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A year in the acoustic world of bowhead whales in the Bering, Chukchi and Beaufort seas

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ABSTRACT

Bowhead whales, *Balaena mysticetus*, in the Bering–Chukchi–Beaufort (BCB) population, experience a variable acoustic environment among the regions they inhabit throughout the year. A total of 41,698 h of acoustic data were recorded from 1 August 2009 through 4 October 2010 at 20 sites spread along a 2300 km transect from the Bering Sea to the southeast Beaufort Sea. These data represent the combined output from six research teams using four recorder types. Recorders sampled areas in which bowheads occur and in which there are natural and anthropogenic sources producing varying amounts of underwater noise. We describe and quantify the occurrence of bowheads throughout their range in the Bering, Chukchi, and Beaufort seas over a 14-month period by aggregating our acoustic detections of bowhead whale sounds. We also describe the spatial–temporal variability in the bowhead acoustic environment using sound level measurements within a frequency band in which their sounds occur, by dividing a year into three, 4-month seasons (Summer–Fall 2009, August–November 2009: Winter 2009–2010, December 2009–March 2010: and Spring–Summer 2010, April–July 2010) and their home range into five zones. Statistical analyses revealed no significant relationship between acoustic occurrence, distance offshore, and water depth during Summer–Fall 2009, but there was a significant relationship during Spring–Summer 2010. A continuous period with elevated broadband sound levels lasting ca. 38 days occurred in the Bering Sea during the Winter 2009–2010 season as a result of singing bowheads, while a second period of elevated levels lasting at least 30 days occurred during the early spring–summer season as a result of singing bearded seals. The lowest noise levels occurred in the Chukchi Sea from the latter part of November into May. In late summer 2009 very faint sounds from a seismic airgun survey approximately 700 km away in the eastern Beaufort Sea were detected on Chukchi recorders. Throughout the year, but most obviously during the November into May period, clusters of intermittent, nearly synchronized, high-level events were evident on multiple recorders hundreds of miles apart. In some cases, these clusters occurred over 2–5 day periods and appear to be associated with high wind conditions.

1. Introduction

Bowhead whales (*Balaena mysticetus*) are well adapted to extreme arctic and sub-arctic conditions (Niebauer and Schell, 1993; Seim et al., 2014). For much of their year there is little to no sunlight. In late winter and early spring they migrate in almost total darkness through dynamic fields of multi-year and young ice in which they can be trapped and die. The Arctic's physical acoustic environment in the low-frequency (<1 kHz) band is also highly dynamic, in part as a function of extremes in temperature, ice and wind conditions (see Lewis and Denner, 1988; Roth et al., 2012), but also as influenced by biotic and anthropogenic sources (see Blackwell et al., 2007; Hildebrand, 2009). Here we analyze a large corpus of acoustic recordings collected throughout a 14-month period and spanning a 2300 km range to describe and quantify relationships between the Bering–Chukchi–Beaufort

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(BCB) population of bowhead whales and an ecologically important portion of its acoustic environment. Applying the term acoustic ecology as the study of acoustics involved in the interactions of living organisms (see Van Opzeeland et al., 2010; Pijanowski et al., 2011), this paper is an acoustic ecology study for one year in the world of the BCB bowhead population.

Ljungblad et al. (1982) were the first to formally document and record bowhead calls and songs using sonobuoys deployed from an aircraft during spring and fall observations in the Beaufort Sea. Calls were described as "simple" (frequency-modulated, FM) or "complex" (amplitude-modulated, AM) signals, with repetitive call sequences ("simple songs") identified in a single springtime recording. These and later recording efforts over the last 30 years have further advanced understanding of the bowhead's remarkable suite of acoustic behaviors including broadband impulses (referred to as gunshot calls, Würsig and Clark, 1993) and complex song compositions consisting of two-voiced, patterned sequences lasting about a minute (Clark and Johnson, 1984; Würsig and Clark, 1993; Delarue et al., 2009; Stafford et al., 2008, 2012; Tervo et al., 2009; Johnson et al., 2014). Most bowhead sounds are distinctly different from sounds produced by other marine mammals endemic to the sub-arctic and arctic habitats. As a result, monitoring for the occurrence of bowhead sounds is a very effective mechanism for detecting their presence throughout the year.

Three issues have primarily driven applications of passive acoustic monitoring in the Arctic: the need to know how many bowhead whales were in the BCB population (e.g. Clark et al., 1986; George et al., 2004; Givens et al., 2013), the need to understand the potential impacts of offshore oil and gas operations on bowheads (e.g. Richardson et al., 1995; Blackwell et al., 2013), and the desire to understand how large-scale changes in arctic sea ice conditions might impact marine mammals (Stroeve et al., 2011, 2008; Comiso et al., 2008). These efforts have been facilitated by the development of long-duration autonomous seafloor recorders, which has driven a dramatic increase in acoustic sampling throughout the Bering, Chukchi, and Beaufort seas (Moore et al., 2006, 2010; Delarue et al., 2009; Hannay et al., 2013; Jones et al., 2014). As a result we can now "listen" throughout the year for the acoustic occurrence of bowhead whales across most of their range. With those same data we can quantify the spatial–temporal dynamics of the acoustic environment throughout that range, with the eventual goal of analytically evaluating the relationships between whale occurrence and environmental (e.g. wind, sea-ice), oceanographic (e.g. currents, primary productivity) and anthropogenic factors (see Moore et al., 2012).

The overarching objective of this synthesis was to demonstrate that it is possible to aggregate data from six different projects and obtain meaningful results about bowhead whale occurrence and their acoustic environment throughout a large portion of their home range. We analyzed data from acoustic recorders sampling throughout a 14-month period along a 2300 km transect. We present results showing bowhead acoustic occurrence relative to season and geographic region. We evaluate bowhead occurrence as a function of distance offshore and water depth. We compare differences in ambient noise metrics across and between seasons and geographic regions. The result is a 1-year, acoustic ecology snapshot for BCB bowhead whales from the northern Bering Sea to the southeast Beaufort Sea. This level of multi-project, acoustic data aggregation has never before been attempted, and our synthesis yields results that would be unobservable from any single project.

2. Methods

We compiled a list of acoustic data from the Bering, Chukchi, and Beaufort seas, and initially considered only data collected by autonomous seafloor recorders that sampled over most of a year. This led us to focus on the 12-month period spanning August 2009 through July 2010. We extended this sampling range and period to include bowhead sound detection results from sites in the Beaufort Sea, east of ≈150°W, during August–October 2009 and 2010.

2.1. Acoustic data recording

Six different research groups, referred to as Cornell, Greeneridge, JASCO, NOAA, SIO, and UW, collected the acoustic data.[1] There were four types of passive acoustic recording devices used, referred to as AURAL-M2s, HARPs, DASARs and MARUs.[2] Each research group used different strategies in terms of when they recorded (sampling period) and where they recorded (sampling region, Table 1), as well as sampling rate (number of acoustic samples per second, in kHz), recording schedule (number of minutes of recording per time period, i.e., duty cycle) and bowhead sound detection analysis effort (Table 2).

2.1.1. Recording sites, zones and seasons

Recording sites ranged from the northern Bering Sea to the southeast Beaufort Sea, a linear distance of ca. 2300 km. To simplify visual and statistical comparisons between acoustic detections and noise level results, the overall area sampled was subdivided into five zones, referred to as Zone I, II, III, IV and V (Fig. 1). Each zone encompasses a bowhead whale "hotspot" (Citta et al., 2015), with the exception of Zone III, which includes the primary spring migration corridor.

Within the 12-month period from 1 August 2009 through 31 July 2010, 14 devices recorded for 6–12 months at sites in Zone I, II, III and IV. The addition of 11 recorders at six sites in the Beaufort Sea (Zone IV and Zone V), east of ≈150°W, contributed bowhead sound detection results for August–October 2009 and 2010 (Fig. 1). All available bowhead detection results as provided by each research group are included in some of our results, while acoustic data collected between 1 August 2009 through 31 July 2010 are included in a comparative noise analysis.

To standardize the analytical comparison of results between different blocks of time within a year, we divided the total sampling period into 4-month sub-periods. These are referred to as the Summer–Fall 2009 season (1 August–30 November 2009), the Winter 2009–2010 season (1 December 2009–31 March 2010), the Spring–Summer 2010 season (1 April–31 July 2010), and Summer–Fall 2010 season (1 August–30 November 2010). The Summer–Fall 2010 season includes only data from Zone V in the eastern Beaufort Sea (Sites V.17–V.20) during 1 August through 4 October 2010.

2.2. Bowhead acoustic occurrence

Prior to this study, analysts in each research group with expertise in the recognition of bowhead sounds had scored their recordings for whether or not a bowhead sound was or was not detected.

[1] Cornell – Bioacoustics Research Program at the Cornell Laboratory of Ornithology; Greeneridge – Greeneridge Sciences, Inc.; JASCO – JASCO Applied Sciences; NOAA – National Oceanic and Atmospheric Administration, Alaska Fisheries Science Center; SIO – Scripps Institution of Oceanography; and UW – Applied Physics Lab at the University of Washington.

[2] AURAL-M2 – Autonomous Underwater Recorder for Acoustic Listening-Model 2, Multi-Électronique, Rimouski, QC, http://www.multi-electronique.com/pages/auralm2en.htm; HARP – High-frequency Acoustic Recording Packages, http://cetus.ucsd.edu/technologies_AutonomousRecorders.html (Wiggins and Hildebrand, 2007); DASAR – Directional Autonomous Seafloor Acoustic Recorders (Greene et al., 2004); and MARU – Marine Autonomous Recording Units, http://www.birds.cornell.edu/brp/hardware (Parks et al., 2009).

Table 1
Metadata for acoustic recorders at 20 recording sites. "SR (kHz)" is a recorder's original sampling rate. Greeneridge and Cornell recorders at Sites IV.15, IV.16, and V.17–20 were only deployed in the 2009 and 2010 summer–fall seasons. Greeneridge longitude (lon) and latitude (lat) values were nearly identical year to year, so those listed are for the Summer–Fall 2009 deployment. Shaded rows indicate the ten AURAL-M2 recorders used in ambient noise analysis.

Zone	Group	Site ID	Recorder Type	SR (kHz)	Start Date	End Date	Lon	Lat
Zone I	NOAA	I.1	AURAL-M2	8	30-Sep-09	06-May-10	-174.6590	62.1958
Zone II	UW	II.2	AURAL-M2	8	01-Sep-09	01-Mar-10	-168.9600	66.3270
	JASCO	II.3	AURAL-M2	16	16-Oct-09	18-Jul-10	-167.7831	69.4959
Zone III	JASCO	III.4	AURAL-M2	16	16-Oct-09	21-May-10	-164.5890	70.4035
	JASCO	III.5	AURAL-M2	16	13-Oct-09	26-Jul-10	-164.6290	71.0614
	JASCO	III.6	AURAL-M2	16	14-Oct-09	21-Jul-10	-161.0493	71.1031
	JASCO	III.7	AURAL-M2	16	14-Oct-09	07-Jul-10	-161.5345	71.3112
	JASCO	III.8	AURAL-M2	16	13-Oct-09	17-Aug-10	-161.5378	71.9743
	SIO	III.9	HARP	32	14-Sep-09	19-Aug-10	-158.3990	72.7990
Zone IV	SIO	IV.10	HARP	32	14-Sep-09	28-Jul-10	-157.3915	72.4612
	JASCO	IV.11	AURAL-M2	16	12-Oct-09	29-Jul-10	-156.9334	71.3633
	NOAA	IV.12	AURAL-M2	8	07-Aug-09	18-Mar-10	-155.5919	71.5417
	UW	IV.13	AURAL-M2	8	01-Aug-09	06-Aug-10	-154.4826	71.7506
	NOAA	IV.14	AURAL-M2	8	04-Aug-09	04-Aug-10	-152.4501	71.4250
	Greeneridge	IV.15	DASAR	1	26-Aug-09	04-Oct-09	-150.4923	70.8864
				1	6-Aug-10	29-Sep-10		
	Greeneridge	IV.16	DASAR	1	25-Aug-09	04-Oct-09	-148.7896	70.7332
Zone V	Greeneridge	V.17	DASAR	1	23-Aug-09	01-Oct-09	-146.6411	70.4806
				1	12-Aug-10	01-Oct-10		
	Greeneridge	V.18	DASAR	1	19-Aug-09	01-Oct-09	-145.5606	70.3452
				1	12-Aug-10	03-Oct-10		
	Greeneridge	V.19	DASAR	1	21-Aug-09	06-Oct-09	-143.1520	70.3407
				1	11-Aug-10	04-Oct-10		
	Cornell	V.20	MARU	2	29-Jul-09	21-Sep-09	-135.5889	70.5476
				2	16-Aug-10	24-Sep-10	-134.3300	70.8048

Table 2
Specifications by which each of the six different research groups analyzed their acoustic data for the presence of bowhead whale sounds (see Table 1). "Recording Duty Cycle" refers to recording schedule. "Samples/h" refers to the number of recording samples per hour, but note that JASCO recorded a single 40-min sample once every 4 h. "Dur. (min)" refers to the analysis duration for each recording sample. "Total Dur. Per 12-h (h)" is the total number of hours analyzed per 12-h period. "Available Detection Resolution" indicates the temporal resolution at which a group tabulated their detection data.

