Passive acoustic monitoring of Cook Inlet beluga whales (*Delphinapterus leucas*)

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The endangered beluga whale (*Delphinapterus leucas*) population in Cook Inlet, AK faces threats from a variety of anthropogenic factors, including coastal development, oil and gas exploration, vessel traffic, and military activities. To address existing gaps in understanding about the occurrence of belugas in Cook Inlet, a project was developed to use passive acoustic monitoring to document the year-round distribution of belugas, as well as killer whales (*Orcinus orca*), which prey on belugas. Beginning in June 2009, ten moorings were deployed throughout the Inlet and refurbished every two to eight months. Despite challenging conditions consisting of strong tidal currents carrying debris and seasonal ice cover, 83% of mooring deployments were successfully recovered. Noise from water flow, vessel traffic, and/or industrial activities was present at several sites, potentially masking some signals. However, belugas were successfully detected at multiple locations. Detections were relatively common in the upper inlet and less common or absent at middle and lower inlet locations. Killer whale signals were also recorded. Some seasonal variability in the occurrence of both belugas and killer whales was evident. © 2013 Acoustical Society of America. [http://dx.doi.org/10.1121/1.4816575]

I. INTRODUCTION

Beluga whales (*Delphinapterus leucas*) are one of two cetacean species in the family Monodontidae occurring in Arctic and sub-Arctic waters; the narwal (*Monodon monoceros*) is the other species. Belugas occupy a discontinuous circumpolar distribution in waters ranging from 50°N to 80°N latitude, primarily along the coasts of Alaska, Canada, Greenland, and Russia. A genetically distinct population of belugas occurs in Cook Inlet, a 300 km-long estuary in south central Alaska that stretches northeast from the Gulf of Alaska at 59°N to Alaska's largest city, Anchorage, at 61°15′N. The land surrounding Cook Inlet is home to nearly half the state's human population and the waters are subject to myriad anthropogenic activities, including coastal development, oil and gas exploration and extraction, commercial shipping, recreational boating, and military activities.

The Cook Inlet beluga whale population has declined from an estimated 653 animals in 1994 to 345 in 2011 (Allen and Angliss, 2012). It was listed as "endangered" under the U.S. Endangered Species Act in 2008, and has shown no signs of recovery since the primary cause of the decline, over-harvest, was sharply curtailed in 1999 (Lowry *et al.*, 2006). The Cook Inlet population is currently the smallest in Alaska and population viability analyses indicate a relatively high risk of extinction (Hobbs *et al.*, 2006). As a result, state and federal regulatory agencies are evaluating management and conservation strategies, and a recovery plan is being

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drafted. To establish an effective recovery program, substantial gaps in understanding about the population will need to be addressed, including these principal information needs: quantifiable measures of seasonal beluga presence in Cook Inlet, temporal and spatial patterns of habitat preference, and the occurrence of animals in areas impacted by, or considered for, industrial development and military use.

To address these information needs, in 2008 we initiated a collaborative research project based on a passive acoustic monitoring strategy to address the primary objective of examining the seasonal distribution of beluga whales in Cook Inlet. An acoustic approach was chosen because Cook Inlet is a notoriously challenging place for conducting traditional vessel and aircraft-based visual surveys on a year-round basis due to frequent inclement weather conditions, turbid silt-laden waters, and heavy seasonal ice cover that make the detection of belugas problematic. To date, these challenges have resulted in a paucity of information on the seasonal distribution of belugas, in particular, since the sharp decline in abundance that occurred in the late 1990s. Acoustic moorings are less limited by weather and surface conditions and are thus able to provide continuous observations of cetacean activity near a mooring site. Beluga whales are well suited for acoustic monitoring because they are notoriously vociferous animals with a diverse repertoire of signals (Sjare and Smith, 1986; Chmelnitsky and Ferguson, 2012). Acoustic monitoring also allows the investigation of the ambient noise environment that characterizes Cook Inlet, which is important for evaluating the potential effects of noise pollution on belugas. Further, acoustic monitoring can help document the presence of other marine mammals, such as killer whales (*Orcinus orca*), which are known predators of beluga whales. Here, we detail the methodologies being applied in this research project and describe the challenges, successes, and initial results from the first year (June 2009–May 2010) of the project.

II. METHODS

A. Acoustic mooring design

Cook Inlet is characterized by large, semi-diurnal tidal variations (as great as 10 m) resulting in strong currents that regularly exceed 3.6 m/s at their peak. In addition, vast quantities of sediment, glacial silt, and large debris are continually washed into the inlet through a network of rivers and streams originating in the surrounding mountains, which results in much of the inlet being characterized by mudflats and continually shifting bottom sediment under a turbid water column. The upper half of Cook Inlet is covered by seasonal ice from November to May, which due to the strong tidal currents is generally broken and free flowing across the inlet, converging in some areas and diverging in others. These conditions pose a significant challenge to the use of acoustic moorings due to the potential for entanglement with debris, entrapment by sediment, collisions with sub-surface ice, and excessive water flow noise on recordings that can mask signals of interest.

