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BOEM 2023-074

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U.S. Department of the Interior
Bureau of Ocean Energy Management
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ABOUT THE COVER

ST-600 and F-PODs in rock silos at the mouth of the Tuxedni River, Alaska (Verena Gill, NOAA Fisheries)

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Using passive acoustics to identify a winter foraging refugia and quiet space for an endangered beluga population in Alaska.

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Abstract

Cook Inlet beluga (CIB), *Delphinapterus leucas*, have been endangered since 2008 and have failed to recover from the overharvest that led to their drastic decline. Reasons for this lack of recovery are still unclear despite numerous conservation and research efforts. In the CIB Recovery Plan noise is categorized as one of three high threats to this population. Beluga are highly dependent on sound to communicate, navigate, and find prey, and chronic exposure to noise can lead to survival and reproduction impacts. Securing baseline information on habitat use and their soundscape is crucial in evaluating the current and future level of impacts from industry actions. Using passive acoustic monitoring methods, we documented the foraging occurrence and seasonality of CIB, together with orca (*Orcinus orca*), harbor porpoise (*Phocoena phocoena*) and humpback whale (*Megaptera novaeangliae*), for 12 consecutive months (Sept. 2021-2022) in two historically important but recently overlooked bays and rivers (Chinitna and Tuxedni) on the west coast of lower Cook Inlet. This area's ecological interest converges with mining, offshore oil and gas production, renewable energy, and commercial shipping. We also characterized the occurrence of anthropogenic noise sources that have the potential to disturb CIB. Results revealed higher presence of harbor porpoise, orca and humpback whales in Chinitna Bay, but lower CIB presence than in Tuxedni Bay. Belugas were never detected in Chinitna Bay but were in the river for 38 positive hours distributed across 21 days between September and February with one notable exception in June. Prior to this study it was not known if CIB were still using Chinitna River as in historical times. Beluga acoustic crypsis and preferential use of very shallow habitat revealed a strong perceived predation risk by the presence of orca. This particular behavior prevents generalizing acoustic results to large areas and calls for fine spatial scale sampling. Tuxedni Bay was identified as an important fall and

winter foraging ground for CIB with acoustic detections in 540 hours in 127 days; however, further research is recommended to understand winter prey preferences. We suggest a seasonal restriction for high sound producing anthropogenic activities, such as seismic surveys and pile driving, in and adjacent to Tuxedni Bay from September 1st to May 15th when CIB are present. The low level of anthropogenic noise disturbance quantified in both Chinitna Bay and Tuxedni Bay make these areas some of the most pristine and undisturbed sections of their critical habitat, but at the same time highly sensitive to further noise disturbance. Commercial shipping noise was the main anthropogenic noise source identified in both bays. Generating wideband and acute masking within the bays, this noise class is likely to lead to acoustic disturbance despite current, relatively low, levels of temporal overlap with beluga presence. Unpermitted pile driving was identified in Chinitna Bay, suggesting the need for further enforcement and outreach to increase the awareness towards this endangered population of belugas and the negative consequences of underwater noise in their protected habitat. Managing future industrial activities in this fall and wintering areas to minimize habitat degradation and acoustic disturbance to CIB will be a key component to support the recovery of this endangered population.

Keywords: Beluga, white whale, humpback whale, killer whale, harbor porpoise, F-POD, endangered, acoustics, anthropogenic noise, predation pressure, ship noise, foraging, recovery, Cook Inlet.

Introduction

Cook Inlet beluga whales (CIB), which are year-round residents of Cook Inlet, Alaska, were listed as endangered in 2008 following a major decline in abundance (~50%) in the 1990s associated with overhunting (NMFS, 2016). Subsequent cooperative management efforts between the National Marine Fisheries Service (NMFS) and Alaska Native subsistence users dramatically reduced the harvest, with the last large hunt in 1998 and last whale taken in 2005 (Mahoney and Shelden, 2000; Shelden et al., 2021). The best historical abundance estimate of the CIB population is 1,293 belugas from a survey in 1979 (Calkins, 1989). It was assumed once subsistence hunting ceased the population would rebound but CIB numbers have continued to decrease until very recently. The latest population estimate from 2022 indicates there are only 331 animals left, and the 10-year trend suggests the population is stable and may have initiated a slight rebound increasing at a yearly rate of 0.2 to 0.9% (Goetz et al., 2023).

In 2011 critical habitat was designated for CIB, in 2015 they were declared a NOAA Species in the Spotlight (SIS) and a Priority Action Plan outlining five key actions was published (NMFS, 2021), and in 2016 a Recovery Plan (NMFS, 2016) was released with 64 recovery actions. Despite all of these conservation and research efforts CIB have failed to recover and the reason(s) why are unknown. In the Recovery Plan ten potential threats to recovery were identified with three of those categorized as a high threat; catastrophic events; cumulative effects of multiple stressors, and noise. The SIS Action Plan also identified an improved understanding of the acoustic environment as a key benefit to CIB recovery (NMFS, 2021).