Group	Recorder type	Recording duty cycle	Samples/h	Dur. (min)	Total Dur. Per 12-h (h)	Available detection resolution	Detection method	Reference
NOAA	AURAL-M2	9 min every 20 min	3	9	5.4	1-h, 3-h	Analyst	–
UW	AURAL-M2	9 min every 30 min	2	9	3.6	3-h	Analyst	–
JASCO	AURAL-M2	40 min every 4 h	0.25	40	2	4-h	Automated and analyst	Hannay et al. (2013)
SIO	HARP	Continuous	1	15	3	Every call	Automated and analyst	Jones et al. (2014)
Greeneridge	DASAR	Continuous	1	60	12	Every call	Automated and analyst	Thode et al. (2012)
Cornell	MARU	Continuous	6	1	1.2	1-h	Analyst	Charif et al. (2013)

Analysis sampling and analyses schemes were not standardized among the six groups (Table 2). In cases where an array of recorders was available (Sites IV.15, IV.16, V.17–V.20), only detection results from the recorder in the middle of the array (shown in Fig. 1) were included in the analyses in order to keep detection radii fairly consistent among sites. In cases where multiple recorders were available at the same site (NOAA Site IV.14), detection results from the recorder with the longest period of recording effort were used. We assume that bowhead detection results are a direct measure of bowhead acoustic occurrence, and the term acoustic occurrence is used to refer to detection results.

The likelihood of recording at least one bowhead sound should increase with an increase in the time span over which data are examined. For instance, an acoustic detection or lack thereof in any hour of data from the Greeneridge analysis is exactly known because each minute of every hour was examined for whale calls. For the JASCO data, on the other hand, the probability of detecting a bowhead whale sound depended on sampling only 5 min of a 4-h period. Clearly the subsampled data could under-represent the acoustic occurrence of bowheads in a 4-h period. Nevertheless, while recognizing that the different analytical sampling strategies likely impose some level of bias, we argue that the overall seasonal patterns of bowhead whale acoustic occurrence can be adequately summarized and compared at a coarse scale by using a longer time window for detection. Therefore, daily acoustic detection data from each group site and day were aggregated into two 12-h bins to score bowhead acoustic occurrence based on the detection of at least one bowhead sound during the 00:00–12:00 h local and 12:00–24:00 h local periods. Only 12-h periods for which data were available for the entire period were considered in further analysis. By this procedure there were either one or two scores per day: with a score of "0" for no acoustic detections, and a "1" for one or more acoustic detections. We assume that there are no false positive detections in any of these acoustic occurrence data (i.e., no 12-h sample periods scored "1" for the detection of a bowhead sound, when none occurred), while recognizing the

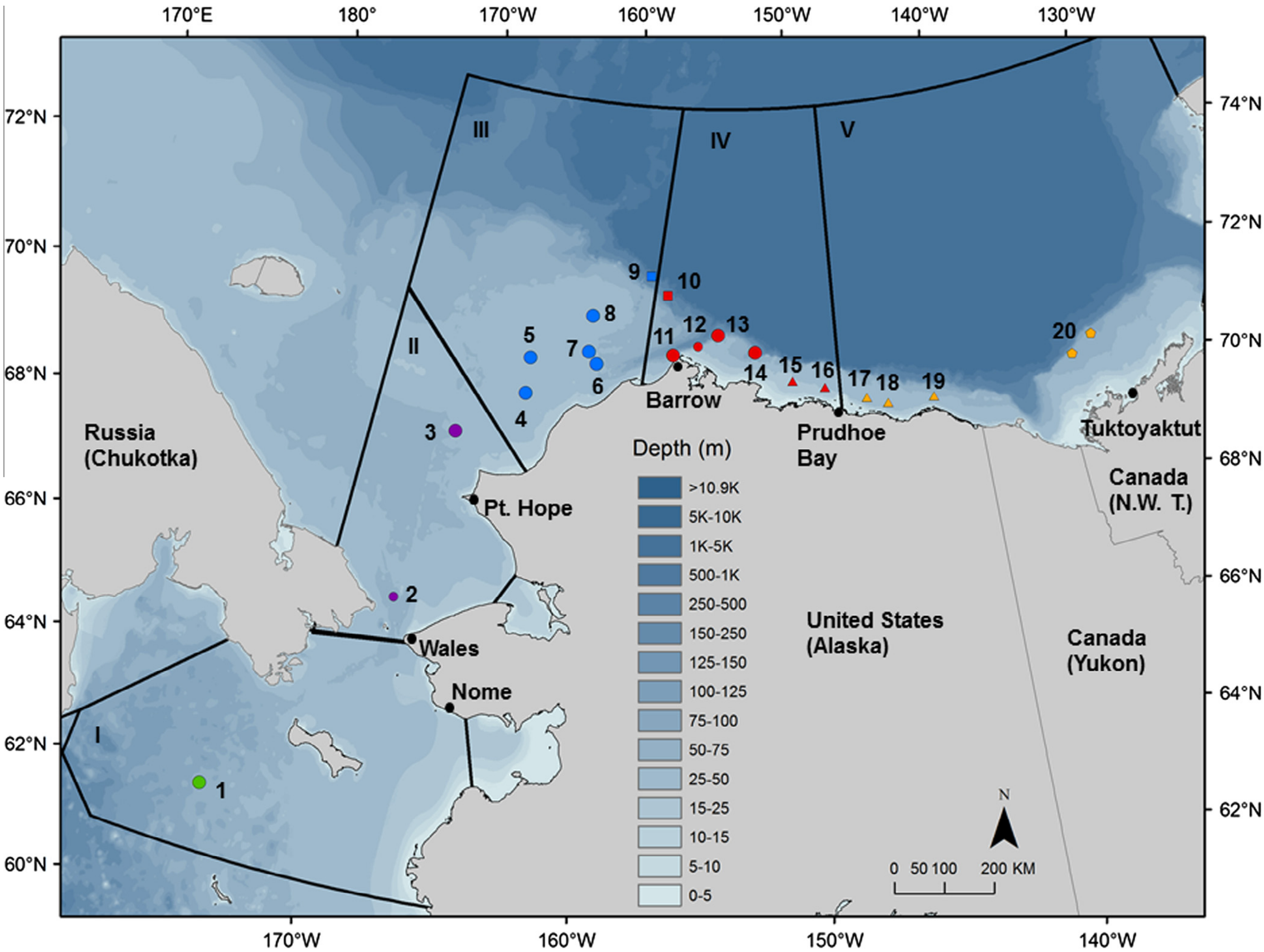

Fig. 1. Locations of 20 acoustic recorder sites in five zones throughout a 2300 km transect within the home range of the Bering–Chukchi–Beaufort (BCB) bowhead whale population. Recorder type is coded by shape: AURAL – circle; DASAR – triangle; HARP – square; and MARU – pentagon. Size of a recorder's shape codes for whether or not the recorder's data were included in noise analysis: large-included; small-not included. Recorder color codes for zone: Zone I – green; Zone II – purple; Zone III – blue; Zone IV – red; Zone V – orange. The five zones and the sites in each zone are: Zone I with one site (northern Bering Sea, Site I.1); Zone II with two sites (Bering Strait and southern Chukchi Sea, Sites II.2 and II.3, respectively); Zone III with six sites (Chukchi Sea, Sites III.4–III.9); Zone IV with seven sites (western Beaufort, Sites IV.10–IV.16); and Zone V with four sites (eastern Beaufort Sites V.17–V.20).

possibility of false negatives (i.e., a 12-h sample period scored for no detection, when at least one occurred).

To examine whether the above process resulted in a loss of important information when assessing occurrence at seasonal and regional scales, detection evaluations from recording sites in the Bering and Beaufort seas were undertaken for two exemplar locations and methods. For Bering Sea Site I.1, the NOAA group's internal evaluation of detection as a function of sampling duration in winter revealed an average probability of 0.92 for detecting a bowhead within the first 9 min of sampling a 20-min file. When the first 9 min of three 20-min files were examined and aggregated into 12-h bins, the average probability increased to 0.98. For eastern Beaufort Sea Site V.20, the Cornell group used a stratified random sampling scheme (counts of all bowhead sounds within six random 1-min samples per hour of recording), which resulted in 311 out of 1320 hourly samples with detections (24%). When these same data were binned into 12-h samples, 109 of the 110 12-h samples (99%) had acoustic detections. Both of these examples illustrate that aggregating data over a longer time frame increases the chance of detecting at least one bowhead whale call. Given that our primary motivation was to merge multiple, existing sets of detection data so as to view bowhead occurrence over an annual period throughout most of the population's annual range, the benefits from a finer time scale for acoustic detection seemed small compared to the benefits of using combined results from all six research groups at the 12-h time scale.

The ability of analysts to accurately report bowhead call detections can be influenced by noise conditions, particularly when a seismic airgun survey is underway within a few km of the recorder (Guerra et al., 2011). For the period of time and the sampling locations included in this study, seismic airgun surveys occurred in only Zone V during both the Summer–Fall 2009 and Summer–Fall 2010 seasons. Nevertheless, it is important to note that Charif et al. (2013) reported no significant effect of airgun sounds on the Site V.20 detection results.

2.3. Analysis methods

Two types of comparative acoustic analyses were performed: bowhead acoustic occurrence analysis and ambient sound level analysis. Plots of acoustic occurrence are used to visually compare seasonal and spatial patterns of bowhead distribution and to test for the significance of differences in acoustic occurrence as a function of distance offshore and depth of water. Ambient sound levels are similarly compared within and between seasons and geographic zones along the bowhead range to test for the significance of differences in noise distributions.

2.3.1. Bowhead occurrence, water depth and offshore distance

We applied generalized linear models (GLM) to test for the significance of the variables water depth and distance offshore on acoustic occurrence, as measured by whether or not a bowhead sound was detected in a 12-h sample. The null hypothesis was that there was no significant relationship between acoustic occurrence, distance offshore and water depth during either the Summer–Fall 2009 or the Spring–Summer 2010 seasons. To eliminate possible bias from the sampling strategies of the various research groups (see Table 2), only data from the seven JASCO recorders were included in the analyses (Sites II.3, III.4–III.8 and IV.11, Table 3), which reduced these analyses to Zone III and the western portion of Zone IV. Models were run separately for distance offshore and water depth and revealed that each was a significant variable on acoustic occurrence. A model combining the two variables was run and revealed that the combination of variables was also significant with a lower AIC score. We therefore report results from the combined model. The Summer–Fall 2009 season in seven sites corresponds with the westward fall migration through the Chukchi Sea, and the Spring–Summer 2010 season in the seven sites corresponds with the eastward spring migration through the Chukchi Sea. There is some inshore sampling bias given that these data do not include samples from sites >ca 145 km offshore, thereby possibly excluding information about a component of the fall migration occurring at greater distances offshore (Moore and Reeves, 1993; Quakenbush et al., 2010, 2013; Citta et al., 2012, 2015).

2.3.2. Ambient noise analysis

For consistency, only data from AURAL-M2s were considered for ambient noise analysis. Two AURAL-M2s (Site II.2 and Site IV.12) were contaminated by low-frequency self-noise and excluded, resulting in a total of ten AURAL-M2 data sets used in ambient noise analysis (Table 1). Prior to noise analysis, data from all ten recorders were copied onto a common data storage system at Cornell. JASCO data sampled at 16,384 Hz were converted to a 8192 Hz sampling rate, so that all data used in noise analysis were sampled at 8192 Hz. Cornell and JASCO acousticians independently cross-validated instrument frequency response functions and noise level metrics. None of the AURAL-M2s was individually calibrated across multiple frequencies. Instead, frequency response and sensitivity values were based on manufacturer specifications. JASCO performed piston phone calibrations using a GRAS Type 42AA calibrator in the field before deployments as a means of validating those specifications at 250 Hz (Hannay et al., 2013).