Beluga and killer whale signals span a broad range of frequencies. Social sounds, including calls, whistles, and buzzes generally occur at frequencies below approximately

12 kHz, although many sounds are broadband and have energy extending above 20 kHz (Sjare and Smith, 1986; Ford, 1989; Thomsen *et al.*, 2001; Chmelnitsky and Ferguson, 2012). Echolocation clicks, on the other hand, have considerably higher peak frequencies than social sounds. The clicks of beluga whales range in peak frequency between 40 and 120 kHz and have bandwidths between 20 and 40 kHz (Au *et al.*, 1985). Killer whale clicks have broadband bimodal frequency spectra with low and high frequency peaks between 24 and 108 kHz and bandwidths between 35 and 50 kHz (Au *et al.*, 2004; Simon *et al.*, 2007).

To account for the wide frequency range of both beluga and killer whale signals and to increase the likelihood of recording them under the difficult conditions present in Cook Inlet, two types of acoustic sensors were utilized in tandem: an ecological acoustic recorder (EAR) and a C-POD. The EAR is a computer-based recorder with a programmable duty cycle and bandwidth (up to 40 kHz) produced by Oceanwide Science Institute (Honolulu, HI; Lammers *et al.*, 2008). The C-POD (v.0) is a click logger produced by Chelonia, Ltd. (Cornwall, UK) that detects and classifies odontocetes echolocation signals. The EAR was used to record primarily the calls, whistles, and buzzes produced by beluga and killer whales, but also the lower frequency components (if present) of echolocation clicks. The C-POD was used to log and classify echolocation clicks exclusively. Here, we present the methods and detection results obtained using only EARs. A comparison and integration of the detections obtained by both instruments will be presented in a subsequent manuscript.

All EARs were programmed to record at a sampling rate of 25 kHz on a 10% duty cycle of 30 s "on" every 5 min. These settings were selected to maximize the EAR's available data storage capacity and battery power, allowing for a deployment life of approximately 22–24 weeks. This duty cycle was assumed to be sufficient to capture the signals of acoustically active belugas milling or transiting within the EAR's listening range over a minimum 10–20 min period. Although the EAR's listening range was not empirically established for all mooring locations, an informal test using an artificial 15–20 kHz frequency modulation sweep projected with a source level of 140 dB re 1 μPa was conducted at two Cook Inlet sites: Port of Anchorage (61°13.5'N, 149°54.6'W, depth: ~10 m) and Chickaloon Bay (61°00.5'N, 150°11.7'W, depth: ~8 m). In each case, the EAR was suspended at a depth of 3 m from a stationary vessel while the artificial source was projected at a depth of 2–4 m from several distances off a mobile vessel. The maximum range of detection was ~2.2 km at the Port of Anchorage and ~3.3 km at Chickaloon Bay.

Two mooring configurations were utilized during this deployment period: a "standard" and a "sandwich" design (Fig. 1). Standard moorings consisted of a 70 kg sacrificial steel anchor and anchor line with anti-strum hair faring, an acoustic release (Push Off Release Transponder, PORT, ORE Offshore, West Wareham, MA), C-POD, and EAR all suspended linearly from a cylindrical syntactic foam collar. Sandwich moorings consisted of the same components in a standard mooring arranged in a lower profile cluster.
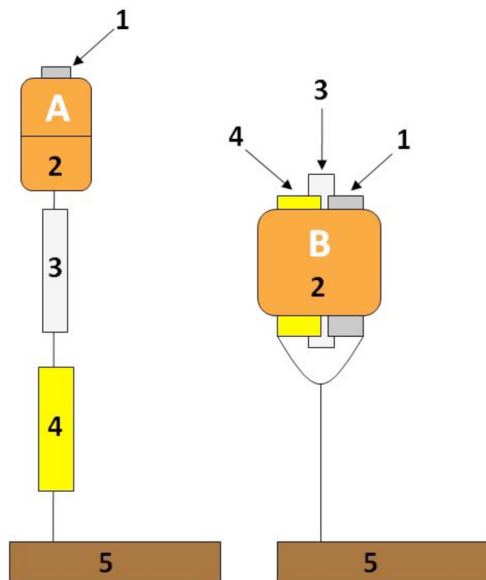
FIG. 1. (Color online) The two acoustic mooring designs used in the study: (a) "Standard" and (b) "Sandwich". 1 = EAR, 2 = syntactic foam float, 3 = C-POD, 4 = ORE Push Off Release Transponder™ (PORT), 5 = sacrificial 70 kg anchor (railroad track).