From late spring through early fall, almost the entire CIB population is now found predominantly in upper Cook Inlet (UCI) with their historic range contracting north from lower Cook Inlet (LCI) as their numbers plummeted (Shelden et al., 2018). Most of the recent work on

CIB has thus focused in UCI while much less is known about the contemporary use of LCI by CIB. This is compounded by limited knowledge of the whales' distribution during early fall to late spring because of the combination of poor sighting conditions (e.g. sea ice, short daylight), remoteness of the LCI coastal areas, a dearth of studies on marine mammals in LCI and whale behavior (offshore, longer dives) making visual detection difficult (Shelden, 2015). Limited satellite telemetry data from 1999-2003 showed winter use of the mid and LCI (Hobbs et al., 2005; Shelden et al., 2018). This was also the case from 2018-2023 when NMFS flew aerial distribution surveys for CIB in the winter (V. Gill, unpublished) and found belugas utilizing LCI from Tuxedni Bay and the Kasilof River north to the UCI. Other sources of information during this time of year come from a NMFS-supported community science effort; the Alaska Beluga Monitoring Program (AKBMP). Since 2019, citizen scientists have monitored for CIB daily from March-May and August-November from six road accessible coastal sites (https://akbmp.org/). Two of the six AKBMP sites are on the east coast of LCI at the Kenai and Kasilof Rivers but none are located on the west coast due to its remoteness which also limits access to vessels and aircraft only. The only consistent, continued, sampling effort in LCI in the recent past has been some passive acoustic monitoring efforts (Castellote et al., 2020) demonstrating seasonal presence of CIB in areas of mid and LCI.

The west coast of LCI is remote, roadless and relatively pristine compared to the east coast of LCI where there are numerous roads and urban concentrations with fishing ports, a natural gas liquefaction facility, oil and gas support infrastructure, and is a seasonal tourist hub. The west coast of LCI has no harbors or ports, and only one seasonal boat launch ramp is operational in this region (ADOT, 2016). LCI supports a rich marine ecosystem (Abookire and Piatt, 2005; Arimitsu et al., 2021) with large salmon runs (Hollowell et al., 2015), important seabird colonies

(Speckman et al., 2005), the most northerly nonbreeding location for shorebirds in the Pacific Basin (Ruthrauff et al., 2013), and many species of baleen and toothed cetaceans (Young et al., 2023). Two of the most productive bays along the west coast of LCI are Tuxedni and Chinitna along with the salmon-producing rivers that flow into them. Both bays have a large coastal brown bear population that attract ecotourism for brown bear viewing (Pinero, 2023) as well as lucrative fly-in sport fishing for salmon (Booz et al., 2019). Prior to the early 1990s, both Chinitna and Tuxedni Bays were important habitat for CIB (Rugh et al., 2000) but sightings have been uncommon in these areas as the population declined and contracted its distribution into UCI (Rugh et al., 2010). Consequentially, research focus moved to UCI. Pictographs with radiocarbon ages of 1700 years before present have been discovered on the walls of rock shelters near both Chinitna and Tuxedni Bays (Baird et al., 2022), a clear indication that these bays have been important whale habitat for some time.

Although the west side of LCI is relatively undisturbed there are still potential threats from large-scale exploration and development. Big mining projects are proposed that could have impacts in marine waters. If approved, Pebble Mine, an open pit copper-gold-molybdenum mine, will build ports on the coast and have vessels crossing LCI to processing facilities on the east side of LCI (USACE, 2020). The Johnson Tract Mine is a poly-metallic (gold, copper, zinc, silver, lead) project with Tuxedni Channel cited as a possible location for a marine ore terminal (Brown et al., 2022). Both Tuxedni and Chinitna bays directly adjoin the Federal Outer Continental Shelf (OCS) waters of the Bureau of Ocean Energy Management (BOEM) Cook Inlet Planning Area (CIPL). In the past decade BOEM has held two OCS oil and gas lease sales (LS) in the Cook Inlet OCS waters; LS 258 (December 2022) and LS 244 (June 2017), both of which had successful bids. As a result, offshore oil & gas exploratory surveys have been completed in recent years (Hilcorp Alaska, 2018; NOAA, 2019), that despite mitigation measures for the near-distance take of marine mammals, caused unavoidable disturbance (Gordon et al., 2003; Kavanagh et al., 2019). Further exploration and development of both fossil fuels and renewable energy is expected to occur in the OCS that may adversely impact offshore habitats in LCI as well as adjacent coastal habitat including Tuxedni and Chinitna Bays.

Securing year-round baseline information on soundscape, marine mammal occurrence and habitat use is crucial in evaluating the level of impacts new exploration and development may have on threatened and endangered cetaceans in LCI. Using passive acoustic monitoring methods, we documented the seasonal distribution and foraging occurrence of CIB, and seasonality of harbor porpoise, orca, and humpback whale, in two main bays and rivers (Tuxedni and Chinitna) on the west coast of LCI for one year (September 2021-2022). We also characterized the occurrence and levels of anthropogenic noise that have the potential to disturb CIB in these pristine areas. To enable recovery of CIB, it is essential to understand when and how these whales use these pristine areas in order to mitigate impacts to them from additional noise and disturbance.

