-Oct) Shipping (Aug-Oct) Wind	

National Center for Environmental Prediction (NCEP) Eta Regional Model. The wind speed measurements selected for this study were recorded at 10 m above sea surface level (Danielson et al., 2014; Huntington et al., 2013).

To examine the influence of wind speed on noise levels, 3-h averages of interpolated wind speeds were plotted against mean broadband SPL. A linear polynomial was calculated in Matlab to determine correlation coefficients between the two variables.

Sea-ice concentration (AMSR-E Aqua 12.5 km resolution) data were obtained from the National Snow and Ice Data Center (Cavalieri et al., 2014). The zonal statistics toolbox in ArcMap 10.0 (ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute) was used to determine mean daily sea-ice concentration within a 20-km radius around each mooring site.

3. Results

3.1. Acoustic environment by region and season

3.1.1. Region 1: Anadyr Strait/Saint Lawrence Island in winter (January, February, and March)

Overall, this region had the highest average monthly SPL ranging from 70.8 to 78.9 dB re 1 µPa with biotic signals dominating the acoustic environment. The acoustic detections of both targeted species show that bowhead whale sounds were present in almost every hour of every day from January through March while belugas were recorded more often from the end of February through March (Fig. 2a). These results were expected as this is a known wintering area for both bowhead and beluga whales from January through March (Citta et al., 2012, 2015, 2017). Depth-of-dive data from tagged bowheads seems to suggest that this region, and particularly the Gulf of Anadyr and Anadyr Strait, may be important feeding grounds for wintering bowheads (Citta et al., 2015). Loud, broadband, bowhead whale songs occurred more often in January, and produced the highest SPL values (78.9 ± 7.9 dB re 1 µPa), while the signals in February and March appeared to be from more distant (or quieter) animals, yielding lower SPLs (70.4 ± 1.7 dB re 1 µPa and 70.8 ± 7.0 dB re 1 µPa, respectively). It is possible that the decrease in loud bowhead whale detections from January through March could be due to changes in prey availability, which might determine when bowheads leave this region (Citta et al., 2015). This area is also believed to be an overwintering region for both eastern Beaufort and eastern Chukchi belugas, although this is based on relatively few satellite-tagged whales (Citta et al., 2017). Their habitat preferences for this area might be driven by avoidance of predation by killer whales, habitat partitioning among beluga populations, or a combination of both, thus their detection distribution within the January-March period is less predictable.

In addition to bowheads and belugas, bearded seal trills and walrus knocks were recorded daily (Fig. 2b). An example spectrogram from late March shows the overlapping signals of all four species dominating the acoustic environment (Fig. 3a). During the months of January through March, no anthropogenic sound sources were identified.

The long-term spectrogram displays pulse-like increases (short but broadband) in ambient noise across all months, and these events appear to become more frequent as the season progresses (Fig. 4a). Initially the broadband pulses were hypothesized to be driven by fluctuations in air