Sound level metrics were computed using a high-performance computing platform, which greatly facilitated data processing speed and provided the capability to efficiently reprocess data as needed (Dugan et al., 2011). All recorded data were processed into root-mean-squared (RMS) sound level values (decibels, dB re 1 μPa) within the 10–4096 Hz frequency band (to capture the main frequency range of the bowhead sound repertoire) at 1 s and 1 Hz resolutions, and rounded to the nearest dB.

The peripheral auditory system of the mammalian inner ear is reasonably modeled as a set of band-pass filters with a sensitivity of approximately 1/3 of an octave (Richardson et al., 1995; Madsen et al., 2006). Third-octave sound levels (dB re μPa) were calculated for each of the 26 1/3-octave bands spanning the 10–4096 Hz frequency range, resulting in sound level measures within the 10–3548 Hz frequency band at 1 s and 1 dB resolutions. These measures are used to produce long-term spectrograms for each of the ten sites.

For comparative noise analysis aggregate sound levels were calculated for the 17 1/3-octave bands within the 71–3548 Hz frequency band. Energy in the 10–71 Hz band was excluded because it contained varying amounts of mechanical self-noise from the recorders. Sound level measurements within this 71–3548 Hz band, regardless of the time period over which a measurement is calculated, are referred to as broadband levels.

For each site these basic sound analyses results were used to compute, illustrate and compare: (a) 1/3-octave spectrograms, (b) median broadband levels (50th percentile) for each 12-h period (including 25th percentile and 75th percentile levels to illustrate variability), (c) cumulative distributions of median, 12-h broadband levels within each season for each zone, (d) cumulative distributions of median, 12-h broadband levels within each zone for each season, and (e) 1/3-octave band level statistics for each zone and season; calculated as the median level within each 1/3-octave band over the 71–3548 Hz frequency range for each zone and season.

Spectrogram figures and noise distribution plots revealed a variety of acoustic events. These, in combination with additional analysis and careful listening, were used as best as possible to identify sound source contributors and to eliminate some sound sources as possible candidates for acoustic events. It is important to note that this noise analysis process was not customized to detect anthropogenic activities such as vessel traffic or seismic airgun surveys. Instead, given the qualifications of the multiple data sets, it was designed to describe and quantify ambient noise conditions at a coarse level within a frequency band in which most bowhead sounds occur.

2.3.3. Ambient noise comparisons

Differences in median broadband level distributions for Zones I, II, III, and IV and for the Summer–Fall 2009, Winter 2009–2010, and Spring–Summer 2010 seasons were evaluated using the Kolmogorov–Smirnov (K–S) test. Cumulative distributions of 12-h median broadband levels were computed for each of the zones and each of the seasons, and differences in distributions were tested for every possible pairwise combination of zone and season. By this process there were 12 within-zone, between-season and 18 between-zone, within-season K–S tests. The null hypothesis was that both samples have identical distributions at either the p-value of 0.01 or 0.05. The false discovery rate (FDR) correction procedure (Benjamin and Hochberg, 1995) was applied to both sets of tests to control for the proportion of false positives among the set of rejected hypotheses.

During the noise analyses it became apparent that there were periods, especially in the Winter 2009–2010 season, during which the measured noise levels were at the minimum of an AURAL-M2 recorder's sensitivity level (referred to as the instrument's noise floor). These noise floor levels will be evident in figures showing median broadband level time series and distributions, and could result in a bias in the K–S tests. That is, during an extremely quiet period the reported median noise level will be higher than it is in reality, which will tend to make between-site, within-season comparisons less different than they actually are. This bias is partially mitigated by comparing within and between seasonal periods that are four months long and by lumping site data by zone.

3. Results

A total of 41,698 h of acoustic recordings were collected from 1 August 2009–4 October 2010 at 20 sites spread along the 2300 km transect from the Bering Sea to the southeast Beaufort Sea (Fig. 1). Bowhead songs and calls were recorded throughout the year, but the regions in which they were detected varied across seasons. Although the bowhead whale was the only species for which detection analysis was performed by all six research groups,

Table 3
Acoustic detection results for each of the 20 sites by season. "12-h Detects" is the number of 12-h samples with at least one acoustic occurrence of a bowhead sound. "Dist Offsh (km)" refers to distance offshore, the recorder's distance to the closest landfall. "ND" indicates no data available. The gray-shaded rows indicate which data were used in the GLM to test for the significance of distance offshore and water depth on acoustic occurrence in a 12-h sample.

	Summer-Fall 2009 1 Aug - 30 Nov		Winter 2009-2010 1 Dec - 31 Mar		Spring-Summer 2010 1 Apr - 31 Jul		Summer-Fall 2010 1 Aug - 30 Nov			
Site ID	12-h Samples	12-h Detects	12-h Samples	12-h Detects	12-h Samples	12-h Detects	12-h Samples	12-h Detects	Dist Offsh (km)	Water depth (m)
I.1	124	6	242	237	72	29	ND	ND	196	74
II.2	182	27	182	159	ND	ND	ND	ND	39	48
II.3	92	33	242	16	218	47	ND	ND	92	45
II Total	274	60	424	175	218	47	ND	ND	--	--
III.4	92	40	242	1	102	32	ND	ND	86	43
III.5	98	51	242	0	234	30	ND	ND	128	40
III.6	96	27	242	0	224	61	ND	ND	62	47
III.7	96	50	242	0	196	23	ND	ND	90	48
III.8	98	17	242	0	244	2	34	0	145	37
III.9	156	0	242	0	244	86	38	3	167	337
III Total	636	185	1452	1	1244	234	72	3	--	--
IV.10	156	11	242	0	238	113	ND	ND	121	235
IV.11	100	27	242	2	240	104	ND	ND	9	75
IV.12	232	151	215	0	ND	ND	ND	ND	29	66
IV.13	244	101	242	0	244	140	12	2	68	100
IV.14	238	101	242	0	244	130	8	0	58	137
IV.15	78	71	ND	ND	ND	ND	109	64	32	24
IV.16	81	75	ND	ND	ND	ND	ND	ND	15	26
IV Total	1129	537	1183	2	966	487	129	66	--	--
V.17	79	72	ND	ND	ND	ND	100	98	12	37
V.18	87	79	ND	ND	ND	ND	105	104	11	35
V.19	92	88	ND	ND	ND	ND	110	110	11	52
V.20	104	103	ND	ND	ND	ND	80	75	90	66
V Total	362	342	ND	ND	ND	ND	395	387	--	--
Totals	2525	1130	3301	415	2500	797	596	456	--	--

sounds from other marine mammals (e.g. bearded seals, beluga whales, ringed seals, ribbon seals and walrus) were also detected to varying degrees by each of the groups. Other than bowhead, the bearded seal, whose song overlaps the bowhead song frequency band, was the most obvious biotic contributor to the acoustic environment, while ice- and wind-generated noise were the most obvious abiotic contributors (Fig. 2). As expected, ambient noise conditions varied throughout the year and across regions, but tended to be quietest in the Winter 2009–2010 season. At our 12-h level of analysis, elevated noise levels from vessel traffic were not obvious, either for individual vessels transiting close to a recorder or for aggregated vessel traffic. The latter was not unexpected given the relatively low level of vessel traffic in any of the regions, and that traffic is presently limited to summer and early fall. Elevated noise levels from seismic airgun surveys were not obvious in the Chukchi Sea and western Beaufort Sea areas, most likely because surveys in 2009 were in the eastern Beaufort Sea.

3.1. Bowhead acoustic detections

Bowhead acoustic detections across the sites clearly show that bowheads were not uniformly detected throughout the year or throughout the regions in which they are known to occur (Fig. 3, Table 3). Bowhead whale sounds were detected on 2798 of the total possible 8922 12-h samples (31%) during the period from 1 August 2009 through 4 October 2010. By season alone, the majority of detections occurred during the Summer–Fall 2009 season (40%). When considering seasonal changes by zone, the majority of detections shift from high levels in Zones IV and V during Summer–Fall 2009 (48% and 94%, respectively) to high levels in Zones I and II during Winter 2009–2010 (98% and 41%, respectively).

The following sections summarize the relationships between the acoustic occurrence results for each of the three seasons and a site's distance offshore and water depth during the Summer–Fall 2009 and Spring–Summer 2010 migrations.

3.1.1. Summer–Fall-2009 (1 August–30 November 2009)

During the Summer–Fall 2009 season, when most animals are in the southeast Beaufort Sea region, bowheads were detected in 342 of the possible 362 12-h samples (94%, range 91–99%) from Sites V.17 to V.20. In the western Beaufort Sea (Sites IV.10–IV.16) bowheads were detected in 537 of the possible 1129 12-h samples (48%, range 7–93%). In the eastern Chukchi Sea (Sites III.4–III.8) bowheads were detected in 185 of the possible 636 12-h samples (29%, range 0–52%). In the southern Chukchi Sea (Sites II.2 and II.3), near the Bering Strait, bowheads were detected in 60 of the possible 274 12-h samples (22%, range 15–36%).

GLM analysis based on just the JASCO data for the Summer–Fall 2009 season using the distance offshore and water depth variables, with and without their cross-product term, revealed that none of these was a significant variable on acoustic occurrence (lowest p-value, 0.11). Therefore, the null hypothesis of no significant relationship between distance offshore, water depth and acoustic occurrence for the Summer–Fall 2009 season is accepted. It is noted that the sites considered in this analysis did not include very shallow sites where reduced acoustic occurrence in fall has been observed in the Chukchi Sea southwest of Wainwright, Alaska (Hannay et al., 2013).

3.1.2. Winter (1 December 2009–31 March 2010)

Our summary of results for this season starts in the southwestern-most region sampled (Bering Sea, Zone I) and progresses to the western Beaufort (Zone IV). In the Bering Sea (Site

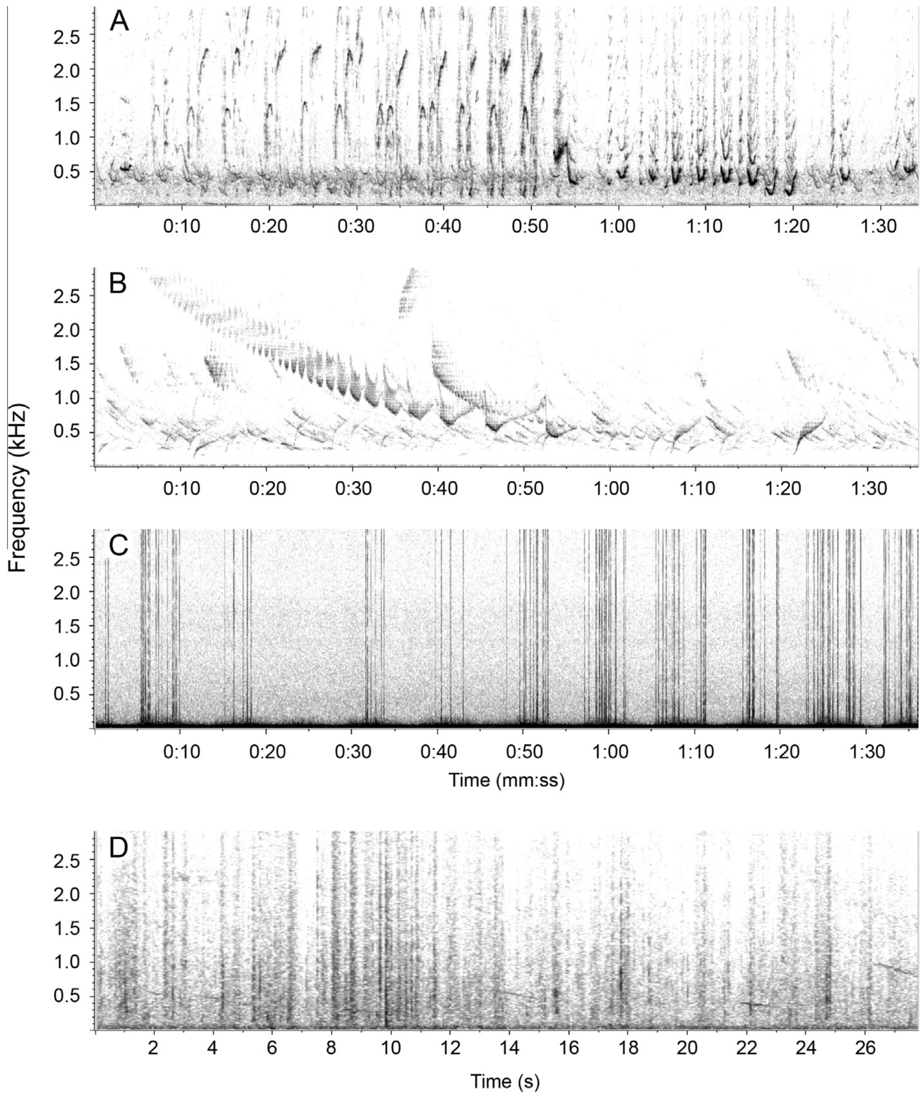

Fig. 2. Example spectrograms of (A) bowhead song chorus as recorded at Site I.1 on 24 December 2009; (B) bearded seal song chorus at Site I.1 on 29 April 2010; (C) broadband noise during a period of high wind at Site III.6 on 22 October 2009 and (D) ice noise as recorded at Site I.1 on 22 January 2010 (8192 sample rate, 1024 pt. FFT, Hann window, 50% overlap).