This research is a companion study to Kumar et al. (2024) in which CIB were acoustically monitored on the east coast of LCI in urbanized rivers (the Kenai and Kasilof) with high disturbance and noise from seasonal fishing.

Methodology

Study area

Tuxedni Bay and Chinitna Bay are fjord estuaries located on the west coast of LCI (**Figure 1**) in CIB critical habitat, and are characterized by brackish waters, high turbidity, ice presence in winter, and shallow depths (<60m). Both estuaries have several rivers flowing into them, but their main fresh water inflow is generated at the bay-head by a glacial river under the same name as each of the bays. Both bays are surrounded by Lake Clark National Park and Preserve and the Chigmit Mountains of the Alaska Range. Two islands, Chisik and Duck, at the mouth of Tuxedni are part of the Alaska Maritime National Wildlife Refuge and have been afforded protection in some form since 1909.

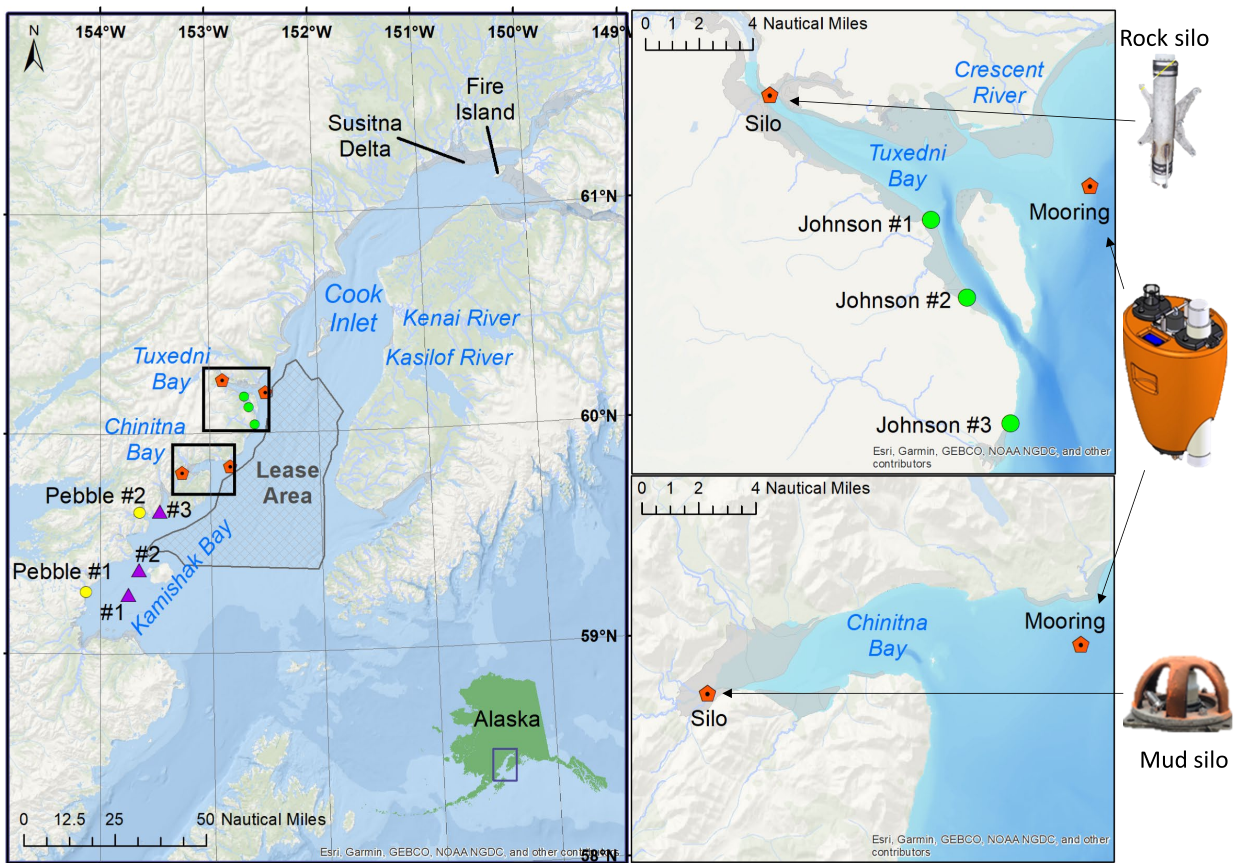

Figure 1: Left panel – Map of Cook Inlet, AK, depicting the locations of the different industrial activities around Chinitna Bay and Tuxedni Bay: BOEM Cook Inlet Planning Area (grey hatched polygon), Johnson Tract Mine proposed ore terminals (green circles) in Tuxedni Bay, and Pebble Mine proposed port facilities (yellow circles) and lightering stations (purple triangles) in Kamishak Bay. Right panels – Location of the mooring and silos in Tuxedni Bay (upper panel), and Chinitna Bay (lower panel), in lower Cook Inlet, AK.