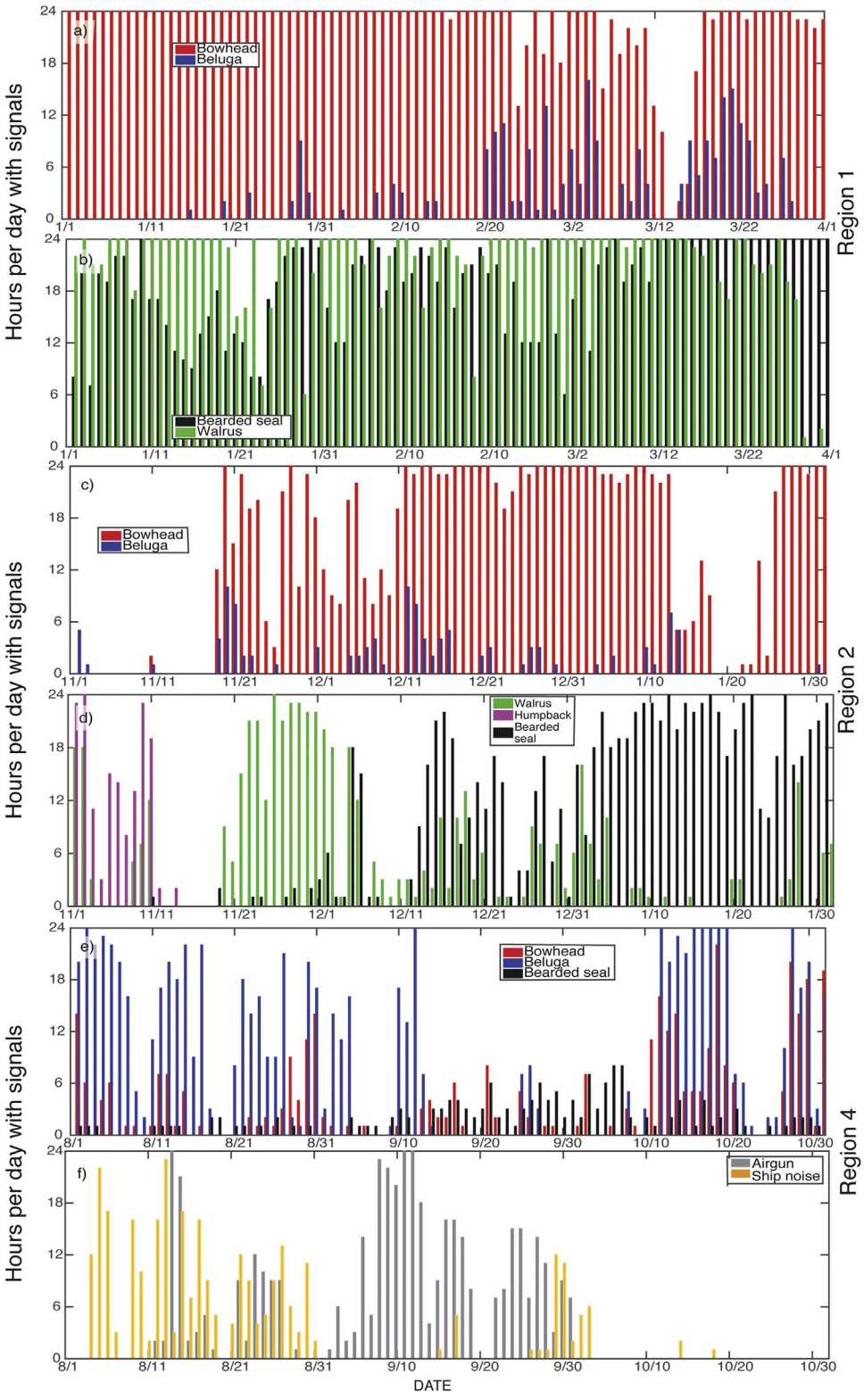

Fig. 2. Histograms of manually detected biotic and abiotic signals from the core-use areas and seasons. For all histograms the y-axis represents the number of hours per day with at least one signal of interest detected. Region 1: a) bowhead (red) and beluga (blue) whales and b) bearded seal (black) and walrus (green) signals from 1 January to 31 March 2009; Region 2: c) bowhead (red) and beluga (blue) whales and d) bearded seal (black), walrus (green) and humpback whale (purple) signals from 1 November 2009 to 31 January 2010; Region 4: e) bowhead (red), beluga (blue) and bearded seal (black), f) from ships (orange) and airguns (gray) from 1 August 2009 to 31 October 2009 (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

temperature that can cause ice fractures, but upon further examination of the individual spectrograms for those dates and times where received mean SPLs were greater than 72 dB re 1 μPa (n = 88), it became clear that these increases were most often the result of walrus knock sequences (24%), bowhead whale song (18%), or a combination of the two (18%). Only 3% of the loudest files could be attributed to ice alone while the remaining files were a combination of ice noise and bowhead, bearded seal, and/or walrus. Effectively, then, in the Anadyr Strait/Saint Lawrence Island winter area, biotic signals of marine mammals are dominating the acoustic environment from January through March.

Both the SPDs and PSDs for each month (Fig. 5a-c) show the clear contribution from bowhead whale vocalizations in January, which can be seen as a pronounced hump from 100 Hz to 700 Hz (Fig. 5a). Although this contribution can also be seen in February and March (Figs. 5b, c), levels are much lower than in January (Fig. 5a). The flattening of the spectral percentile results suggests that at higher

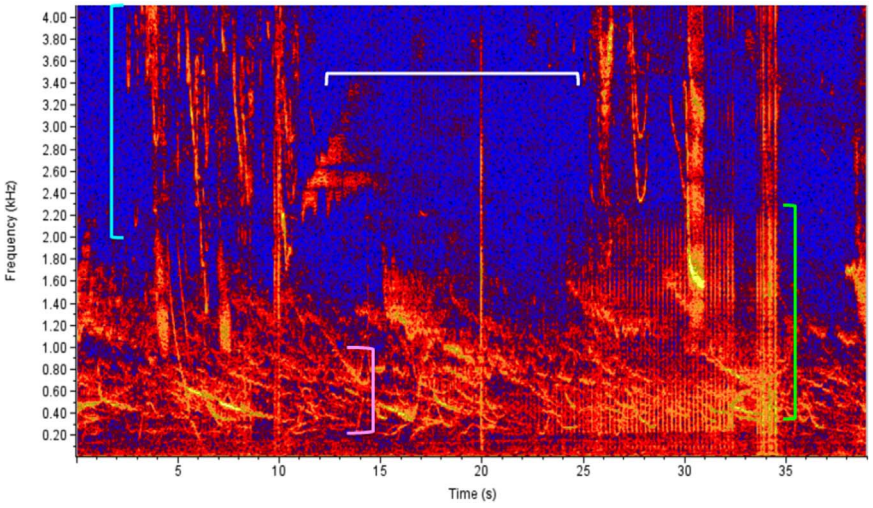

Fig. 3. Region 1: Spectrogram of acoustic data from 20 March 2009 showing signals of belugas (light blue bracket), bowheads (purple bracket), bearded seals (white bracket) and walrus (green bracket; 1024 pt FFT, 50% overlap, Hanning window) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

frequencies (> 1000 Hz), the recordings are approaching the noise floor of the Aural (Fig. 5a-c). Days with ambient noise levels below this threshold will therefore not be correctly characterized in our recordings for this region. In the data presented here, frequencies above 1 kHz approached the noise floor (Fig. 5a-c).

When comparing wind and ice data to the noise levels (Fig. 6a), there was no correlation between wind speed and ambient noise levels for any of the three months examined (January R^2 = 0.01, February R^2 = 0.06, March R^2 = 0.02). From January to March, the hydrophone location was completely ice-covered. The mean sea-ice concentration in the 30-km buffer around the hydrophone never dropped below 100% (Fig. 4a). These results illustrate the role of heavy sea-ice in decoupling the underwater environment from atmospheric processes. This is similar to the results of Roth et al. (2012) who found that wind speed best predicted noise levels in open water versus ice cover greater than 75%.