B. Mooring deployment locations

Acoustic moorings were deployed at ten locations throughout Cook Inlet beginning on 4 June 2009 (Fig. 2). Deployment depths ranged between 10.0 m and 28.3 m at mean low low water. Upper inlet moorings (Beluga River to North Eagle Bay) were more readily accessible and therefore brought to the surface and examined several times during July–September prior to overwintering under the ice. Middle inlet (Trading Bay and Kenai River) and lower inlet moorings (Tuxedni Bay and Homer Spit) were not refurbished until early December. Following the spring thaw, all moorings

were recovered, refurbished, and redeployed again during May 2010.

C. Data processing and analysis

EAR acoustic data were analyzed using the MATLAB™ script Triton, developed by Sean Wiggins (Scripps Institution of Oceanography, La Jolla, CA) and adapted for use with EAR data. Triton was used to create long-term spectral averages (LTSAs) of the recordings for each deployment. LTSAs provide a visual representation of the acoustic energy across frequency and time over the deployment period. The LTSA is a composite spectrogram made up of Fourier transforms averaged over a user-defined period. For this study, 10 s of recording time were used for each average. Beluga and killer whale encounters were located by visually examining the LTSA for the presence of "hot spots" of acoustic energy in the frequency bands associated with whale signals [Fig. 3(a)]. The compressed nature of the LTSA allows an analyst to rapidly scan hours of data and identify periods of possible whale presence. Suspected beluga or killer whale calls are confirmed by examining a 1024-point, Hanning-windowed spectrogram of the original recording [Fig. 3(b)].

A whale "encounter" was logged when calls, whistles, clicks, and/or buzzes were first detected. Subsequent signals were considered part of the same encounter if the time lag between them was less than 60 min. Signals separated by 60 min or more were logged as separate encounters. To quantify each encounter, two parameters were extracted from the data: encounter duration and relative signaling abundance. For each encounter, the duration was recorded by noting the start and end time of signaling. The abundance of signaling in an encounter was then quantified by assigning a scalar value based on the types of signals present (calls, whistles, clicks, and/or buzzes) and the signaling rate
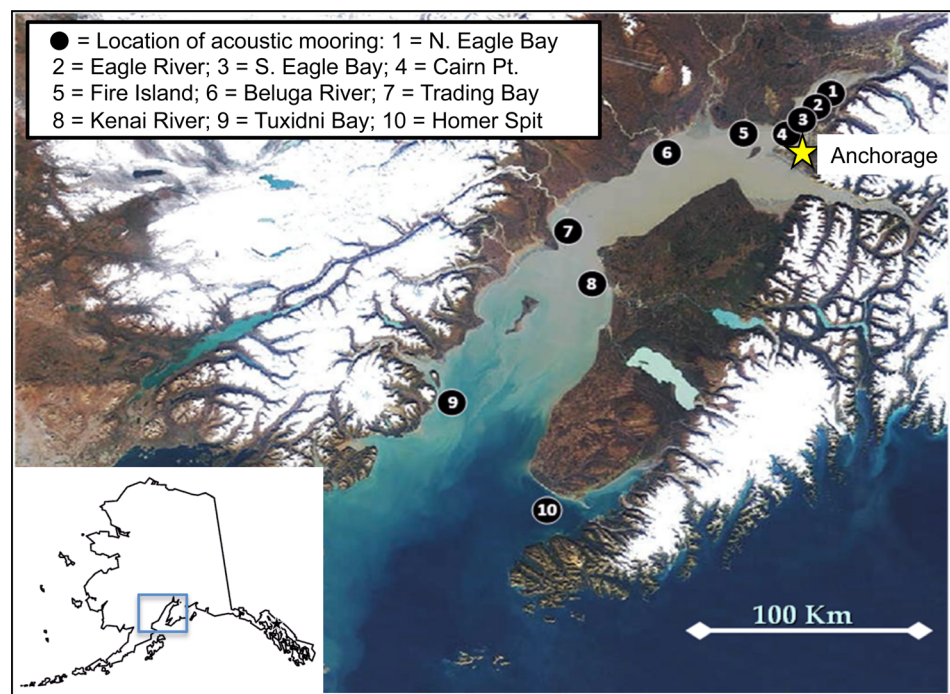