Instrument deployment

Two types of instrument deployment methods were used in this study: low-profile moorings (Castellote et al., 2016; Castellote et al., 2020) and silos (Polasek et al., 2021). Moorings include two collocated acoustic instruments: an acoustic recorder (ST-600, Ocean Acoustics NZ) to sample the ambient noise and record marine mammal social signals, and an echolocation logger (F-POD, Chelonia ltd.) to detect odontocete echolocation, including feeding buzzes. Both instruments are contained in a syntactic foam mooring package with an acoustical release (Vemco AR-2, Innovasea Systems Inc.) for recovery. Silos are single or dual instrument housings (for ST-600, F-POD, or both) made of stainless steel and a low acoustic impedance plastic (ABS) to protect the instrument and hydrophone from ice and vegetation debris. Silos are inserted in a pre-drilled slot in hard sediment, or bolted to rocks, at the lower end of the inter-tidal zone during a strong low tide. Silo stations also included collocated ST-600 and F-PODs. This approach allowed sampling extremely shallow and intertidal areas near the shoreline or riverbanks typically visited by belugas. All moorings and silos included a temperature and pressure sensor (HOBO U-20, Onset Corp.) to investigate the influence of tidal depth on beluga presence. One temperature and pressure sensor was also attached to a tree next to the silo locations to sample the barometric pressure, used to calculate water depth. For this study, one mooring was deployed at the entrance of each bay and a silo station at the end of the bay within the tidally-influenced reaches of each river. The moorings were deployed at a depth of 18 m at mean lower low water to prevent interaction with sea ice and towards the north side of the bay entrances because beluga access was expected to occur from this direction. River bank mud-drilled silos where used in Chinitna River and a dual rock silo was used in Tuxedni River. For the winter period (September 2021 to May 2022), an additional mud silo and single rock silo were deployed in these stations, respectively, each housing a second F-POD programmed with a 4-month delayed start. This second set of instrumentation enabled continuous sampling throughout the entire deployment period as they were configured to begin sampling when the initial set of instruments exhausted their power supply or memory storage capacity.

The ST-600 sound recorder was programed to sample on a duty cycle of 5 minutes on and 10 minutes off with a sampling rate of 48 kHz, which encompasses beluga social signals (i.e., calls and whistles), other marine mammal signals, and environmental noise of both natural and anthropogenic origin. The F-POD echolocation logger records snippets of sound and acoustic parameters of detections while processing the incoming signal in real time on a continuous basis to log the occurrence of high frequency short impulsive signals in the range of 40 to 160 kHz, typically used by odontocetes for echolocation purposes. Moorings and silos were serviced in the spring and fall by boat and helicopter respectively to maintain a continued sampling for the period of September 2021 to September 2022.

Data analysis

Echolocation detection

Echolocation data was analyzed with the dedicated software F-POD.exe (v 4.5.2023), following Castellote et al. (2016), where all algorithm-based (KERNO-F classifier v1.0) echolocation detections were manually validated to exclude false detections or correct misclassified detections. The current F-POD algorithms only classify delphinid vs. narrowband high frequency (NBHF) click trains. In this study area, delphinid detections can only be assigned to beluga click trains, and NBHF to harbor porpoise click trains as no other odontocete species are present. Even though Dall's porpoises (*Phocoenoides dalli*) are observed in LCI and Kachemak Bay, they tend to prefer waters deeper than 180 m, and only harbor porpoises have been reported in Chinitna Bay and Tuxedni Bay from decades of aerial surveys (Shelden et al., 2014).

Beluga feeding behavior detection

F-POD full-train detail exports were used to identify beluga feeding events based on a combination of the inter-click interval (ICI) of click trains and the increment range of these intervals throughout the click train, as described in Castellote et al. (2020). Specifically, buzzes with minimum ICI <8.98 ms and consistently decreasing ICI trend (ICI increment range <1.49 ms) were classed as terminal buzzes related to prey capture. Beluga feeding events were summarized in positive minutes per day (any minute with at least one terminal buzz).

Beluga social signals detection

We implemented a machine learning ensemble model as proposed by Zhong et al. (2020) for Cook Inlet beluga vocalizations. The ensemble combines the results of four pre-trained convolutional neural networks (CNN): AlexNet, VGG16, ResNet50, and DenseNet, each generating a predictive numeric score for each 2 s of data. The scoring ranged from 0 (no resemblance to pre-trained beluga social signals) to 1 (full resemblance). For each of the 4 datasets obtained in this study (mooring or silo from Tuxedni or Chinitna), a manual scoring verification of a subsample of the 2 s scorings was made using a custom built application that allowed us to visualize each 2 s window in as spectrogram and aurally review the corresponding 2s audio clip, as well as a 10 s window to assess context, and assign a label or make corrections to the classification as needed. The subsample consisted of a selection of 500 events (or as many as available if less than 500) for each scoring from 0.5 to 1 on a 1 decimal step. The verification aimed at identifying a threshold score that would keep beluga false positive rate at or below 2.5%. All scorings at or above the selected threshold were manually validated.