3.1.2. Region 2: Bering Strait in late fall and early winter (November, December, and January)

Acoustic detections of bowhead whale songs began in late November and continued through the end of January with extensive singing occurring in December and January (Fig. 2c). Beluga whales, on the other hand, were recorded in discrete bouts from early November through early January. As in the Bering Sea, other biotic contributors to the acoustic environment included walrus, particularly from late November through December, and bearded seals from December through January (Fig. 2d). Of note during this time, although not overlapping extensively with any Arctic species except walrus, are the signals of humpback whales that were recorded over about a week in early to mid-November (Fig. 2d).

The Bering Strait region was much more dynamic in terms of environmental variables because the monitored time period started with open water, continued through the development of sea-ice and the marginal ice zone and ended with 100% sea-ice concentration. During the month of November, during open water or ice-formation conditions, several episodes of sustained high ambient noise occurred that spanned the entire frequency range (Fig. 4b). Individual spectrograms of the dates and times for which received SPLs were greater than 72 dB re 1 μPa, and that were not a result of self-noise (this instrument was in a region of high current so self-noise from strumming was prevalent), were almost exclusively from November (n = 131) and were due to a broadband noise with stronger emphasis on lower frequencies attributed to increased winds (Fig. 4b). The few files from December (n = 7) and January (n = 4) with high levels were from ice noise, bowhead songs and/or walrus. Noise levels immediately dropped with the onset of 100% sea-ice cover. These results explain the documented decrease in SPL values from November (76.1 ± 11.9 dB re 1 μPa), where wind seemed to be the main driver for elevated noise levels, to December (62.7 ± 2.6 dB re 1 μPa) and January (58.7 ± 7.9 dB re 1 μPa) despite the continuous presence of vocally active marine mammals.

During the months of November through January, no anthropogenic sound sources were identified. While distant shipping noise from southern regions cannot be ruled out in this region in November-January (Østreng et al., 2013), this mooring presented periods of substantial strumming noise (Fig. 4b) and thus, measured levels most likely were affected by this source of self-noise.

The PSDs for each month show much higher variability in noise levels for all three months than were seen in the Anadyr Strait region (Fig. 5d-f). Particularly in December and January, it is difficult to discern the contribution of any marine mammal species except for bowhead whales in December that are identified in the SPD multimodal distribution for this region, seen as the second yellow band from 300 to 700 Hz (Fig. 5e). The high variability in low frequencies for all months, but particularly December and January are caused by the high variability in self-noise for this instrument, which contributes to the increase in low-frequency noise during periods of high current and is exacerbated by being on a highly instrumented, short mooring (Woodgate et al., 2015). High variability in sea-ice noise, which is broadband, is also a factor.

As in Region 1, there was no correlation between wind speed and ambient noise levels when sea-ice concentration was high (R^2 = 0.09 for December and R^2 = 0.03 for January, Fig. 6b). November, which represented both open water and marginal ice (< 50% concentration), was the only month for which there was a strong correlation between the mean broadband noise level and wind speed (R^2 = 0.52, Fig. 6b).

3.1.3. Region 4: Barrow Canyon in late summer and fall (August, September, and October)

From August through October, beluga whale calls were more commonly recorded than bowheads but both were recorded throughout the entire monitoring period (Fig. 2e). These results match the habitat use description for belugas as an important foraging core-use area throughout much of the summer, and for bowheads mainly in the fall (Citta et al., 2015; Hauser et al., 2014). Bowhead detections consisted primarily of simple low frequency, frequency- and amplitude-modulated signals, rather than the more elaborated song displays, as expected for this time of the year (Würsig and Clark, 1993; Ljungblad et al., 1982). In addition to these two species, bearded seal trills were recorded at low levels throughout the fall (Fig. 2f). The Barrow Canyon region was the only seasonal core-use area in which anthropogenic signals were recorded. Vessel noise (Fig. 7a, b), which included both propeller cavitation and occasionally echosounders (Fig. 7a), as well as seismic airgun surveys occurred in August and September (Fig. 2f).