FIG. 2. (Color online) Satellite view of Cook Inlet, AK showing the locations of the acoustic moorings.
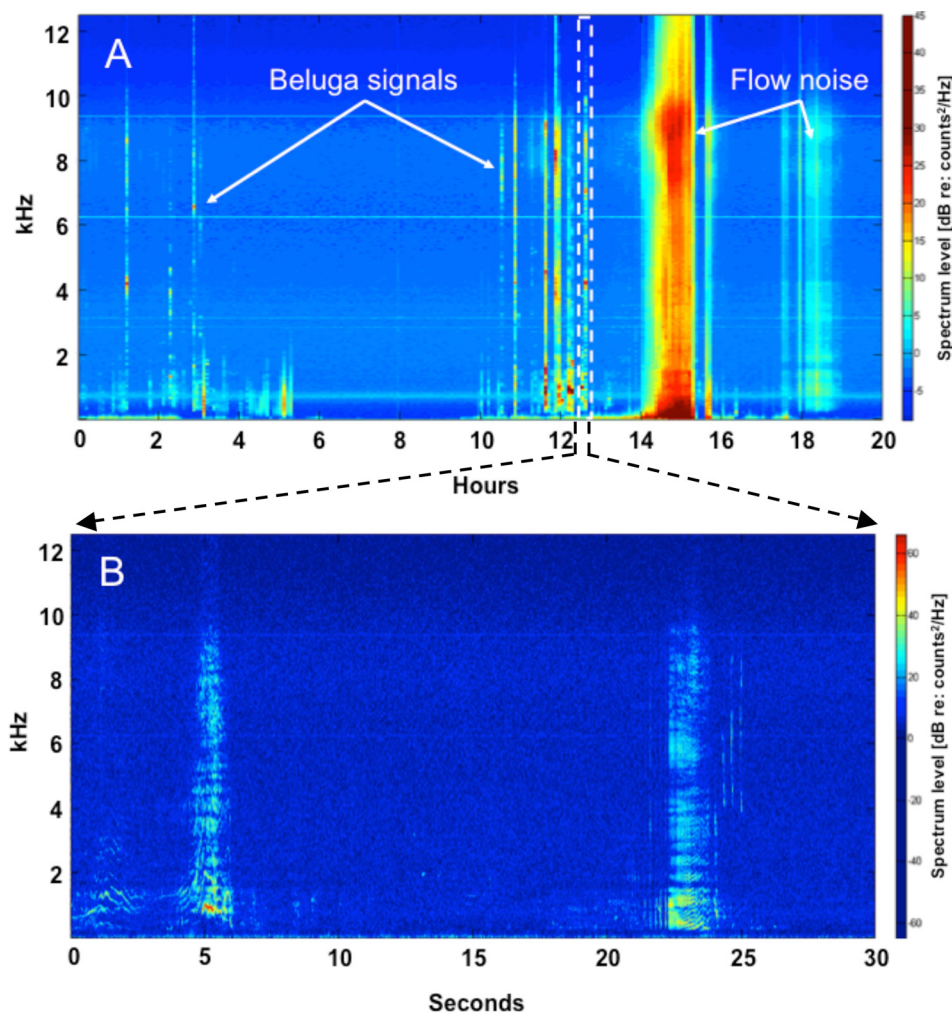
FIG. 3. (Color online) (a) Example of a 20-h LTSA window produced by Triton showing the presence of beluga calls and tidal flow noise recorded at Eagle River. (b) Expanded view of an EAR recording used to confirm the presence and identity of calls noted in the LTSA.

(Table I). A scalar value was given to the five 30-s recording periods with the highest abundance of signals in the encounter. For encounters with fewer than five recording periods with signals, zeros were scored for the missing number of periods (up to four periods). The abundance values were then summed and divided by five to produce a normalized measure of the amount of signaling for each encounter, termed the encounter call abundance (ECA) metric. Finally, to obtain a measure of the amount of daily whale acoustic activity (DWAA), each ECA value was multiplied by the encounter duration, represented in fractions of the 24-h day (e.g., 6 h = 0.25 days) and summed for the day.

To characterize the ambient noise level occurring at each site (due to natural, anthropogenic, and/or mooring-related sources), the average root-mean-square (RMS) sound pressure level (SPL) of each recording was calculated for bandpass limited data between 0–2 kHz, 2–6 kHz, and 6–12 kHz using a custom MATLAB^{TM} script. Factory calibrations of the EAR hydrophones (Sensor Tech SQ-26, Collingwood, Canada) and known hardware gain settings were used for these calculations. RMS SPLs were measured for a one-month period in summer and winter at eight mooring locations (Eagle River was considered to be representative of both North and South Eagle Bay, which were less than 2 km and 4 km away, respectively). To further evaluate the effects of masking on the detection of beluga and killer whale signals, the percentage of time in a 24-h period was calculated when the power spectral density level on the LTSA was equal to or greater than the received levels of animal sounds encountered in Cook Inlet (typically between 105 and 125 dB RMS re 1 μPa).

III. RESULTS

A. Mooring recovery success

A total of 24 mooring deployments were made between June 2009 and May 2010. Of these, 20 were recovered

TABLE I. Scalar metric used to quantify the relative abundance of calling, whistling, buzzing, and clicking in a 30 s recording.