I.1) during the Winter 2009–2010 season, bowheads were detected in 237 of the possible 242 12-h samples (98%). Near the Bering Strait (Sites II.2 and II.3) bowheads were detected in 175 of the possible 424 12-h samples (41%). There was more than a tenfold difference between detection percentages at the site near the Bering Strait (Site II.2, 87%) compared to Site II.3 (7%), 350 km north of Site II.2. Given the similar sampling schemes used for the two sites, we conclude that this measurable difference reflects the proximity of Site II.2 to the Bering Strait, a narrow region through which all southbound bowhead whales must pass. Given the funneling effect of the strait, we assume the density of the animals and the resultant acoustic occurrence rates would be greater at this site than the northern site. In the eastern Chukchi Sea (Sites III.4–III.8) and western Beaufort Sea (Sites IV.10–IV.14) bowhead whales were detected in only 3 of the 2635 12-h samples (Table 3).

3.1.3. Spring–Summer-2010 (1 April–31 July 2010)

As with the Winter 2009–2010 season, our summary of results for the spring–summer season starts in the southwestern-most region sampled (Bering Sea, Zone I) and progresses to the western Beaufort (Zone IV). In the Bering Sea (Site I.1), bowheads were detected in 29 of the possible 72 12-h samples (40%). In the southern Chukchi Sea (Site II.3) bowheads were detected in 47 of the possible 218 12-h (22%). In the eastern Chukchi Sea (Sites III.4–III.9) bowheads were detected in 234 of the possible 1244 12-h samples (19%, range 1–35%). In the western Beaufort Sea (Sites IV.10, IV.11, IV.13, IV.14) bowheads were detected in 487 of the possible 966 12-h samples (50%, range 43–57%).

The lowest Akaike Information Criteria (AIC) value for the Spring–Summer 2010 season (1 April–31 July 2010) was for the GLM model using the distance offshore and water depth occurrence variables separately (AIC, 74.498; distance offshore p-value ~ 0; water depth p-value, 0.003). Therefore, the null hypothesis of no significant relationship is rejected, and the hypothesis of a significant relationship between distance offshore, water depth and acoustic occurrence is accepted.

3.2. Ambient noise environment

Ambient noise levels varied within and between each of the four zones. Fig. 4 presents long-term, 1/3rd-octave spectrograms for each of the ten sites over the one-year period from 1 August 2009 through

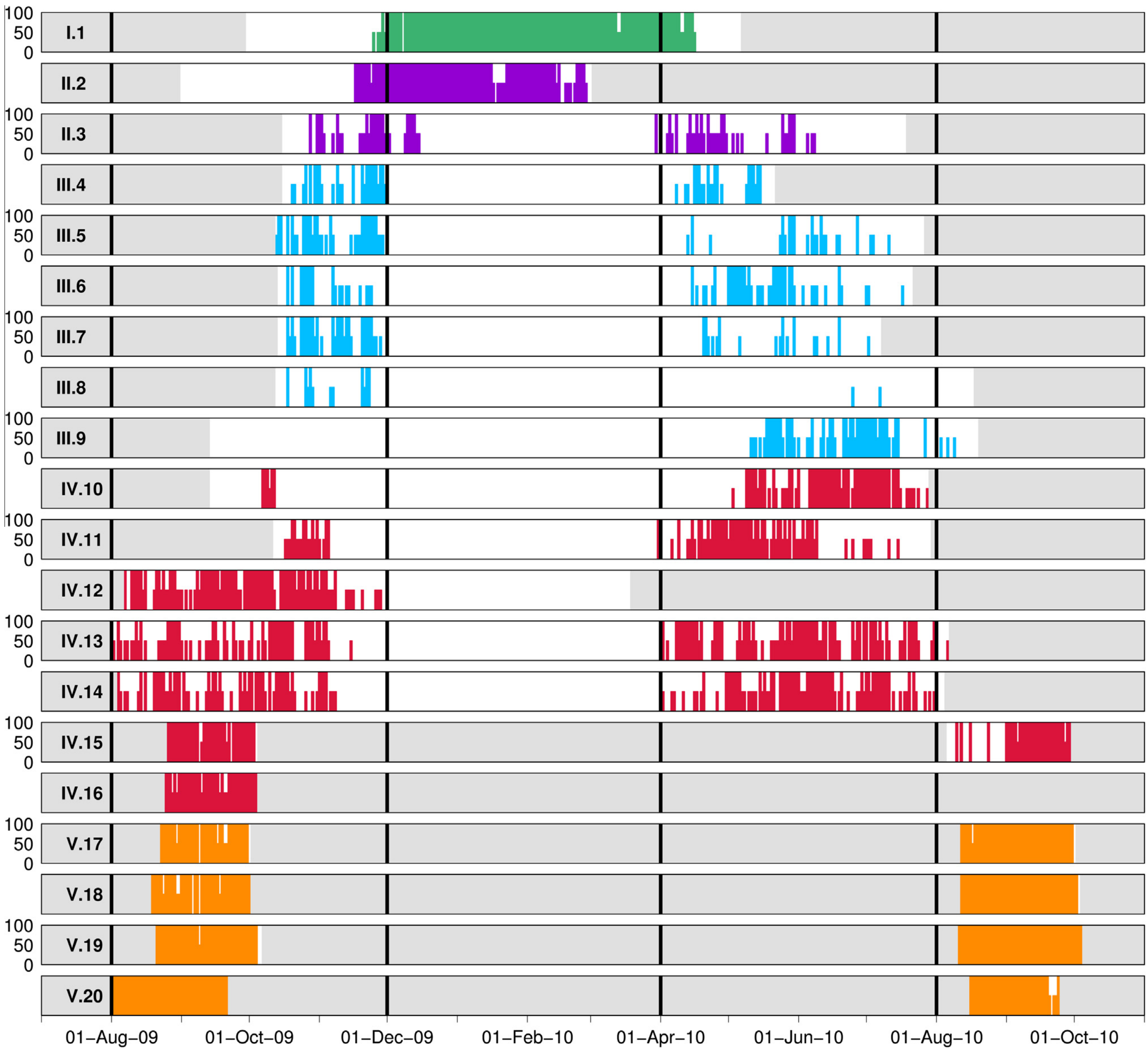

Fig. 3. Bowhead whale acoustic occurrence from 1 August 2009 through 4 October 2010 at the 20 sample sites. Acoustic occurrence is based on the detection of at least one bowhead sound during each of two daily 12-h periods: 00:00–12:00 h and 12:00–24:00 h, local Alaskan time (AKDT). Black vertical lines denote the 4-month sub-periods referred to as seasons. Gray shading indicates no data available.

31 July 2010. Part A of Fig. 4 includes Zones I, II, and IV, representing samples from the Bering and Beaufort seas, whereas part B includes zone III, representing samples from the Chukchi Sea. Time-varying median broadband levels (including 25th and 75th percentiles) at each of the ten sites are shown in Fig. 5, with parts A and B split as they are in Fig. 4 (see above). Median monthly noise levels (including 25th and 75th percentiles) at each of the sites (I.1, II.3–III.8, IV.11, IV.13, and IV.14) are given in Table 4.

3.3. Ambient noise level distributions

Results of within-zone, between-season K–S tests (Fig. 6A) resulted in significant differences between Summer–Fall 2009 and Winter 2009–2010 seasons and between Summer–Fall 2009 and Spring–Summer 2010 seasons for Zone II cumulative noise distributions, and between Summer–Fall 2009 and Winter 2009–2010 seasons for Zones III and IV cumulative noise distributions. Although between-season, cumulative broadband distributions were not significantly different within Zone I, some differences are apparent in third-octave distributions (Fig. 7). In Zone I, Winter 2009–2010 third-octave levels were noticeably different than levels in the Summer–Fall 2009 and Spring–Summer 2010 seasons, while levels in the Spring–Summer 2010 season were different than those in the Summer–Fall 2009. In contrast, third-octave noise level distributions in Zone IV were remarkably similar for all three seasons (Fig. 7).

Results of within-season, between-zone K–S tests revealed significant differences during the Winter 2009–2010 season and during the Spring–Summer 2010 season (Fig. 6B). For the Winter 2009–2010 season, five out of six pairwise comparisons were significant, with the exception being between Zones II and III. For the Spring–Summer 2010 season, three out of six pairwise comparisons were significant, all being between Zone I and Zones II, III and IV. In the Winter 2009–2010 and Spring–Summer 2010, 1/3rd-octave noise level distributions in Zone I were higher than all other distributions (Fig. 7).

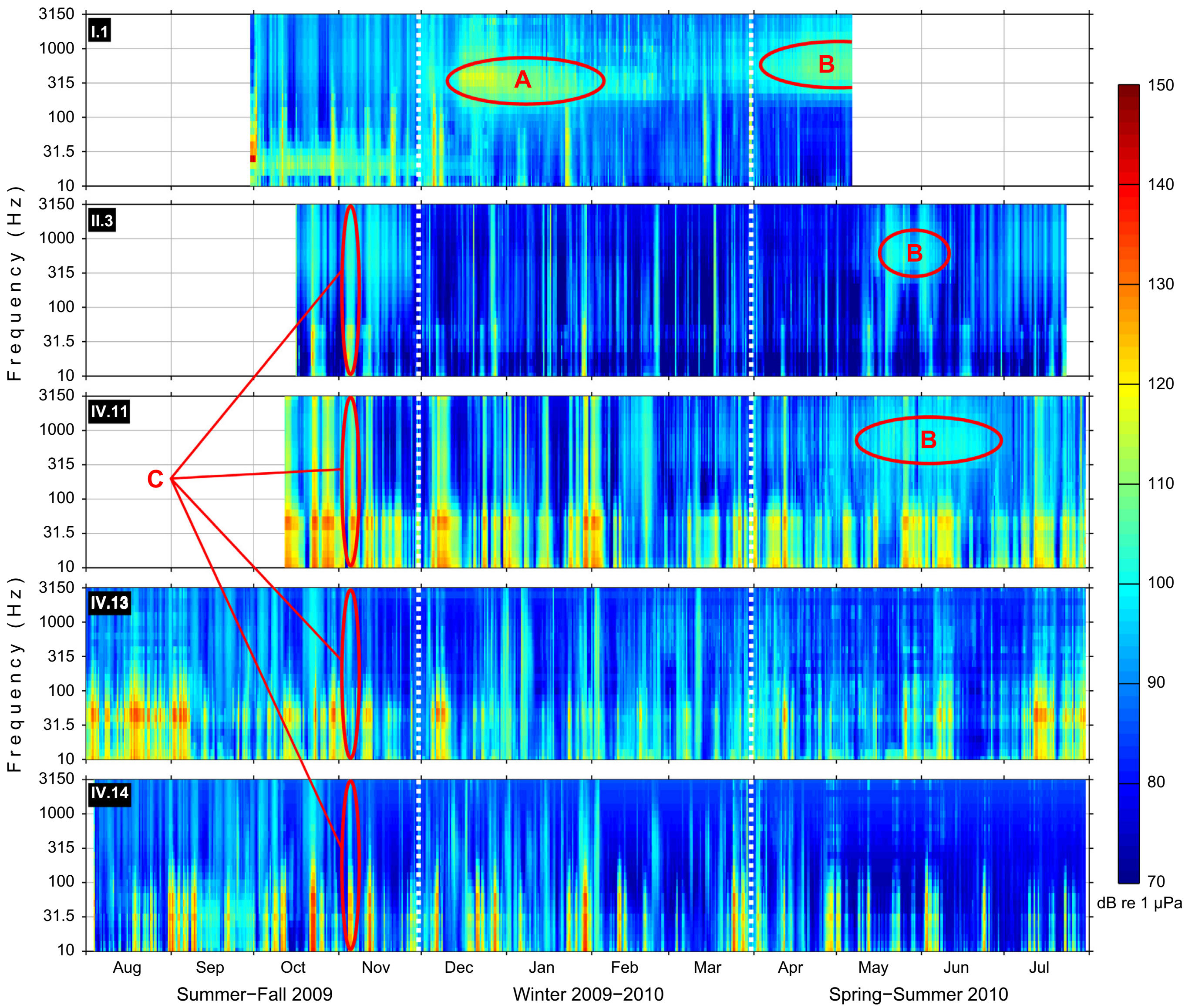

Fig. 4a. Long-term, 1/3-octave spectrograms for Sites I.1, II.3, IV.11, IV.13, and IV.14 during the 12-month period from 1 August 2009 through 31 July 2010. Indications of biological and physical acoustic phenomena are noted as: A, bowhead song chorus; B, bearded seal song chorus; and C, wind. The color bar indicates the RMS level in dB re 1 μPa (see Section 2 for details). The two white dashed vertical lines delimit the three seasons.