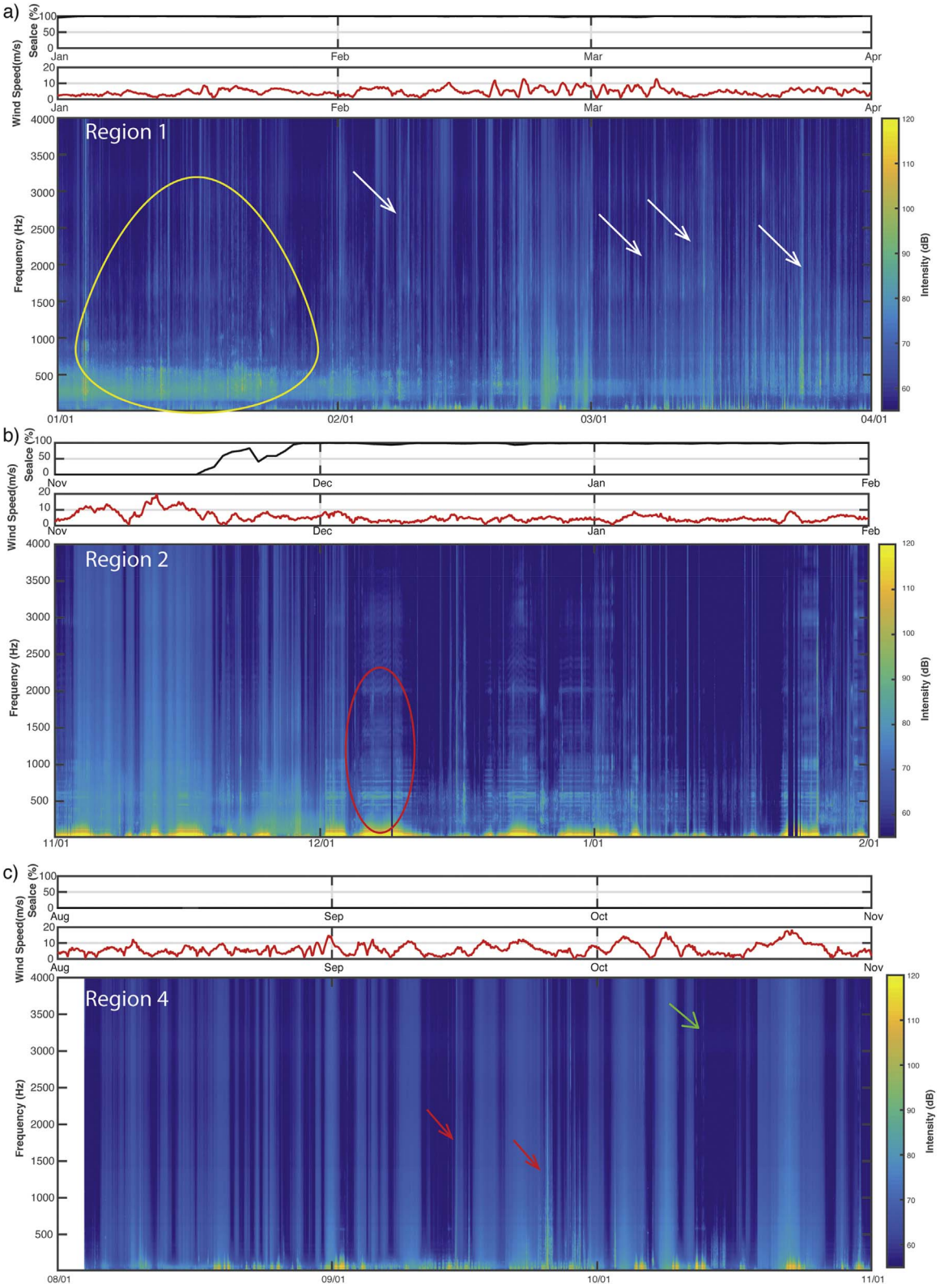

Fig. 4. Environmental data and long-term spectrograms for the three core-use areas. A) Region 1 sea ice concentration, wind, and LTS (dB re 1 μPa) from January-March 2009. Yellow circle is around some of the bowhead whale signals and white arrows point out a few examples of walrus knock series; b) Region 2 sea ice concentration, wind, and LTS (dB re 1 μPa) from November 2009-January 2010. Red circle highlights instrument strumming noise; c) Region 4 sea ice concentration, wind, and LTS (dB re 1 μPa) from Augusts to October 2009. Two examples of ship passages are indicated by red arrows and beluga whale noise by the green arrow (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