Signal type and frequency	Abundance scale
1–5 calls/whistles	1
<5 buzzes/click trains	1
1–5 calls/whistles, <5 buzzes/click trains	1
1–5 calls/whistles, > 5 buzzes/click trains	2
6–10 calls/whistles	2
>5 buzzes/click trains	2
6–10 calls/whistles, <5 buzzes/click trains	2
6–10 calls/whistles, >5 buzzes/click trains	3
> 10 calls/whistles	3
>10 calls/whistles, <5 buzzes/click trains	3
>10 calls/whistles, >5 buzzes/click trains	4

successfully and four were lost. The four lost moorings were from North Eagle Bay (early summer 2009), Eagle River (over winter 2009–2010), Cairn Point (late summer 2009), and Fire Island (overwinter 2009–2010). The moorings at North Eagle Bay and Fire Island were each later found on a beach several km from their deployment sites in the spring and fall of 2010, respectively, and the data were successfully recovered. Of the 24 mooring deployments made, 21 were standard design and 3 were "sandwich" design moorings. Of the four moorings that were not successfully recovered, three were standard and one was a "sandwich" design mooring. The cause of the mooring failures could not be established conclusively, but in the standard moorings it is suspected that debris and/or sediment may have become entangled with the mooring and prevented surfacing. The sandwich mooring is believed to have been destroyed by winter ice.

B. The acoustic environment and masking

The large tidal variations characteristic of Cook Inlet produced cyclical periods of strong water flow, during which EAR recordings were sometimes saturated by flow noise. This caused beluga signals to be partially or fully masked (Fig. 3). In addition, other natural and anthropogenic noises were also present in recordings. Natural noises originated predominantly from debris striking the mooring and, at some locations, pebbles or stones moving along the bottom with the tide. These did not generally interfere with the detection of beluga calls because their occurrence was low and/or because the predominant energy was in a lower frequency band. Anthropogenic noise originated from a variety of sources at the different locations including: vessel traffic (Cairn Point, Fire Island, Trading Bay, Homer Spit), industrial/construction activities (Cairn Point), and aircraft (Cairn Point, Eagle River, Eagle Bay). Some of these noise sources did overlap in frequency with beluga and killer whale signals and may therefore have contributed to masking. Table II summarizes the average daily percentage of time that partial or full masking occurred at each site in the winter and summer. Masking periods varied in duration between a few minutes to the majority of the 24-h day, depending on the location. In the summer, the duration of masking was relatively low at Tuxedni Bay, Trading Bay, Beluga River, Kenai River, and Eagle River. It was intermediate at Cairn

TABLE II. The average daily number of hours that beluga and killer whale calls were masked by flow/mooring noise, as well as other natural and also anthropogenic sound sources in summer and winter.

Location	Average (standard deviation) daily hours of masking in summer	Average (standard deviation) daily hours of masking in winter
Eagle River	2.2 (0.4)	N/A
Cairn Point	3.7 (3.5)	0.9 (0.8)
Fire Island	9.9 (5.9)	16.3 (6.5)
Beluga River	1.3 (2.4)	9.3 (6.0)
Trading Bay	1.0 (1.4)	4.5 (2.3)
Kenai River	1.5 (2.2)	0.7 (1.8)
Tuxedni Bay	0.1 (0.1)	0.3 (0.7)
Homer Spit	4.0 (2.6)	2.3 (1.6)

Point and Homer Spit and was high at Fire Island. In the winter, masking decreased substantially in duration at Cairn Point and Homer Spit, increased by several hours at Trading Bay, Beluga Rive, and Fire Island, and did not change much at Kenai River and Tuxedni Bay.

Figure 4 shows a comparison of the summer and winter noise levels measured in three frequency bands at each site, representing contributions from all sound sources. In all cases, the 0–2 kHz frequency band had the highest RMS SPLs, the 2–6 kHz band was intermediate, and the 6–12 kHz band had the lowest levels. The highest ambient noise levels measured in the summer were at Cairn Point and Fire Island. The lowest were at Eagle River. In the winter, average levels mostly decreased or remained unchanged ($+/-1$ dB) in all bands, except at Beluga River and Fire Island, where RMS SPLs in the 2–6 kHz band increased by 2.2 and 2.0 dB re: 1 μPa, respectively. Of note is the substantial decrease in wintertime noise at Cairn Point, where the average level in the 0–2 kHz band decreased by 13.6 dB re: 1 μPa.

C. Beluga and killer whale detections

Beluga signals or killer whale signals were detected at all locations except North and South Eagle Bay (which were monitored for only 17 and 31 days, respectively). Table III summarizes the incidence of signals at the ten mooring sites. Beluga whales were recorded at Eagle River, Cairn Point, Fire Island, Beluga River, Trading Bay, and Kenai River. Killer whale calls occurred at Tuxedni Bay and Homer Spit. The majority of beluga detections took place at Beluga River. However, relative to the number of recording days, Eagle River had a slightly higher incidence than Beluga River, with 0.23 encounters per day versus 0.22, respectively. Both Beluga River and Eagle River also had the highest encounter durations.