Anthropogenic noise analysis

Ambient noise was analyzed following Castellote et al. (2019) to characterize the occurrence and contribution of the different identifiable anthropogenic sources. Recordings were processed using the Triton package (https://www.cetus. ucsd.edu/technologies _ triton.html) within the MATLAB software (MathWorks Inc., Natick, MA), generating long-term spectral averages (LTSA) with an averaging scale of 10s and 10Hz. LTSAs are spectrograms with each time slice typically covering a window of many seconds (10 s for analysis here) that consist of an average of many, non-overlapping, fast Fourier transforms (FFTs). FFTs were calculated using Welch's method (Welch, 1967) with Hanning windows. This approach allows highlighting periods and frequencies when noise departs from the average values, typically caused by transient signals (Wiggins and Hildebrand, 2007). These signals were evaluated visually and aurally by generating non-averaged spectrograms to identify the source. The Triton module (remora) Logger (Wiggins et al., 2007) was used to log the start and end date and times of each classed event. The remora Soundscape-Metrics (https://github.com/MarineBioAcousticsRC/Triton/tree/master/Remoras/Soundscape-Metrics) was used to obtain 1 minute average broadband (20 Hz–24 kHz) sound pressure levels (SPL) and one-third octave levels (TOL) ranging from the nominal center frequencies of 25 Hz to 20 kHz. SPLs and TOLs were computed for all anthropogenic noise events that lasted at least 1 minute, and results were summarized by noise class and study site for number of events, events per day, duration, and percent of time. In this study noise from commercial shipping is distinguished from service diesel generator noise, even if generators are within commercial vessels, these two noise classes can be distinguished by the spectral characteristics of their sound. Generator noise is masked by other more predominant sources of noise in commercial vessels under propulsion (Urick, 1983; Ross, 1987), therefore, generator noise is typically detected when vessels are in idle mode or anchored. It should also be noted that smaller, non-commercial vessels might also radiate noise form generators (Malinowski and Gloza, 2002).

Consolidating cetacean detections

The anthropogenic noise analysis via LTSA allowed a thorough review of all the sampled periods for cetacean social signals including beluga, humpback whale and orca. All species detections were labelled during that analysis process. Calls from these species were also identified during the manual validation of the CNN ensemble output. Therefore, results from all methods (LTSA and CNN ensemble for beluga, humpback whale and orca, and also FPOD for beluga) were combined to summarize the presence and absence of each species in detection positive hours per day (DPH, any hour with at least one detection from either analysis method).

Anthropogenic noise disturbance analysis

In order to evaluate whether the identified anthropogenic noise sources have the potential to interfere with beluga communication, three TOL metrics were calculated from the anthropogenic noise events per location to compare to beluga hearing thresholds: the median (50^{th} percentile), the maximum (event of highest SPL), and the maximum composite (maximum level for each third octave band from all events of each class), and following Brewer et al. (2023), results were graphically represented to evaluate the level of noise exceeding hearing thresholds, i.e. the level of beluga auditory masking by anthropogenic noise. TOL from background noise in quiet conditions were also represented graphically to provide context for the evaluation of anthropogenic noise contribution to the soundscape of each bay, as well as define when beluga hearing is limited by the natural background noise within its habitat. Beluga hearing data consists of minimum TOL thresholds over all individuals tested both with in water auditory evoked potentials (AEP) and behavioral methods (Castellote et al., 2014; Erbe et al., 2016; Mooney et al., 2018) including a Cook Inlet beluga whale calf (Mooney et al., 2020). A total of 50 1-minute periods of quiet conditions were arbitrarily selected through all months of the sampling period for each bay based on the characteristics observed in the LTSAs. In particular, the selection criteria considered: no anthropogenic sources discerned in the 20Hz – 24 kHz spectrogram, low sea state (i.e., no discernable breaking wave noise), absence of rain, ice, or biological transient signals, and no flow noise caused by high current periods. The same methods used in anthropogenic noise events were applied here to compute 1 minute average TOLs and SPLs representing these quiet periods.

A second approach to assess the potential for noise disturbance was by quantifying the amount of temporal overlap between beluga acoustic presence and anthropogenic noise occurrence. Beluga detections were grouped into acoustic encounters (i.e., Lammers et al., 2013), that is, lumping detections that occur within 60 minutes of each other. Beluga detections separated by 60 minutes or more were logged as separate encounters. The rational for this grouping is to account for the time period when belugas are present but in silent mode in between detections. Encounter start and end periods were compared to the start and end times of anthropogenic noise events, and the level of temporal overlap was quantified for each beluga encounter.

Beluga relationship with tides

Data from the temperature and pressure sensors were processed with HOBOware Pro software (v. 3.7.25 Onset Computer Corp.) using the Barometric Compensation Assistant. This module uses water pressure data and compensates it with barometric pressure to create a water depth series.

Because pressure sampling was conducted at intervals between 10 and 20 minute to ensure sampling throughout the deployment period at silos and moorings, data was linearly interpolated to approximate a depth value every minute. A rolling average of 30 minutes of data was used to assign an increasing (flooding) or decreasing (ebbing) tidal trend for each minute. High and low tidal states were identified by inflections in the trend. Slack periods were defined as the 22 minutes before and after these inflection points. The 45 minute slack period duration was chosen based on visual inspection of depth data from the sampled sites.