3.4. Major contributors to noise levels

The noise analyses revealed comparative differences in sound levels and some temporal coincidences of acoustic events across the different recording sites. Third-octave spectrograms by site (Fig. 4) and noise level distributions by season and zone provide some insights into differences in noise level distribution (Fig. 6). Thus, for example, the 1/3-octave distributions in Zone I (Bering Sea) during the Winter 2009–2010 and spring–summer seasons (Fig. 7 upper left panel) show elevated noise level in the 125–630 Hz and 250–1600 Hz frequency ranges, respectively. A comparison of the Zone I broadband level distribution with all other distributions (Fig. 6B upper right panel) reveals that during the Winter 2009–2010, Zone I's distribution was remarkably higher than all other zones. As shown in Fig. 4 there are some acoustic events, both narrowband and broadband that are either obviously unique to a particular site or that seem to occur simultaneously at multiple sites. Identification of these different acoustic phenomena, or elimination of possible identifications of some events (i.e., what they were not) was achieved by a combination of listening to recordings and by inspection of their high-resolution waveforms and spectrograms.

One of the most obvious acoustic phenomena is shown in the top panel of Fig. 4A (Bering Sea, Site I.1, label A), where there is a major increase in sound level in the ca. 200–2000 Hz band starting around mid-December 2009 and persisting at least into February 2010 before resuming in late March (see Table 4). Closer visual and aural inspection of this phenomenon revealed that this December–February bloom of acoustic energy was the result of a chorus of singing bowhead whales (Fig. 2, panel A), while the resumption in late March was a combination of mostly singing bearded seals (Fig. 4, label B; Fig. 2, panel B) and some singing bowheads.

Another obvious feature in Fig. 4 is the repeated occurrence of broadband acoustic events lasting several days (Fig. 4, label C; Fig. 2, panel C). At the scale of the analysis presented here, these events appear to occur nearly simultaneously at Sites II.3–III.8. From listening in combination with visually inspecting the data

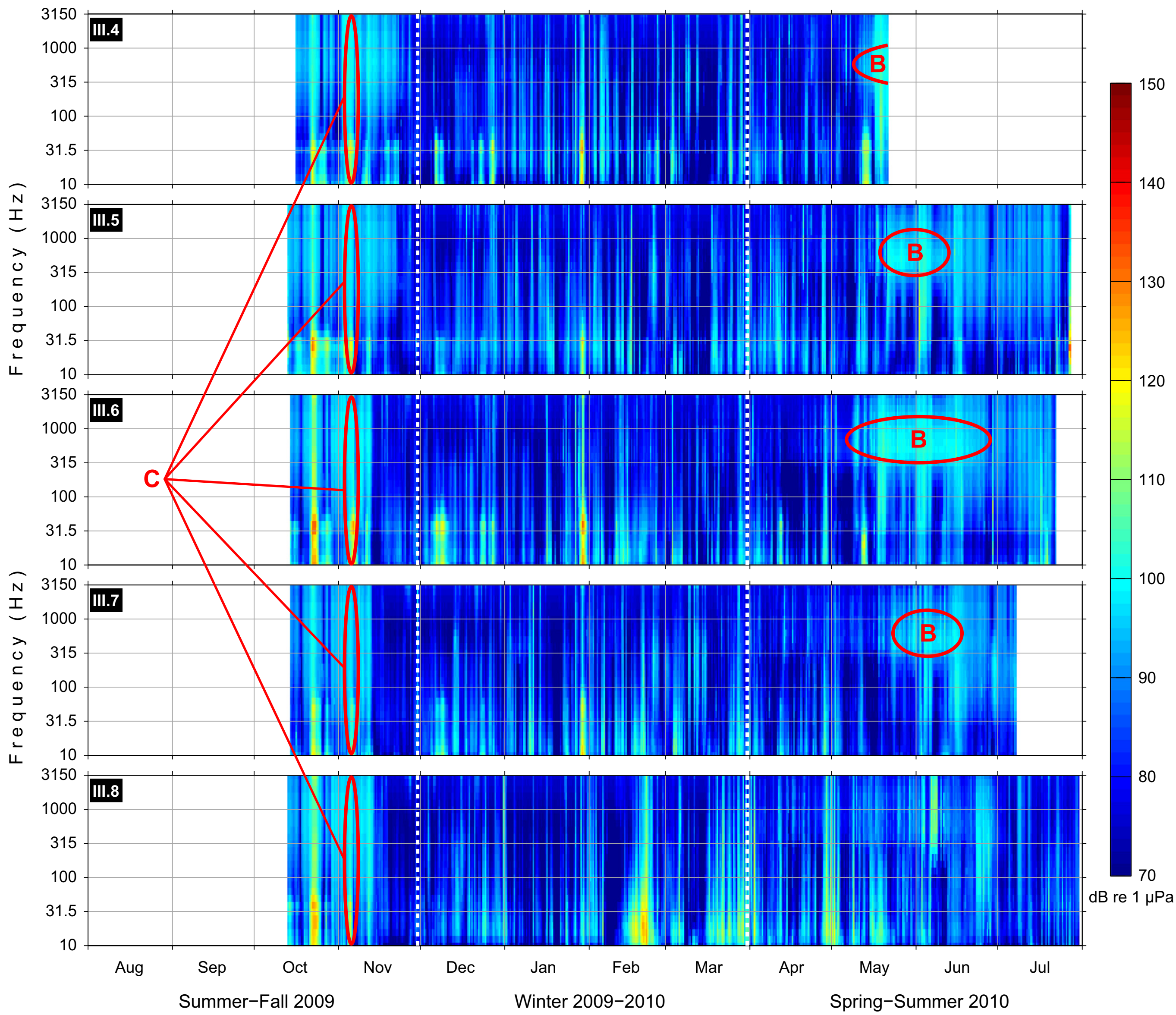

Fig. 4b. Long-term, 1/3-octave spectrograms for Sites III.4–III.8 during the 12-month period from 1 August 2009 through 31 July 2010. Indications of biological and physical acoustic phenomena are noted as: B, bearded seal song chorus; and C, wind. The color bar indicates the RMS level in dB re 1 μPa (see Section 2 for details). The two white dashed vertical lines delimit the three seasons.

at higher resolutions it was evident that most of these are not composed of discrete noise events, such as from rubbing or breaking ice (Fig. 2, panel D). Rather they are best characterized as continuous and last many hours; and therefore most likely are a result of wind or major ice movements during storms occurring throughout the Chukchi Sea region (see Roth et al., 2012).

4. Discussion

4.1. Bowhead whale acoustic occurrence

The Arctic is an acoustically dynamic region with seasonally varying sound contributions from animals, wind, ice, and anthropogenic sources. Here we present the first year-round acoustic study that covers much of the entire range of western Arctic bowhead whales. The acoustic data mark their migration from summer habitat in the eastern and western Beaufort Sea, movements west and south through the Chukchi Sea in the fall and southward into the northern Bering Sea in Winter 2009–2010. Beginning in April the following year, acoustic detections progress northward and eastward along the seasonal migratory route, completing the circuit back in the Canadian Beaufort the following year.

The spatial and temporal patterns of acoustic occurrence reported here are consistent with what is known about bowhead distributions from combinations of both traditional knowledge and surveys conducted over the past 35 years (see Clarke et al., 2013a,b; Citta et al., 2015; George et al., 2004; Koski and Miller, 2009; Moore et al., 2010; Quakenbush et al., 2013). Bowheads spend their winter months in areas where pack ice is not so solid as to significantly reduce access to the ocean surface for breathing, or areas where there is some open water or ice thin enough to break (i.e. northern Bering Sea, see George et al., 1989; Citta et al., 2012, 2015). The central core use area for wintering bowheads based on satellite telemetry data is somewhat northwest of our mooring I.1 (Citta et al., 2015). However, bowhead whale sounds were detected in 98% of the acoustic samples from Winter 2009–2010 suggesting that the region around the mooring

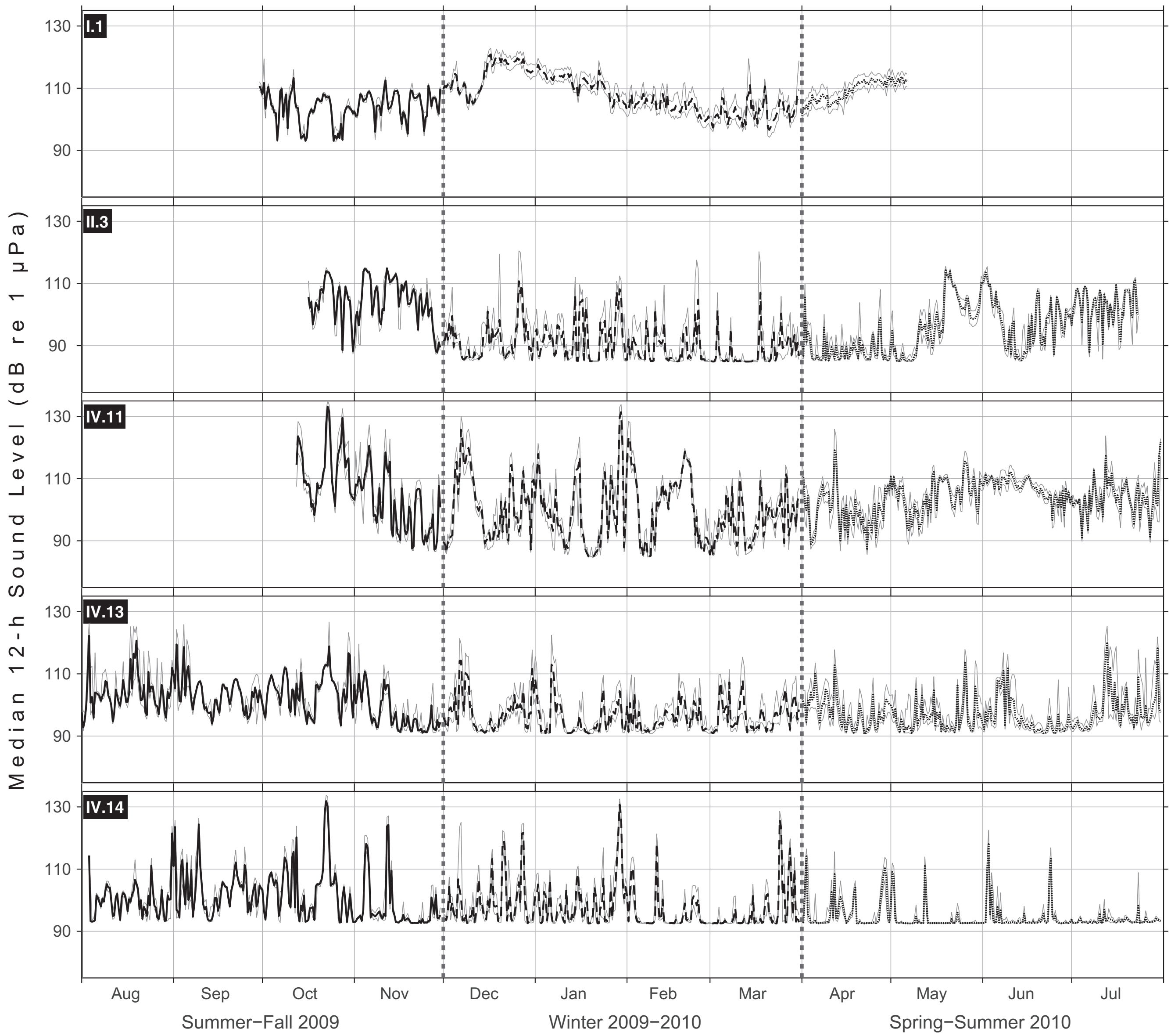

Fig. 5a. Time-varying, median broadband levels for Sites I.1, II.3, IV.11, IV.13, and IV.14 during the 12-month period from 1 August 2009 through 31 July 2010. The light gray lines below and above the median levels indicate the 25th and 75th percentile levels, respectively. The two black dashed vertical lines delimit the three seasons.

was occupied continuously by bowhead whales and that the core use area might be larger than that detected by satellite tracks alone. Long-term acoustic data from other regions in the Bering Sea, including the central core area would add valuable information about the wintering behavior of bowhead whales.