Beluga detections did not take place with regularity at any location, but rather occurred as multi-day episodes separated by long intervals of absence (Fig. 5). Episodes of beluga presence varied in duration between 1 and 30 days. Belugas were heard at upper inlet locations in summer (Eagle River, Cairn Point, Fire Island, and Beluga River), fall (Fire Island and Beluga River), winter (Fire Island and Beluga River), and spring (Beluga River) and were detected in the middle inlet (Trading Bay and Kenai River) in the fall, winter, and spring, but not in summer. Belugas were not detected at any lower inlet locations, but signals produced by killer whales were recorded multiple times at Homer Spit (Fig. 5) and once at Tuxedni Bay (Oct. 28, 2009). Calls recorded at Homer Spit and Tuxedni Bay were tentatively identified as belonging to resident killer whales of the AB clan (C. Matkin, personal communication). Killer whale detections at Homer Spit occurred with regularity in the summer and fall and more episodically in winter and spring (Fig. 5).

IV. DISCUSSION

The results of this phase of the project reveal that investigating the occurrence and distribution of beluga whales in Cook Inlet using an acoustic approach is feasible, despite the challenging conditions. Eighty-three percent of the moorings deployed for longer than one month were successfully

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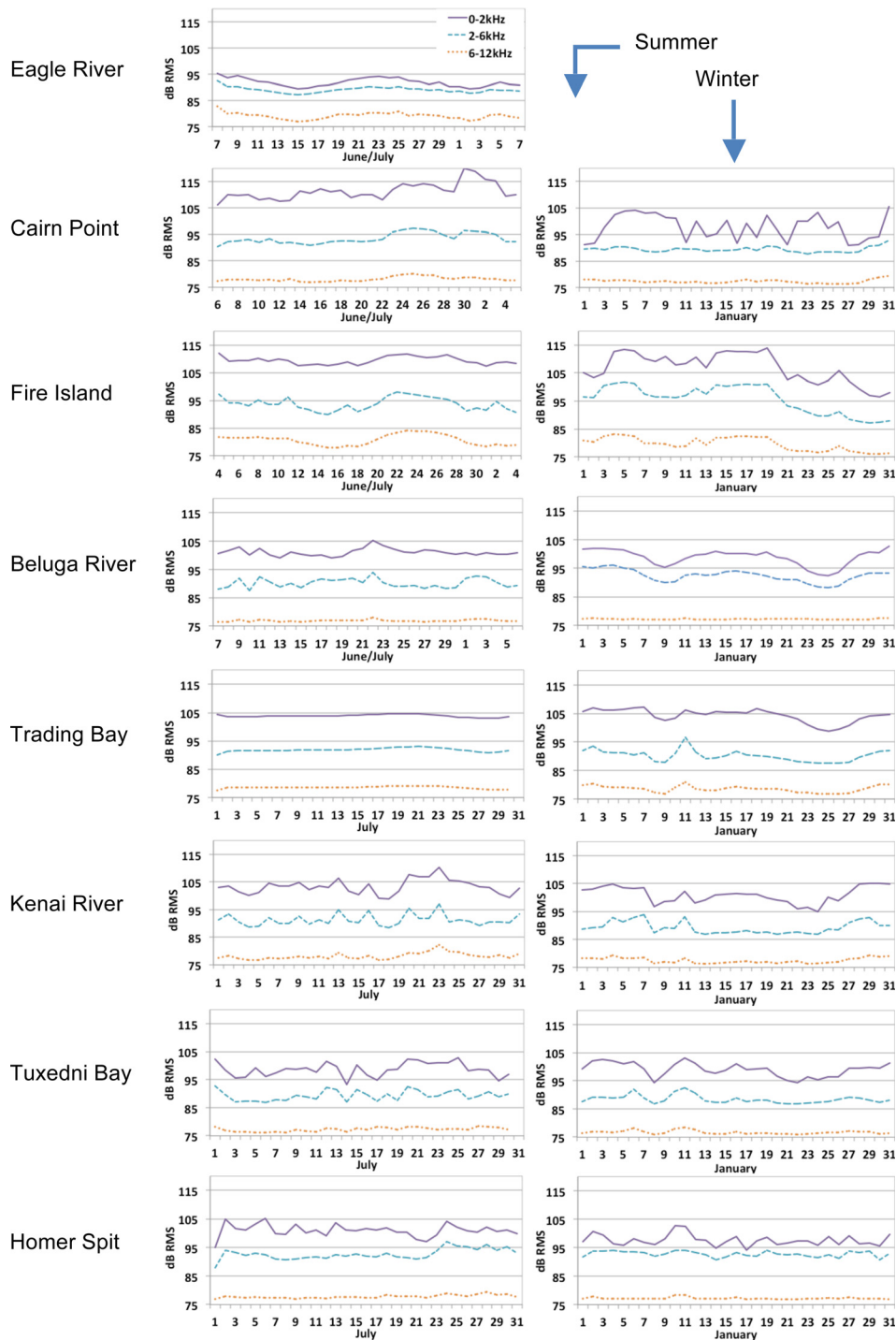Lammers *et al.*: Passive acoustic monitoring of belugas 2501