Minute-level beluga acoustic detections were associated with the corresponding depth and tidal trend (flooding, ebbing, high, low) and summarized graphically. A contingency table and $\chi 2$ test for independence was applied to evaluate whether the beluga acoustic detections were randomly distributed across the 4 tidal periods for each sampled site.

Results

Gaps in sampled periods

Initial instrument deployments were completed in August and September 2021 for silos and moorings respectively. A servicing of all instruments was completed in May 2022, and a final recovery in September and October 2022 for moorings and silos respectively. The project suffered considerable data gaps due to damaged instruments, ice entrapment, or F-POD malfunction. The sound recorder deployed in Chinitna River, in a mud silo in August 2021, stopped recording on October 4th. Tide data showed the date and time of the last sound recorder files corresponding to a low tide period that exposed the silos to the air for several hours. The two F-PODs in mud silos next to this recorder were recovered with its hydrophone guard crushed and one of them with its hydrophone destroyed, but both instruments sampled correctly and data was recovered, indicating the incident occurred in spring 2022. Marks on the F-POD housings and silos indicated likely interaction with a brown bear. Therefore, we presume the unexpected early termination of the recording might have also been caused by a bear during a low tide when the instruments was exposed to the air, shaking the silo strong enough to impact the electronics. The overwinter period at Chinitna River was therefore only sampled with the F-PODs prior to the bear interaction. A second recorder leaked in the mooring from Chinitna Bay merely 8 hours after re-deployment on May 2022. Sounds in the last files suggest a sea otter interacted with the mooring and chewed the hydrophone until a leakage occurred. The 2022 ice-free season was only sampled with the FPOD for this location. The rock silos installed in Tuxedni River were very likely entrapped in ice from December 10th 2021 until April 2nd 2022 as suggested from the low signal in both the sound recordings and FPOD data. We considered this period as off effort. For both the Chinitna and Tuxedni Rivers, the delayed start F-PODs deployed in fall 2021 failed to save power during the 4-month delay period due to defective firmware, therefore these instrument's power was partially depleted when they started their sampling cycle on January 1st 2022. As consequence, these F-PODs only logged for ~ 2 months instead of the 4 months expected. For Tuxedni River, the recorder sampled the rest of the 2021 winter until the servicing in May 2022, but for the Chinitna River, because the recorder was impacted by a bear earlier in October 2021, sampling effort ended on February 21st 2022 when the delayed start F-POD depleted its power, and sampling effort in this location was not resumed until the servicing in May 2022. The Hobo pressure/temperature sensor in the Chinitna Bay mooring leaked, and data was lost, impeding any analysis of beluga relationship to tide in this study site. These instruments are factory sealed and data is offloaded via an optical port, we are unaware of the cause of the leak. Last and very unfortunately, memory cards containing data from the sound recorders from both Chinitna River and Tuxedni River for the period May-October 2022, as well as their backup in an external drive, were stolen during field work travel (fortunately F-PODs covered those periods).

Chinitna cetacean detections

Chinitna datasets yielded very low beluga presence (**Figure 2**). Belugas were never detected in the Bay despite nearly continuous sampling effort from September 2021 until September 2022 (but note the period May 20th until September 13th 2022 was sampled only with F-POD). Belugas were detected in Chinitna River on 21 days in September, October, December, February, and June, with detection periods reaching a maximum of 4 hours of presence. March and April 2022 were not sampled for this location. Feeding behavior, however, was never detected in Chinitna River. Humpback whales were detected in the bay for 10 days between mid-December and mid-

January with up to 10 hours/day on December 20th and 22nd, and for 7 days between April 25th and May 10th. Orca were detected in the bay on multiple days in December and February to May, with a maximum of 7 hours/day. Orca were also detected once in the river on September 20th 2021 for just 1 hour. Harbor porpoise were detected on a daily basis except for 19 days in January, 2 days in February and 2 days in March with a maximum of 22 hours/day. Harbor porpoises were also detected in the River on August 25th - 28th, September 1st and 8th 2021, and June 7th with a maximum of 4 hours/day.