In the late winter and early spring bowheads migrate from their northern Bering Sea wintering area through the Bering Strait, through the eastern Chukchi Sea off the Alaskan coast, and into the Beaufort Sea. Their summer residency has generally been considered to be the Canadian Beaufort Sea; however, as shown here via acoustic detections and more recent aerial surveys, some bowhead whales are heard and seen in the eastern Chukchi and western Beaufort regions throughout the summer months (Clarke et al., 2013a,b; Quakenbush et al., 2010, Fig. 3, Table 3). It remains to be determined if results from these different data collection modes (passive acoustics, tagging and aerial surveys), which imply an expansion of the summer home range, are a result of increased monitoring systems, changes in the physical environment, reflect the growth of the BCB population (Givens et al., 2013), or, as we suspect, some combination of these.

It is unfortunate that the acoustic data from the eastern Beaufort Sea only covered a few months of each year in 2009 and 2010. Bowhead whale sounds were detected in nearly every 12-h period from late August through early October (Fig. 3). We cannot, therefore, determine when animals arrived or left the area although satellite telemetry data found animals arrived in this region as early as May in some years and left by mid-October (Citta et al., 2015). A more detailed analysis of some of the acoustic data showed considerable variability in the number of sounds per day with some sites showing a slight decrease in detections from late August to late September (Charif et al., 2013). Clearly year-round data from the Canadian Beaufort and near Kaktovik, AK, would improve our understanding of the seasonal occurrence of bowhead whales in the eastern Beaufort Sea.

During the fall migration, depending on oceanographic conditions, bowhead whales may spend time feeding near Barrow, AK

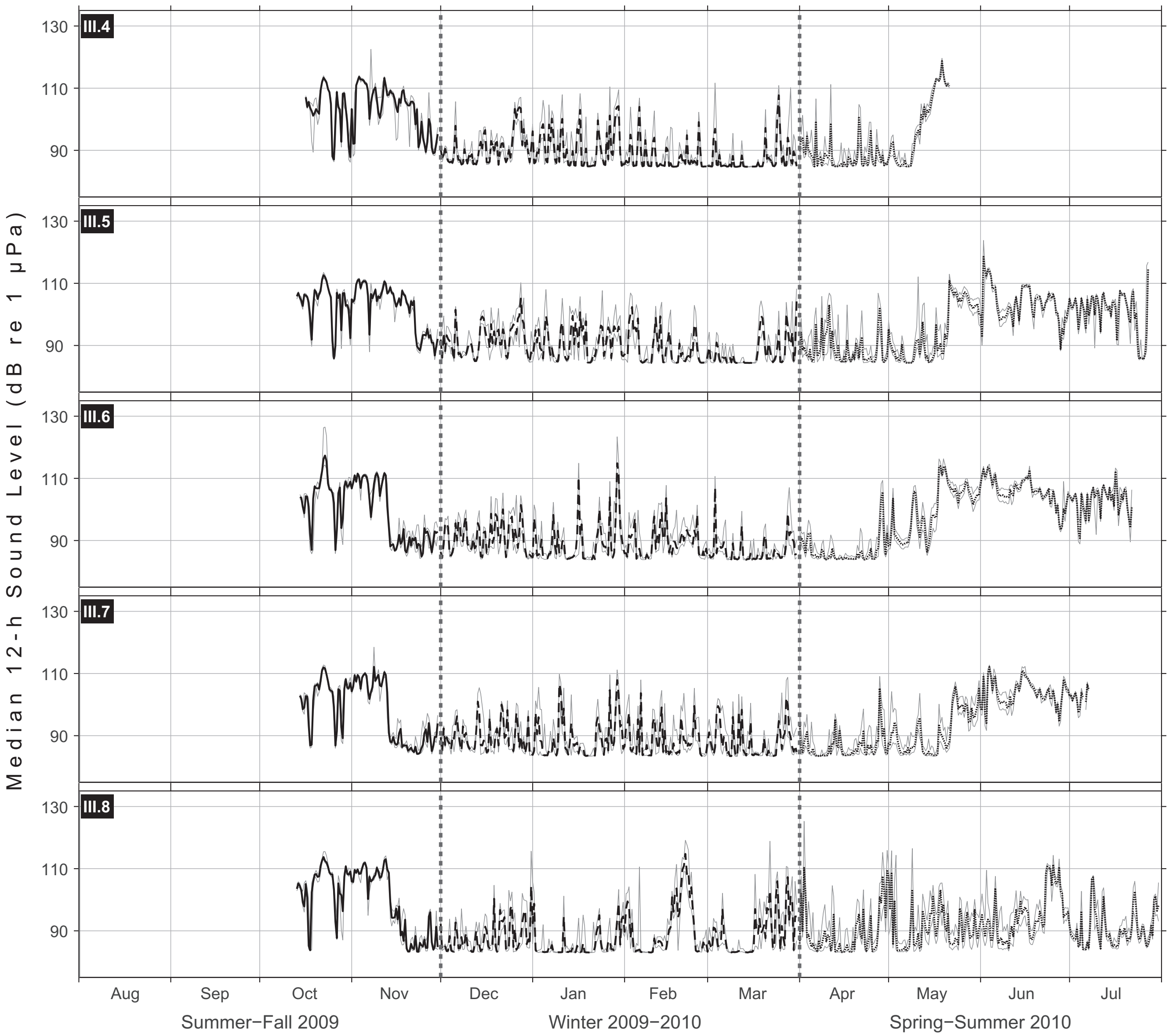

Fig. 5b. Time-varying median broadband levels for Sites III.4–III.8 during the 12-month period from 1 August 2009 through 31 July 2010. The light gray lines below and above the median levels indicate the 25th and 75th percentile levels, respectively. The two black dashed vertical lines delimit the three seasons.

(Ashjian et al., 2010), before heading west toward Herald and Wrangel Islands, rather than turning southwestward into the Chukchi Sea and returning along a nearshore, coastal route. Bowhead whale fall residency near Barrow varies inter-annually based primarily on wind and upstream conditions (Okkonen et al., 2011). Based on the consistent detection of bowhead sounds in the nearshore western Beaufort Sea in fall 2009 until well into November, and lack of sounds in offshore locations, 2009 may have been a good year for feeding near Barrow. This region has seen more or less 100% open water in the fall until late October or early November (Citta et al., 2015), suggesting that the presence of sea ice is not influencing bowhead whale movements at this time.

In contrast, the spring migration is more constrained by offshore, heavy ice conditions and animals seem to prefer the inshore, Alaskan route through the eastern Chukchi Sea. These spatial and temporal differences were seen in the acoustic occurrence data that showed seasonal differences in occurrence as a function of depth and distance to shore (see Fig. 3, Table 3). Based on comparisons within and between the acoustic occurrence data from the Chukchi Sea region and the adjacent western Beaufort region we examined the influence of depth and distance to shore on the detection of bowhead whale calls. For the Summer–Fall 2009 season that included the fall migration within the western Beaufort region and the adjacent Chukchi Sea, there was no significant relationship between acoustic occurrence, distance offshore and water depth (Table 3). These sites, however, do not sample somewhat shallower, very-nearshore waters of the Chukchi, where lower acoustic detections of fall-migrating bowheads were observed southwest of Wainwright, AK (Hannay et al., 2013). In contrast, there was a highly significant relationship between acoustic occurrence, distance offshore, and water depth during the Spring–Summer 2010 season. All things being equal, there were more detections during the Spring–Summer 2010 season at sites closer to shore and shallower in depth than at sites further from shore and in slightly greater depths. Presumably this is reflective of spring-fall differences in both ice conditions and migratory behavior. In the spring, the Chukchi and Beaufort seas are ice-covered, but there are nearshore leads through which bowheads swim

Table 4
Monthly percentile noise levels (dB re 1 μPa) at each of the ten AURAL-M2 recording sites based on distributions of 12-h RMS levels in the 71–3548 Hz frequency band. Top: median, 50th percentile; middle, 25th percentile; and bottom, 75th percentile. "ND" indicates no data available. Cell colors indicate relative noise levels, from lower levels (green) to intermediate levels (yellow and orange) to higher levels (red).

Site #	Median Noise Levels (dB)											
	Summer-fall-2009				Winter				Spring-summer-2010			
	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
I.1	ND	110.5	103.7	106.2	116.5	113.8	106.5	104.3	111.5	114.6	ND	ND
II.3	ND	ND	105.5	105.5	91.6	91.3	88.8	86.7	89.8	100.8	99.2	103.8
III.4	ND	ND	104.4	105.3	89.9	89.6	86.5	85.9	88.6	100.2	ND	ND
III.5	ND	ND	105.5	104.7	91.4	91.4	88.7	89.1	89.6	96.9	104.2	102.8
III.6	ND	ND	105.6	94.4	90.6	87.5	90.3	87.3	87.6	105.1	107.0	104.1
III.7	ND	ND	104.3	93.4	88.8	88.0	89.0	90.0	88.5	95.1	104.9	102.7
III.8	ND	ND	106.1	96.9	88.7	84.0	88.7	90.5	91.8	95.8	98.5	90.1
IV.11	ND	ND	113.0	101.7	101.0	98.7	104.3	99.1	103.5	108.3	108.9	104.5
IV.13	103.5	104.6	105.5	96.2	97.4	94.8	96.0	98.2	100.5	97.4	96.7	98.9
IV.14	99.8	103.4	103.3	94.5	98.0	98.6	93.6	93.6	94.5	92.8	93.3	93.3
Site #	25th Percentile (dB)											
1	ND	109.6	99.5	102.7	110.5	110.9	104.2	101.3	108.2	113.2	ND	ND
I.1	ND	ND	100.9	99.3	87.4	86.8	85.9	85.2	87.4	93.1	92.1	99.7
II.3	ND	ND	100.4	97.2	87.0	86.4	85.1	84.9	86.1	89.5	ND	ND
III.4	ND	ND	101.9	94.4	87.8	87.0	85.2	84.9	87.0	89.3	101.3	98.3
III.5	ND	ND	100.9	89.0	86.9	85.1	86.4	84.9	85.2	94.3	105.0	100.5
III.6	ND	ND	99.5	87.0	86.0	84.7	85.2	84.9	85.4	89.3	102.5	101.3
III.7	ND	ND	101.8	86.3	84.8	83.2	84.5	84.4	86.7	91.1	95.0	87.3
III.8	ND	ND	106.0	93.2	92.6	91.5	94.9	93.6	97.0	104.3	106.7	100.8
IV.11	99.8	100.6	100.3	93.1	93.3	92.2	93.0	94.2	95.6	93.5	93.6	95.0
IV.13	95.8	98.8	96.4	93.1	94.1	93.5	92.6	92.6	92.9	92.7	92.8	92.9
IV.14	95.8	98.8	96.4	93.1	94.1	93.5	92.6	92.6	92.9	92.7	92.8	92.9
Site #	75th Percentile (dB)											
I.1	ND	111.6	107.4	108.4	120.1	116.0	108.8	107.7	114.0	115.5	ND	ND
II.3	ND	ND	109.3	110.3	96.3	98.4	94.6	91.6	93.2	106.5	104.4	107.5
III.4	ND	ND	108.5	109.2	94.3	97.1	91.6	91.5	92.5	110.4	ND	ND
III.5	ND	ND	107.1	107.6	96.1	97.0	95.4	96.2	96.2	105.7	107.7	105.2
III.6	ND	ND	108.2	108.6	96.1	93.8	94.8	91.9	92.5	108.5	109.8	106.0
III.7	ND	ND	106.7	107.3	93.0	94.8	96.2	98.2	93.5	101.9	107.3	103.7
III.8	ND	ND	109.0	108.5	95.4	88.9	99.0	97.3	98.4	101.4	107.1	95.5
IV.11	ND	ND	123.4	109.4	112.4	108.2	111.5	103.9	107.0	111.4	110.8	109.2
IV.13	108.8	107.5	109.2	104.1	103.9	103.0	101.6	103.3	105.1	103.2	103.8	109.0
IV.14	102.6	106.9	107.6	98.6	105.6	104.7	99.0	99.2	100.7	94.2	95.7	94.3

while they migrate north (George et al., 2004). In fall, whales may be found well offshore, unconstrained by sea ice, and animals are more likely to pass by the Chukotka coast, Russia, rather than the US coast of Alaska (Quakenbush et al., 2010).