FIG. 4. (Color online) Average daily RMS SPLs in three frequency bands (0–2 kHz, 2–6 kHz, and 6–12 kHz) for eight mooring locations during one month in winter and summer. No wintertime data are available for Eagle River because the mooring was lost. All dB measures are re: 1 μPa.

recovered, which indicates that data can be obtained throughout the year to develop an understanding of beluga presence and habitat use in Cook Inlet. The primary challenge to the detection of beluga and killer whale signals comes from the effects of masking due to flow-induced noise and other natural and anthropogenic sources. The results of the masking analysis make it clear that some locations, like Fire Island, are poorly suited for acoustic monitoring using the methods described here. However, at most other locations, during at least 80% of the recording time, beluga and killer whale signals were at least detectable. This observation efficiency does represent an important improvement in the ability to monitor the occurrence of beluga and killer whales in Cook Inlet over

more traditional survey methods (e.g., vessel, aircraft, and shore-based surveys) limited by weather, tides, daylight hours, and/or distance. The analysis of acoustic energy recorded at the various mooring sites reveals that Cairn Point and Fire Island had the highest recorded levels in the summer, with elevated energy in the 0–2 kHz band. At Cairn Point, this was due primarily to industrial activities occurring nearby at the Port of Anchorage. These included noise from dredging, pile driving, construction activities, and transiting vessels. In the winter, many of these activities ceased or were reduced and, as a result, the recorded noise levels were lower. At Fire Island, on the other hand, noise levels remained relatively high in winter and even increased in the 2–6 kHz band. Noise

TABLE III. Incidence of beluga and killer whale encounters at the ten monitored locations. ECA refers to the encounter call abundance metric discussed in Sec. II.

Location	Number of recording days	Mooring deployment depth (m)	Number of beluga encounters	Number of killer whale encounters	Average encounter duration (h:mm)	Average ECA
North Eagle Bay	17	13.7	0	0	N/A	N/A
Eagle River	47	10.0	11	0	3:48	1.55
South Eagle Bay	31	12.5	0	0	N/A	N/A
Cairn Point	185	28.3	3	0	0:20	0.47
Fire Island	295	23.5	5	0	1:38	2.40
Beluga River	246	18.0	53	1	3:48	1.14
Trading Bay	271	14.6	33	0	1:35	1.15
Kenai River	211	10.7	10	0	0:48	0.49
Tuxedni Bay	279	25.9	0	1	0:45	0.80
Homer Spit	271	18.6	0	15	1:20	0.83

at this site was primarily due to water flow and from ice during the winter months. Interestingly, a similar wintertime increase in the 2–6 kHz band was observed at Beluga River, suggesting that the two locations may have similar noise contributions from the accumulation and flow of ice.
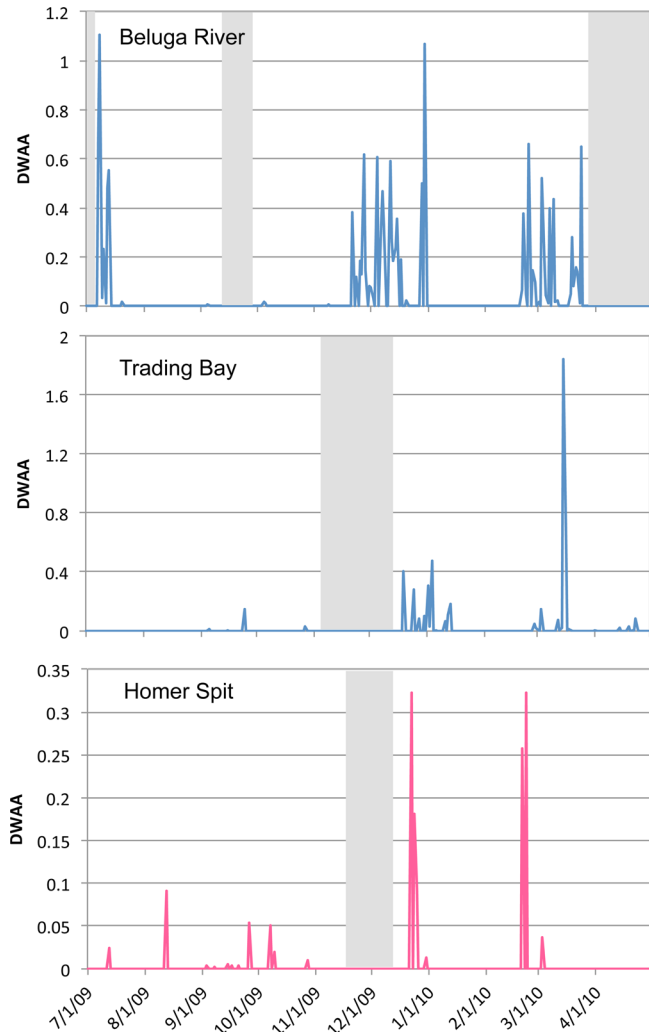

FIG. 5. (Color online) The DWAA measured at Beluga River, Trading Bay, and Homer Spit between 1 July 2009 and 30 April 2010. All detections shown for Beluga River and Trading Bay are of beluga signals and all detections at Homer Spit are of killer whale calls. Shaded areas represent periods when the mooring was not deployed or recorded.