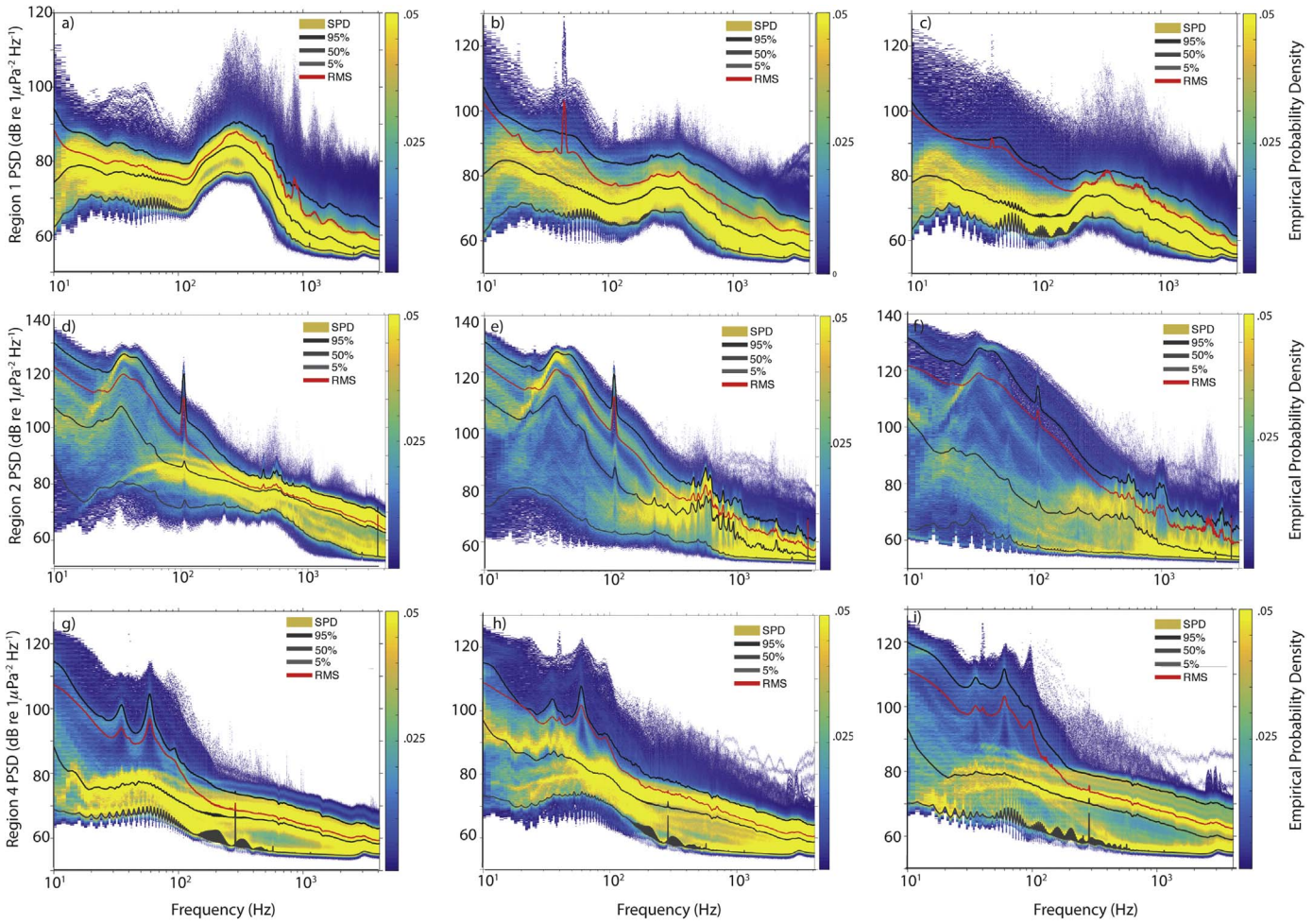

Fig. 5. Power spectral density and empirical probability density functions for ambient noise levels for all three regions. Region 1: a) January 2009; b) February 2009; c) March 2009; Region 2: d) November 2009; e) December 2009; f) January 2010; Region 4: g) August 2009; h) September 2009; i) October 2009. For all plots, the red line is RMS level and black lines represent, from bottom to top, 5th, 50th and 95th percentile values. For e) through i) note the instrument noise limiting measurement of noise levels between ~400 Hz and 4 kHz (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Examples of broadband vessel noise, airguns, and bowhead whale calls are shown in Fig. 7.

The SPL results for this area yielded the lowest levels of all three regions (August 62.1 ± 8.4, September 56.5 ± 5.7, and October 56.3 ± 2.6 dB re 1 μPa). These results suggest that, despite anthropogenic noise occurrence, overall ambient noise levels in Barrow Canyon remained the lowest across the areas and months included in this study. These results are explained by the transient nature of these acute anthropogenic noise events, and very low ambient noise levels outside these disturbance periods, as is reflected in the LTS (Fig. 4c).

The Barrow Canyon region was the only location for which there was open water during the entire time span in which bowheads and belugas occupied the area (Fig. 4c). During this period, high-wind speeds are distinctly associated with higher ambient noise periods underwater (Fig. 4c), sustained in August over scales of a few hours to days, and towards the end of October, for more than a full week. However, these wind-driven increases in ambient noise were not ubiquitous enough to greatly increase overall monthly mean ambient noise levels (Fig. 4). Nevertheless, individual spectrograms of the dates and times for which received SPL (n = 129) were greater than 72 dB re 1 μPa were almost exclusively (94%) due to broadband noise from winds on 8 October (mean SPL 72.8 dB re 1 μPa) and 22–23 October (mean SPL 73.2 dB re 1 μPa). The highest noise levels in September, and the highest levels overall, were from vessel noise on 15 and 25 September (mean SPL76.7 dB re 1 μPa; Fig. 7).

The PSDs for each month show that August had less acoustic variability than either September or October but overall the SPLs were similar among months (Fig. 5g-i). As with the other two regions, instrument noise floor at frequencies above ~800 Hz prevents determination of the lowest ambient noise levels recorded.

The correlation between wind speed and SPL was strong in Region 4 and increased with month. August and September values were R^2 = 0.46 and R^2 = 0.70, respectively. This relationship was particularly strong in October (R^2 = 0.82), likely driven by an overall increase in mean and maximum wind speeds (6.0 ms^{-1} and 17.4 ms^{-1}, respectively) and prolonged wind events between 18 and 26 October (Fig. 4c). This correspondence between wind and SPL matches the Knudsen curves fairly well (Knudsen et al., 1948).

4. Discussion

4.1. Comparing the seasonal acoustic environment of beluga and bowhead whale core-habitat

Changes in the physical environment of the Pacific Arctic can be seen, in the extent and thickness of seasonal sea-ice, increases in east winds, and increased freshwater transport through Bering Strait, for example (Pickart et al., 2013; Stroeve et al., 2012; Woodgate et al., 2012). These changes have the potential to alter the acoustic environment of Arctic marine mammals by permitting increased anthropogenic