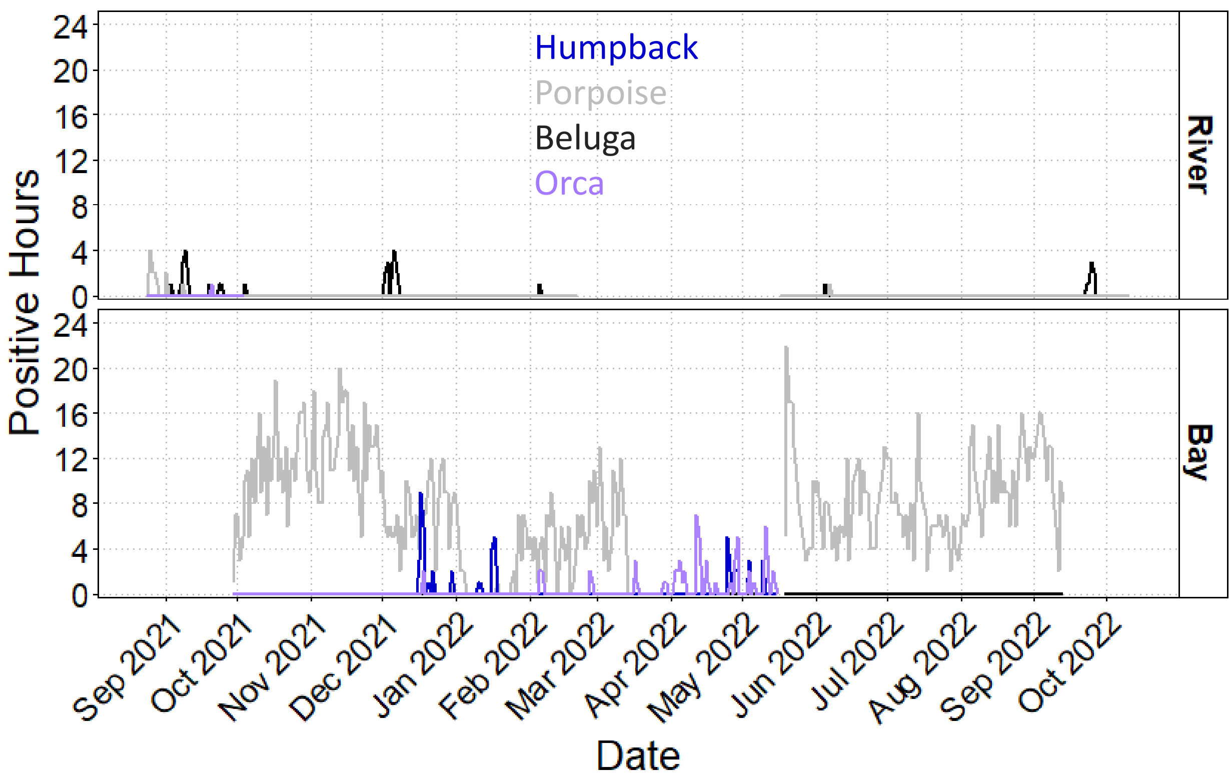

Figure 2: Detection positive hours for humpback whale, harbor porpoise, beluga and orca at Chinitna Bay and River. Gaps in the line series denote no sampling effort.

Chinitna anthropogenic noise

A total of 140 anthropogenic noise events were identified in Chinitna Bay for the period sampled with the recorder (229 days, September 29th 2021 to May 16th 2022), with 4 sources of noise plus an unknown class (later identified as impact hammer pile driving but of unknown origin, see discussion) (**Table 1**). Commercial ship noise was the most prevalent noise contributor, but overall anthropogenic noise was present only 6.5% of the time (**Figure 3**).

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Table 1: Descriptive results for anthropogenic noise events identified in Chinitna Bay, Cook Inlet, Alaska.

	Commercial ship	Unknown	Ship generator	Outboard	Aircraft
%	5.5	0.7	0.2	0.1	0.01
Total (minutes)	17,970.0	2,219.9	759.9	445.8	2.9
Total events	102	11	5	17	5
Events/day	0.4	0.05	0.02	0.0001	0.02
Average duration (minutes)	176.2	201.8	152.0	27.5	0.6
1 x SD	146.9	141.0	96.3	25.9	0.5