Although bowhead whales make different types of sounds at different times of the year, it is clear that they produce sounds year-round. This behavior lends itself to the use of passive acoustic monitoring to study them throughout their range. Knowing the behavioral and ecological contexts in which different sounds are produced, and by which members of the population (e.g. male, female, calf, adult), would greatly increase our predictive capability to determine how they respond to changes in their environment: for example, from such basic factors as physical forcing mechanisms to background noise levels.

4.2. Ambient noise environment

4.2.1. Seasonal and site comparisons of ambient noise

For all regions, except the Bering Sea, broadband noise levels (71–3548 Hz) were lowest in the Winter 2009–2010 season and higher in the Summer-Fall 2009 and Spring-Summer 2010 seasons. In the Bering Sea, noise levels were higher primarily as a result of bowhead singers during the Winter 2009–2010 season and bearded seal singers during the Spring–Summer 2010 season (Figs. 4A, 5A, 6B, and 7; Table 4). In contrast, during the Winter 2009–2010 season in the Chukchi and Beaufort seas, broadband noise levels were often >20 dB lower compared to the Summer–Fall 2009 and Spring–Summer 2010 seasons, with monthly median ambient noise levels 5–15 dB lower in Winter 2009–2010 (Figs. 4, 5, 6B, and 7; Table 4).

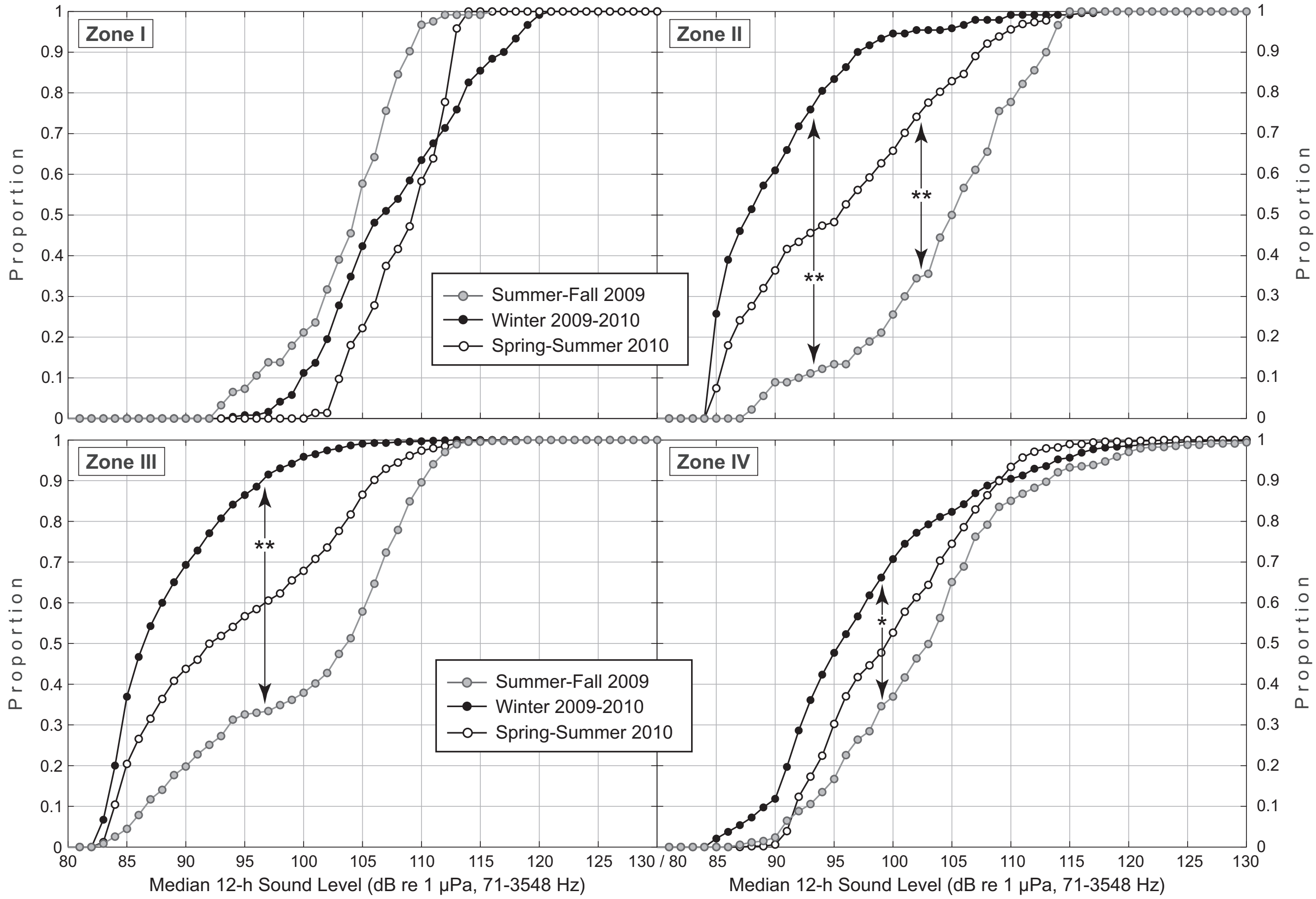

Fig. 6a. Cumulative distributions of median broadband ambient noise levels for each season within Zones I, II, III, and IV. Results of K–S tests for significant differences for within-zone, between-season noise level distributions after FDR correction are indicated as ** for $p \leqslant 0.01$ and * for $p \leqslant 0.05$.

These results are consistent with expectations that under-ice noise levels can be extremely low (Milne and Ganton, 1964). Winter, under-ice noise levels are low partly because there is less wind energy introduced into the water column, ice thickness is high and ice can be very stable (Roth et al., 2012). Roth et al. (2012) found that mean monthly sound spectrum levels in the Chukchi Sea's continental slope at 235 m depth were at least 10 dB lower (re: 1 μPa^2/Hz for the 50–250 Hz band) under conditions with high ice concentration compared to ice-free conditions. In addition, under ice-free conditions they found that wind speed contributed as much as 8–12 dB to ambient noise at 250 Hz.

While Table 4 summarizes monthly median ambient noise levels and thus provides baseline data on the mean noise levels to which a bowhead might be exposed in different locations and different times of year, the time-varying broadband noise levels throughout the bowheads' range show that they traverse acoustically dynamic habitat. For all regions and seasons there are noise "events" that increase ambient levels over both short (<24 h) and longer (days to weeks) time scales (Figs. 4 and 5).

An obvious feature of the winter noise levels reported here was the predominance of values at the lowest possible level that could be measured by a recording instrument, i.e., the instrument's "noise floor" (Fig. 5). In contrast, the Summer–Fall 2009 and Spring–Summer 2010 seasons were punctuated by intermittent periods with high noise levels lasting several days. Many of these periods with high ambient noise levels are associated with high wind conditions during which the sound pressure level exceeded the highest measurable level of the recording instrument, i.e., the instrument's "saturation level". Elevated wind conditions are known to increase low-frequency ambient noise levels in this region (see Blackwell et al., 2007; Guerra et al., 2011; Roth et al., 2012; Hannay et al., 2013), and we assume these wind-generated changes in low-frequency ambient noise could be heard by bowheads and could serve as an important proxy for their assessment of environmental conditions.

4.2.2. Biological sound contributors

Not surprisingly, this study shows that marine mammals are significant seasonal contributors to the arctic acoustic environment. This was particularly evident in the Bering Sea where the winter chorus of singing bowheads dominated the 250–1000 Hz frequency band, and the spring chorus of singing bearded seals dominated the 250–2500 Hz band (Fig. 4A). The change in sound levels (Fig. 5A) indicates that the cumulative contribution of bowhead song decreased from its peak in mid-December (16 December, 120 dB median) to its ebb in late February (1 March, 98 dB median). This is most likely a result of a combination of factors, including lower singer density, singers moving out of the area as they start their northward spring migration, and lower singing effort (i.e., fewer songs, lower acoustic intensity). The increasing sound level in the 250–2500 Hz bearded seal song band indicates that the cumulative contribution of singing bearded seals steadily increased from its first distinct occurrence in late March (21 March, 97 dB median) to its highest level at the end of April when data collection ended (30 April, 112 dB median) (Figs. 4A and 5A). This is most likely a result of the start of male bearded seal reproductive activity in preparation for their breeding season. Unlike the bowhead song chorus, which was only evident at the Bering Sea site,

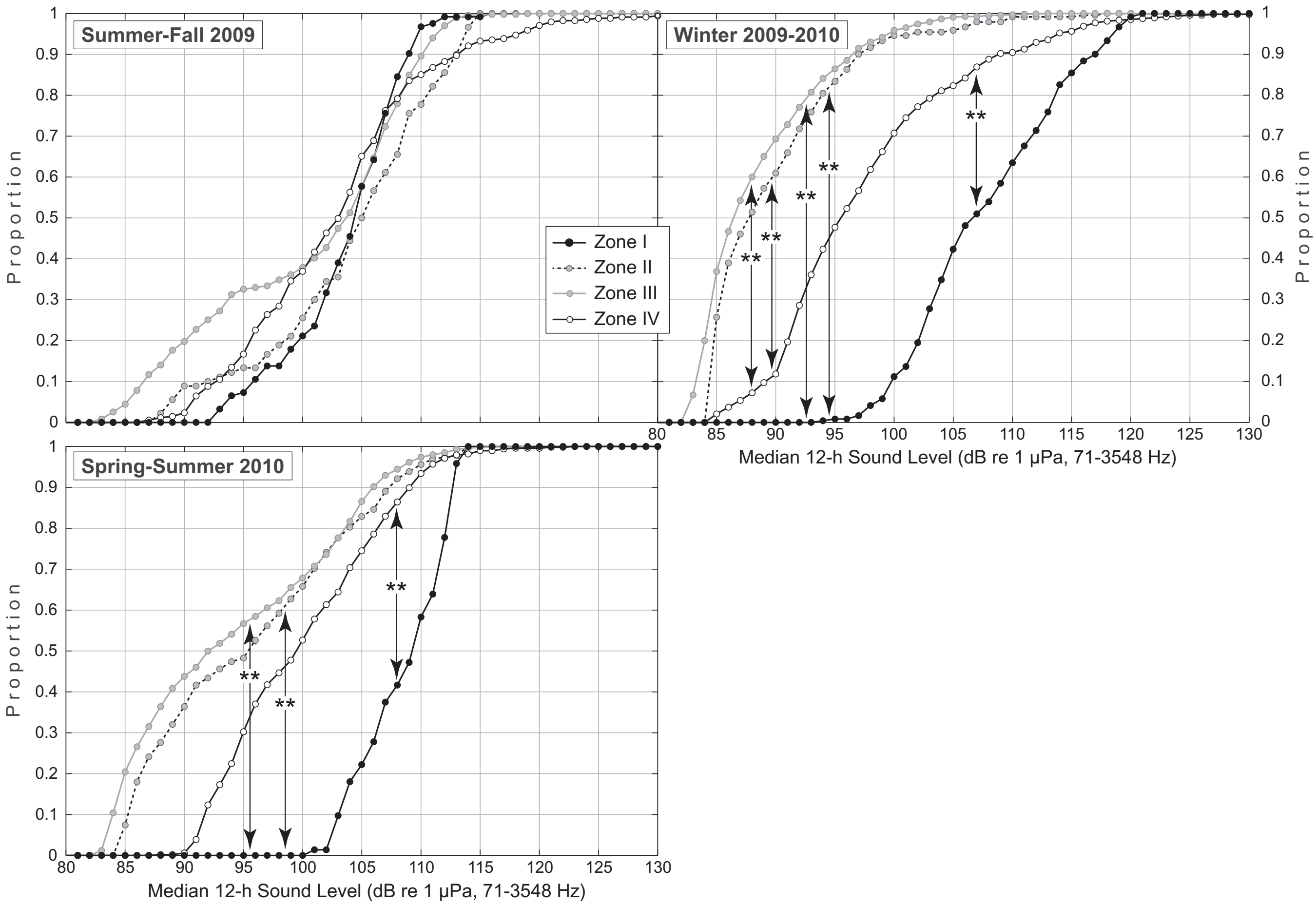

Fig. 6b. Cumulative distributions for median broadband ambient noise levels for Zones I, II, III, and IV within each season. Results of K–S test for significant differences between within-season, between-zone noise level distributions after FDR correction are indicated as ** for $p \leqslant 0.01$.

the bearded seal chorus was modestly evident during the Spring–Summer 2010 season in the eastern Chukchi Sea (Fig. 4, Sites II.3, III.4–III.7) and at one site in the western Beaufort Sea (Fig. 4, Site IV.11). Interestingly, the sound level analysis indicates that the cumulative contribution of bearded seal singing is lower during the Spring–Summer 2010 season in these two regions than it was in the Bering Sea at Site I.1. This might be indicative of lower bearded seal singer density, singers at greater distances from the recorders, or lower song source level intensities.