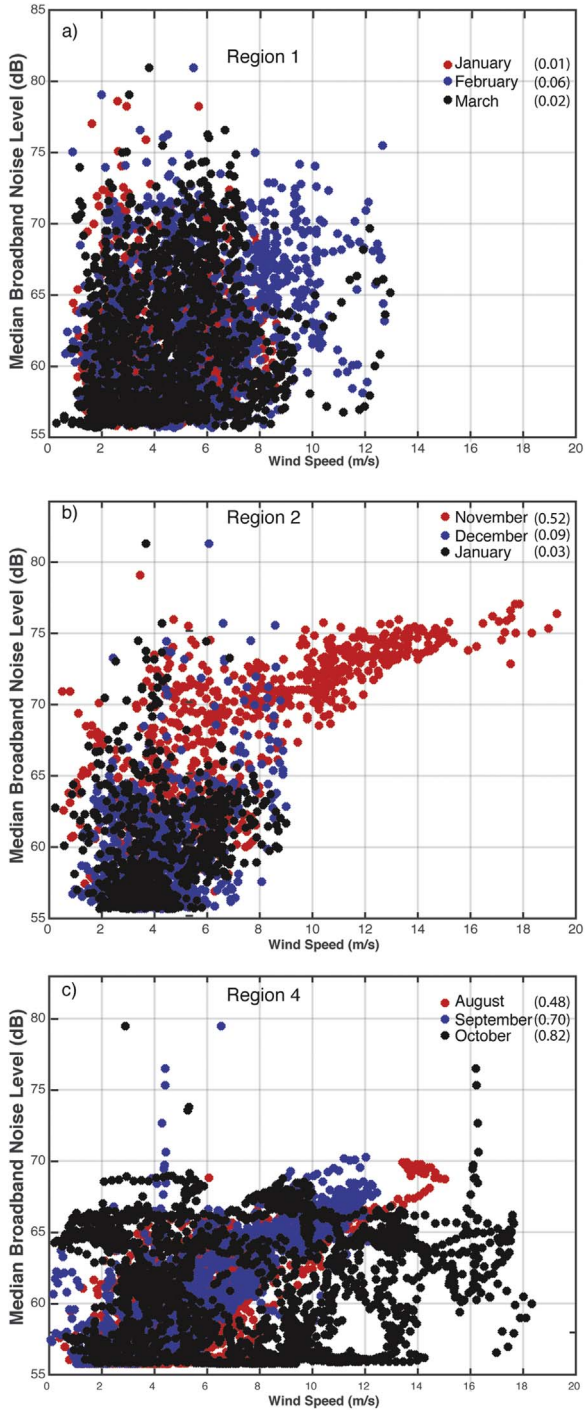

Fig. 6. Median SPL (dB re 1 μPa) versus wind speed by month for a) region 1, b) region 2 and c) region 4. R^2 values for each month are shown in parentheses on the figures.

use of the region due to changes in sea ice, by increased atmospheric processes and wave action, or from the presence of acoustically active subarctic species that seasonally expand their northern distribution limits, or increase their time spent in the Arctic. At present, however, Barrow Canyon (Region 4) during the summer and fall is the only cetacean core-use area discussed here that shows evidence of anthropogenic noise during the months in which bowhead or beluga whales are present. The near shore eastern Beaufort Sea and Amundsen Gulf, not discussed here, are also important to both species and experience anthropogenic sounds from local shipping and oil and gas exploration and extraction (Harwood and Kingsley, 2013; Reeves et al., 2014; Richardson et al., 1987).

Barrow Canyon was the quietest region sampled which suggests that increased noise events have more potential to impact the overall acoustic environment by causing greater changes in the acoustic environment relative to baseline levels.

The acoustic environments of Bering Strait and Anadyr Strait/Saint Lawrence Island from January through March (before the ice break-up occurs) are made up of naturally occurring biotic (whales, walrus, and bearded seals) and abiotic (ice) sources. An unexpected result from the Anadyr Strait/Saint Lawrence Island region was the very high contribution of walrus knock trains to overall ambient noise levels across the entire bandwidth of 10–4000 Hz. Although the species that use this region all produce sounds in this bandwidth, clearly the different species have managed to occupy slightly different acoustic niches. Walrus knocks are the only pulsive short duration signals produced by the four species, and are easily aurally distinguished from background noise. Bearded seal trills vary in bandwidth and can be narrow- or broad band, but tend to be much longer (up to 200 s) than individual calls of bowheads or belugas and modulate over greater frequency ranges. Beluga whale calls have the highest minimum frequency of the winter singers and these are above most bowhead whale and bearded seal sounds. In this data set, the bandwidth examined only covered the lower end of beluga calls. Finally, although loud bowhead songs can extend over several kHz into frequency bands used by the previously discussed species, they also consistently produce very low-frequency moans that stand out below the other animals' signals. The details of how the different species might partition their acoustic environment in temporal or spectral space should be validated by more closely examining both the active space of animals as well as their potential strategies for hearing in noise, particularly in the Bering Strait/Anadyr Strait regions.

From the Bering Sea, both bowheads and belugas migrate north into the Chukchi and Beaufort Seas in April and May. During this time, however, the Bering Strait region is not a core-use area per se as the animals move steadily northwards. In November, however, during their southbound migration, both species appear to spend more time in the Bering Strait region during the sea-ice freeze up transition (Citta et al., 2015; Quakenbush et al., 2010; Citta et al., 2017). From an acoustic perspective, however, both seasons at this location may be especially important to marine mammals. First, these core-use periods occur when sea-ice concentration is particularly heavy and daylight non-existent. This suggests that acoustic communication might be more critical to animals' life histories than at other times of year. Second, at least for bowhead whales, winter and spring are part of the presumed mating season, during which bowhead produce elaborate songs that are likely a reproductive display (Würsig and Clark, 1993).

Furthermore, because it has always had first-year ice cover, not multi-year ice, the Bering Sea is the only Arctic region for which there has not been a long-term change in the duration of seasonal sea-ice extent (Laidre et al., 2015). If this pattern continues to hold, the Anadyr Strait/Saint Lawrence Island region might remain acoustically unchanged assuming marine mammals continue to use the region throughout winter months (December through March). Continued ice presence during these months would also limit the potential increase in commercial and industrial use of the Arctic, preventing these anthropogenic sources from substantially altering the acoustic environment of this region.