In addition to the effects of signal masking, the behavior of belugas themselves may influence their detection. Belugas often produce few or no social signals during certain behavioral periods, such as during rest or when traveling (Karlsen et al., 2002; Belikov and Bel'kovich, 2003). As a result, it can be assumed that some belugas may have been present in a monitored area at times, but were not detected. Simultaneous visual and acoustic observations are necessary to establish the extent to which this might have occurred. A detailed analysis of the incidence of belugas and other cetaceans in Cook Inlet will be presented in a subsequent publication on beluga habitat use that will include data from an additional two years of deployments, as well as C-POD detections. However, some initial trends have begun to emerge and are worth noting. Belugas appeared to restrict their occurrence to the upper parts of the Inlet during the summer months, with no detections made south of Beluga River until September. Their occurrence then shifted further south in the fall, winter, and spring, with increasing detections at Trading Bay and no presence detected north of Fire Island. The furthest south that belugas were heard was at Kenai River where they were detected until the second week of March, when the mooring stopped recording due to battery failure.

Of the sites monitored, Beluga River had the most consistent presence of belugas throughout the year. This finding is in line with results obtained during summer aerial surveys, which have identified Beluga River and the nearby Susitna Delta as the central core of the population's summertime home range (Hobbs et al., 2005; Rugh et al., 2010). Although only seven weeks of recordings were obtained at Eagle River, the high number of detections made during this time suggests that this is also an important part of the range. Average encounter durations were highest at Beluga River and Eagle River, suggesting that these are areas where belugas aggregate. Finally, Trading Bay had the third highest incidence of encounters relative to the recording effort. These mostly occurred in the December to March time period, suggesting that this may be an important wintertime area.

Very few beluga detections were made at Cairn Point even though it is a bottleneck in the transit that many belugas make on their way to Eagle River. The Port of Anchorage on the eastern bank of Knik Arm has undergone annual improvements (e.g., dredging, pile driving, etc.), which has

contributed industrial noise to the ambient sounds of Cook Inlet. It is possible that this noise could have masked the calls of some transiting belugas, however, it is unlikely that this alone would explain the paucity of detections. Another possibility is that belugas may have consistently transited 2 km away along the western bank of Knik Arm, and remained out of the EAR detection range. Visual observations made during this time suggest, however, that although there was a preference for the western bank, belugas did periodically transit near the mooring site (Cornik and Saxon Kendall, 2010). Finally, it is possible that belugas may have suppressed their acoustic behavior while transiting past this area of high anthropogenic activity. Belugas in other locations have been shown to modify their acoustic behavior in response to vessel sounds, which are common near the Port of Anchorage (Lesage *et al.*, 1999). Such modifications may represent a predator avoidance strategy (Karlsen *et al.*, 2002), a response to stress (Castellote and Fossa, 2006), or perhaps a response to signal masking by the noise.

There was no observed overlap in the EAR data between the distribution of belugas and killer whales. Resident killer whales are known to occur in lower Cook Inlet and were detected there (at Homer Spit). However, killer whales were heard only once further north at Tuxedni Bay. It is unclear why this is the case, but it suggests that fish-eating resident killer whales do not directly compete for resources with belugas in Cook Inlet. Alternatively, belugas may actively remain in heavily sedimented, high-current upper inlet waters to avoid predation by their main, non-human predators, marine mammal-eating transient killer whales. Transient killer whales are known to produce fewer calls, whistles, and echolocation clicks than residents, presumably to avoid detection by their prey (Felleman *et al.*, 1991; Barrett-Lennard *et al.*, 1996). Therefore, the relative lack of detected killer whale signals in the upper inlet is not necessarily an accurate indication of their absence from the area.

In conclusion, an acoustic framework for documenting the spatial and temporal distribution of belugas in Cook Inlet has been established. This effort compliments and adds to a growing body of information obtained during similar projects aimed at acoustically monitoring threatened beluga populations in other parts of the world (e.g., Simard *et al.*, 2010; Delarue *et al.*, 2011). The framework created here will help to advance the current understanding of beluga seasonal occurrence in Cook Inlet and will help monitor the population's use of designated critical habitats (76 FR 20180, April 11, 2011). Continued data collection efforts will also provide baseline patterns of occurrence to help gauge the effectiveness of management efforts over time.

ACKNOWLEDGMENTS

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