4.2.3. Industrial sound contributors

The process of aggregating noise analyses results at 12-h resolution meant that relatively short-duration noise events, for example noise from a vessel transiting close to a recorder, would not be very obvious in our noise analysis results. Similarly, noise from prolonged, but very distant noise-generating sources, such as a seismic airgun array survey, would be difficult to distinguish.

During the period from August 2009 to October 2010, the only known active seismic operations occurred in the Canadian Arctic, near site V.20, many hundreds of km from the closest site for which noise analysis was conducted. As a result, at the coarse resolutions of our analyses there were no immediately obvious contributions from industry activities, either from vessel noise or seismic airgun array impulses, to the acoustic environments in Zones I, II, III and IV. Although we know that vessels were present in areas where recorders were operating, because we did not have dates, times, and position of vessels, we did not attempt to evaluate the data for the acoustic occurrence of specific vessel noise events.

We do know a seismic survey was conducted in 2009 from 6 August through 21 September and in 2010 from 16 August through 24 September. Both surveys were conducted in the southeast Beaufort Sea (near Site V.20) and involved a seismic airgun array that was a major contributor to ambient noise at Site V.20 (Charif et al., 2013). The only overlap between the noise analyses results reported here and a seismic airgun array survey occurred in 2009 for Sites IV.13 and IV.14 (Table 1, Fig. 2). During this survey period, based on *post hoc* visual analysis of spectrograms at the 12-h time scale of our analysis, we found no evidence of seismic airgun impulses at Site IV.13 in 100 m water depth at approximately 700 km distance, but some very weak airgun impulses were detectible at Site IV.14 in 137 m water depth at approximately 600 km distance. Very faint airgun impulses were detected throughout September and October 2009 on the SIO HARP recorders at Sites III.9 and IV.10 in water depths of 337 m and 235 m, respectively, but these did not correspond with the Beaufort Sea seismic survey. There were two shallow hazards surveys conducted during this study period. One was a single airgun (400 in^3) survey in Zone III during summer 2009 that occurred just prior to the deployments of the Zone III recorders, so the seismic sounds are not present in the data discussed here. However, a different set of recorders deployed to monitor the hazards survey in Zone III from 7 August to 12 October 2009, clearly detected the sounds from that survey over a wide area from 7 August to 2 October (Hannay pers. com.). The second included single airgun (40 in^3) surveys between 13 August and 6 October 2010 and closest to Site IV-15. None of the seismic sounds from these surveys were obvious in either the

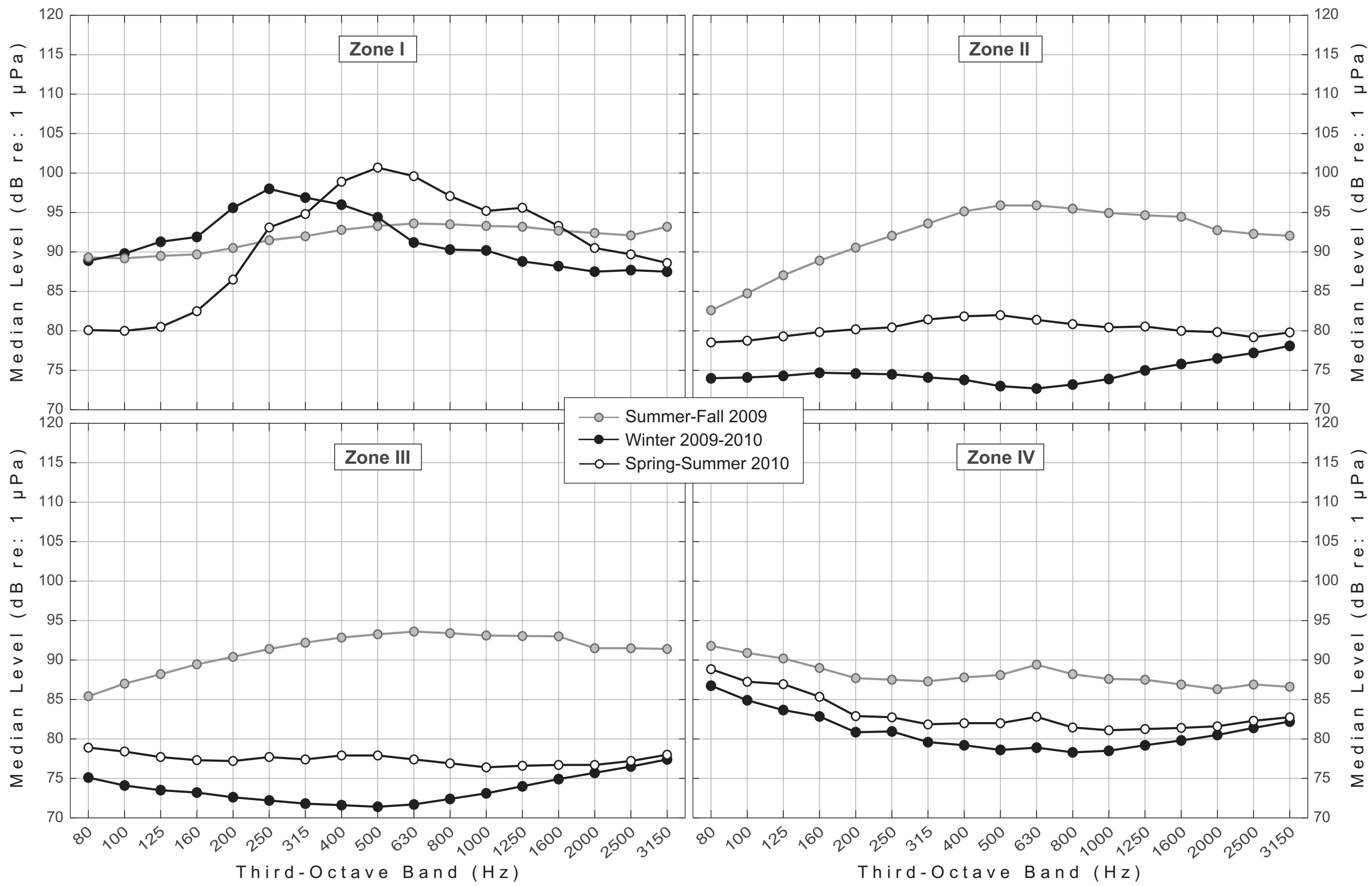

Fig. 7. Median ambient noise levels for 17 1/3-octave bands spanning the 71–3548 Hz frequency range for Zones I, II, III, and IV within each season.

long-term 1/3-octave spectrograms or the time-varying median broadband noise levels for Zones II–IV (Blackwell et al., 2015).

5. Conclusion and recommendations

By aggregating a large collection of ocean acoustic recordings we have documented the dynamics of bowhead occurrence within a 14-month period over a 2300 km transect throughout a major portion of that home range. The results from this collaborative effort underscore the benefits from pooling data and expertise from a cohort of scientists. This research endeavor as a team has been as much an experiment in social cooperation among scientists with expertise in arctic bioacoustics as it has been a process of scientific discovery. The results gained from pooling individual data sets and implementing some rather basic analytical approaches have yielded a more comprehensive portrait of the spatial and temporal occurrences of bowhead whales throughout the range of the BCB population. In so doing we have confirmed some of what Native knowledge and more recent science has observed, while filling in several of the missing pieces in the puzzle. We rightfully acknowledge that these results are not the complete picture of the population's spatio-temporal occurrence throughout its entire range, but we would argue that at this point it is one of the more comprehensive syntheses. Furthermore, the results of ambient noise analyses provide the first broadscale perspective on ambient levels throughout much of the BCB population's range. As such this serves as a benchmark against which further such studies can be compared. This is especially critical given the rapid changes in the Arctic's ocean environment, which by definition includes changes in the spatio-temporal distribution and occurrence of sea ice.

The Iñupiaq who have inhabited the Arctic region of North America for millennia (Noongwook et al., 2007; Huntington and Quakenbush, 2009; Quakenbush and Huntington, 2009) have long known the general spring and fall migration patterns of bowhead whales along the coast of Alaska. Iñupiaq hunters were the first to accumulate knowledge about the sounds of arctic species, which were, and remain today, a core component of their diet (Ray et al., 1969). When scientists began to study the BCB bowhead population in the 1970s, scientific discoveries authenticated bowhead facts and "stories" told to us by Iñupiat whaling captains.

The following narrative illustrates a specific example:

Jim Johnson, Benny Nageaq, our Iñupiaq colleague, and I established our early spring listening tent on the frozen Arctic Ocean offshore of Point Barrow, Alaska and had just deployed a pair of hydrophones over the ice edge. Benny donned the pair of headphones, listened, nodded knowingly, smiled, and proceeded to identify each of the voices contributing to the wild chorus of sounds coming from beneath the ice. Amazingly, he knew all the species by voice. He then patiently explained how his ancestors had listened too, not with a hydrophone, but with an oar paddle placed into the water with the butt of its handle against the jawbone.

[*Christopher W. Clark, Jim Johnson, and Benny Nageaq, Point Barrow, Alaska, 1979*]

That experience serves as a valuable lesson: many of the truths of that arctic world, accumulated over generations by Benny's ancestral culture have since been borne out as truths by scientific investigations. Western science is not the only valid means of obtaining knowledge of our environment, especially for those whose culture and lives depend on it to survive.

The results and struggles of this initial synthesis have provided some clear insights into data and analysis requirements and recommendations for further avenues to study. First, the coarse temporal scale of the available bowhead detection results and our ambient noise analyses highlight the importance of collecting data using standardized equipment and analyzing data in a systematic way. We know that limiting our ambient noise analyses results to 12-h median values tended to obscure details that would only be observable at higher time resolution. With today's technologies it is perfectly feasible to provide readers with online access to these data or tools by which to dilate and compress results dynamically. Second, to examine the impact of anthropogenic sources on ambient noise levels, information on ships and seismic surveys (i.e. number, size, speed, date, location, array volume) are required to quantitatively determine their individual and aggregate contribution to noise levels. Third, the ambient noise data revealed some unexplained phenomena likely caused by physical forcing. Integrating environmental drivers (particularly wind, currents, and sea ice) with both the bowhead whale detections and the ambient noise analysis will not only help interpret relative contributions to ambient noise, but, if well characterized, might allow us to use noise data to inform us about the physical environment (e.g., ice breaking events over local or regional scales).

Finally, it is important to stress that what we present here is part of a progression in arctic passive acoustic science. In this respect we stand on the shoulders of others and each other, some work from 35 years ago (e.g. Ljungblad et al., 1982), some from the middle years (e.g. Clark and Johnson, 1984; Würsig and Clark, 1993), and some from more recent and expansive efforts (e.g., Blackwell et al., 2007; Delarue et al., 2009; Moore et al., 2010, 2012; Roth et al., 2012; Charif et al., 2013; Hannay et al., 2013). In whatever case, it is clear that time is of the essence and that a more complete understanding of the Arctic's dynamic acoustic environment will only emerge when we combine our various data sets and levels of expertise across disciplines. Obviously, progress will be greatly expedited by enabling open access to data, standardizing analyses and visualization tools, and working together to synthesize results. Striving for and achieving a higher level of comprehensive understanding will on the one hand be our legacy, but more importantly it will be our gift in return to the Arctic: our gift of hope for its future health and endurance.

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