4.2. Implications of a changing climate for the acoustic ecology of beluga and bowhead whales

At present, the greatest changes in the acoustic environment of bowhead and beluga whales are likely to happen during the open water season on three fronts. The first is atmospheric. During a long-term year-round study that focused primarily on signals under 500 Hz, Roth et al. (2012) found noise levels near Barrow were highest during the open water season and lower during periods of ice cover. This was to be

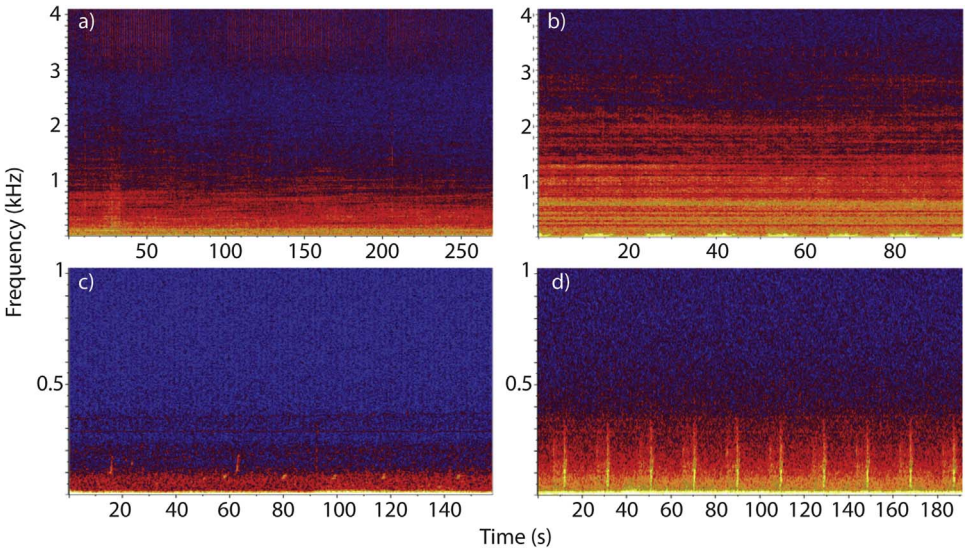

Fig. 7. Region 2: a, b) Spectrograms of ship noise from 15 and 25 September, respectively c) bowhead whale upsweeps and d) seismic airgun pulses.

expected based on earlier work (Makris and Dyer, 1986) but it underlines the impact of wind speed on open water as compared to ice-covered regions. The combination of an open water season that is predicted to continue to increase (Wang and Overland, 2015) and the increase in number and intensity of Arctic storms (Pickart et al., 2013; Thomson et al., 2016) are likely to cause an increase in overall noise levels during summer and fall. Only during the open water season both in Bering Strait (November) and near Barrow (August-October) was there a clear correlation between ambient noise levels and wind speed as seen in both the long-term spectrograms (Fig. 4b,c) and the regression of noise level on wind speed (Fig. 6b,c). In Bering Strait, increased ambient noise is evident in the long-term spectrogram up until sea-ice concentration reached 100% in late November (Fig. 4b). The broadband, pink-noise nature of wind noise will increase ambient noise levels across frequencies used by both bowhead and beluga whales potentially altering the acoustic environment by reducing communication space and decreasing the audibility of external acoustic cues (e.g. Dunlop, 2016). These species have co-evolved with seasonal noise from other animals and from sea-ice, and have likely developed mechanisms to overcome masking for both signaling and signal reception (Erbe et al., 2016), and although not well known, might have a capacity for adapting to these atmospheric changes.

The second source of change in the acoustic environment is biotic due to the expansion of vocal subarctic species into the Arctic in regions and seasons in which they have not been documented previously. The calls and songs of humpback whales overlap in frequency with those of bowheads (e.g. Ljungblad et al., 1982; Thompson et al., 1986; Norris et al., 1999; Johnson et al., 2015) while the social calls of killer whales (*Orcinus orca*) overlap with the lower frequency components of beluga calls (Belikov and Bel'kovich, 2008). Minke whale (*Balaenoptera acutorostrata*) signals recorded in the northeastern Chukchi Sea overlap in frequency with both bowhead and beluga signals (Delarue et al., 2013). Although there have been sightings of killer whales and humpback whales in the Beaufort Sea (Higdon et al., 2012; Clarke et al., 2013), these remain sporadic with most subarctic cetaceans seen, and heard, in the Chukchi Sea from August through October and occasionally into November (Clarke et al., 2013; Hannay et al., 2013; Woodgate et al., 2015).

It is difficult to predict how the presence of these novel species will influence the acoustic ecology of bowhead and beluga whales. Given the vocal plasticity of each (and that of both humpback and killer whales), it is not difficult to imagine a scenario whereby the species introduce novelty into their acoustic repertoires to increase mate attraction (e.g. Parsons et al., 2008), but also to improve signal recognition when multiple species are sharing the same acoustic niche (Bradbury and Vehrencamp, 1998). Humpback whales in the Chukchi produce both simple calls but also songs later in their occupancy of the Arctic, and bowhead whales begin to sing in November (Stafford et al., 2012). How an overlap of a reproductive display by two species that use similar frequency ranges might influence the ecology of bowhead whales is unknown. An increase of transient killer whale sounds might result in a reduction of signaling by bowhead and/or beluga whales to avoid being detected by a potential predator (Castellote et al. 2012b; Stafford et al., 2012), as well as displacement to other available breeding habitats where acoustic displays might infer a lower compromise with the risk of predation.

Finally, the third, and perhaps most significant source of a change in the acoustic environment of bowhead and beluga whales comes from increased anthropogenic noise during the open water season in the Pacific Arctic. In Bering Strait, at present, shipping is restricted to late summer and early fall seasons when neither species is present in the Strait. This relatively narrow (80 km), shallow (50 m) strait is the lone gateway from the Pacific Ocean to the Arctic and is an endpoint for both the Northern Sea Route and the Northwest Passage. Both bowheads and belugas are present in the Barrow Canyon region in late summer and fall and as such are exposed to anthropogenic sounds there. As the open water season expands both earlier and later in the year, not only will wind noise increase in the water column, but behavioral responses in bowhead or beluga whales may occur in the presence noise from commercial and recreational shipping as well as oil and gas exploration and extraction.

Vessel noise, including distant sources, overlaps in frequency with both the calls and songs of bowhead whales but tends to be lower frequency than beluga whale calls suggesting that masking may be more of an issue for bowhead whales because baleen whale hearing is expected to be most sensitive at low frequencies (Ketten, 1994; Cranford and Krysl, 2015). At near distances however, this acoustic disturbance overlaps with the communication channel of both species. The contribution of ferries and whale watching vessels (generally much smaller than large commercial ships, and producing noise in higher frequency bands) have been shown to decrease the communication space of beluga whales in the Saguenay-St Lawrence marine park by 70–85% based on beluga whale hearing sensitivities; both social and echolocation bandwidths used by belugas were impacted (Gervaise et al., 2012). Further, beluga whales have been shown to change their acoustic behavior as a response to the masking effects of small motorboats and ferries in the St Lawrence Estuary (Lesage et al., 1999; Scheifele et al., 2005). Beluga hearing has been shown to be very

sensitive (Castellote et al., 2014) suggesting that even low-level exposure of distant shipping noise will disturb their acoustic space. There is also evidence of beluga disturbance by distant noise sources (Finley et al., 1990; Erbe and Farmer, 2000). Changes in the vocal behavior due to noise have also been documented in bowhead whales. Blackwell et al. (2015) documented an increase in their calling rate in the presence of distant airguns up to a certain level of noise (127 dB re 1 $\mu Pa^2\,s^{-1}$, reported as the cumulative sound exposure level over 10 min intervals), but calling ceased altogether when noise levels exceeded 160 dB re 1 $\mu Pa^2/s$. These beluga and bowhead responses could be interpreted as a mechanism to compensate for the loss of acoustic space, which, as shown for the bowhead whale, might be effective only to a certain extent. This is of importance in the context of temporally or spatially large disturbances of the Arctic acoustic habitat. A recent assessment of the cumulative impact of ship noise and seismic signals on migrating bowhead whales used data from anthropogenic activities that took place in the Beaufort Sea during the open water season to estimate the aggregated sound pressure levels to which modeled bowhead whales were exposed and found that most would experience noise levels well above the natural ambient baseline throughout much of their migration (Ellison et al., 2016). The noise contribution from all human activities occurring in the Pacific Arctic during the open water season should be considered in the context of the cumulative impact to the already changing acoustic habitat. The increase in atmospheric processes contributing to the ambient noise, the spatial expansion of vocal subarctic species, and the increase in commercial and industrial activities all affect the acoustic environment of bowheads and belugas over wide spectral, spatial and temporal scales. This rapid change in the acoustic environment of bowheads and beluga whales, resulting in the loss of communication space (e.g. Clark et al., 2009), could well have consequences on individual- or population-level scales. There is a growing body of literature on the impacts of increased ambient (primarily anthropogenic) noise on cetaceans including increases in stress hormones and decreases in foraging behavior (Rolland et al., 2012; Blair et al., 2016; Isojunno et al., 2016). Such changes to the behavior of marine animals via changes in the acoustic environment of a habitat, have the potential to negatively impact the health of individual animals. Understanding the impact of changing how often, at which frequencies (Hz), or how loudly individuals call (e.g. Blackwell et al., 2015) is difficult due to a poor understanding if, and how, those types of responses to noise affect the short- or long-term health and survival on individuals or populations.

5. Conclusions

Although the acoustic environment of Arctic cetaceans is relatively pristine compared to other oceans of the world, it is changing rapidly due to increases in noise across multiple fronts (atmospheric, biological, anthropogenic) driven by decreases in seasonal sea-ice coverage. Increases in storms and winds are affecting noise levels during the open water season, which itself is growing longer due to reductions in seasonal sea ice. Noise from wind and waves overlaps nearly completely with frequencies used by both beluga and bowhead whales. While these species encounter the signals of other Arctic marine mammals in the spring, there is considerably less overlap in summer and fall. However, vocal subarctic species such as humpback and killer whales, which produce sounds that may be similar to those of beluga and bowhead whales, could present novel signals in the underwater environment as they migrate further north and spend more time in the Arctic as sea-ice declines. Lastly, increases in anthropogenic usage of the Arctic by commercial and recreational shipping and oil and gas exploration and extraction have the potential to alter the acoustic ecology of Arctic marine mammals. These sources have been documented to impact the vocal, foraging, and swimming behavior, and levels of stress hormones in marine mammals in the Arctic and elsewhere. We do not have the ability to moderate the first two of these sources of change, but the third is something that can be addressed by following the recommendations put forward in Reeves et al. (2014) to identify and protect areas and seasons of heightened importance for marine mammals, particularly with regards to core use areas. Characterizing the acoustic habitat of these regions before they are further altered should be considered a priority.

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The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Marine Fisheries Service.

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