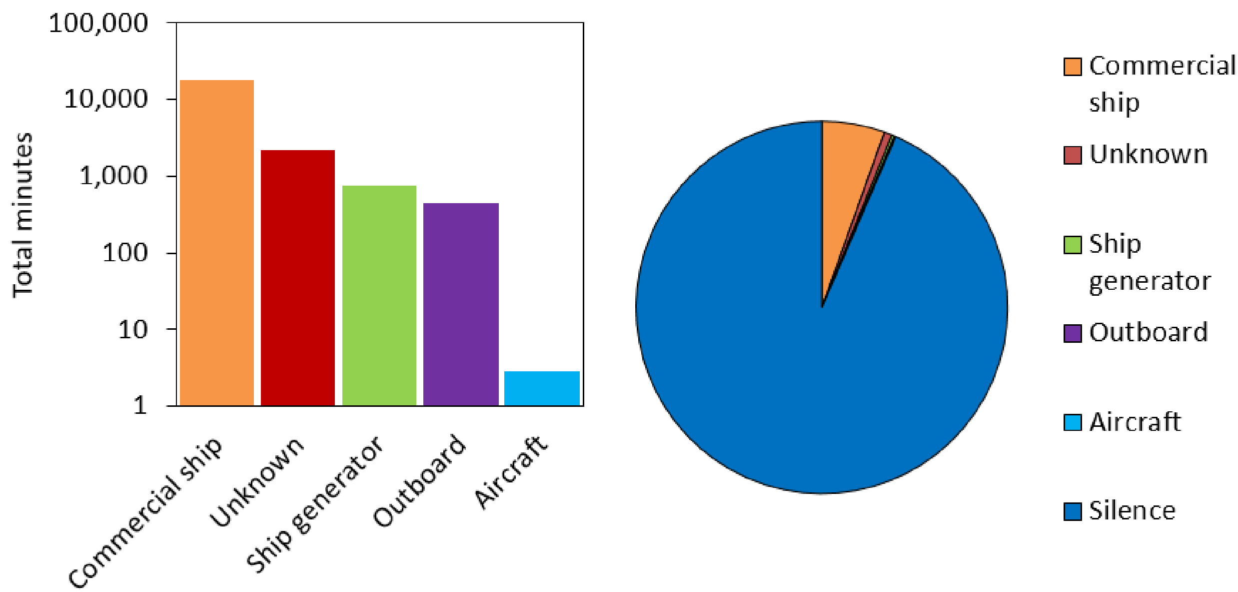

Figure 3: Left – Bar diagram with total number of minutes per noise class, and right – pie chart with percent of time for each noise class and silence (period with no evident contributions from anthropogenic sources) for Chinitna Bay, Cook Inlet, Alaska.

Received levels of anthropogenic sources in Chinitna ranged in the 93 to 132 dB (re 1 μPa for all cases), with commercial ship and ship generator noise as the highest amplitude classes, with outboard motor noise in Tuxedni Bay (**Figure 4**). The SPL for quiet periods ranged from 91 to 106 dB, with a mean of 97 dB (1 x SD of 4 dB).

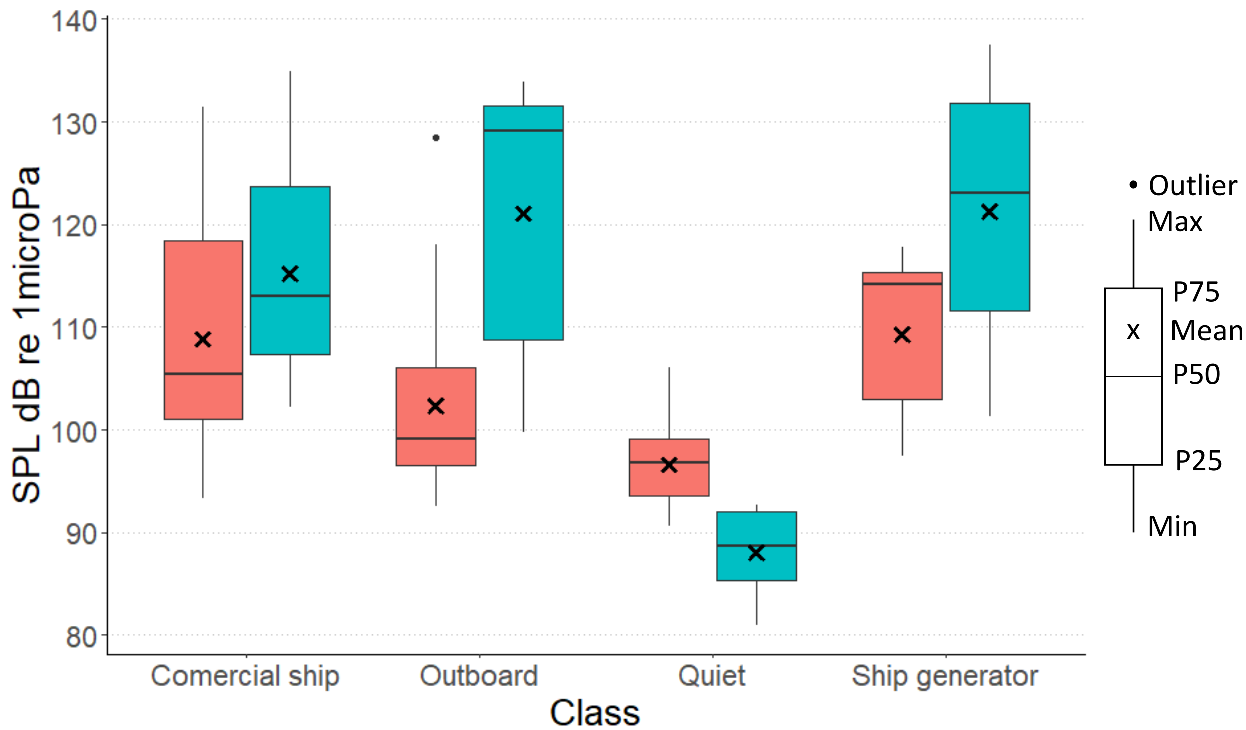

Figure 4: SPL values for identified anthropogenic noise classes in both Chinitna Bay, and Tuxedni Bay, Cook Inlet, Alaska. Horizontal bars give median SPL, crosses give mean SPL, boxes show the interquartile range and whiskers give the full range of SPL.

Chinitna River was very quiet, with only 3 outboard motor events in the sampled period but it should be noted the sampled period was very limited (41 days, August 24th to October 4th 2021) due to the instrument being impacted by a bear. Outboard motor noise events lasted on average 2.2 minutes (SD 0.3) and their SPL ranged from 109 to 128 dB.

Tuxedni cetacean detections

Tuxedni datasets yielded beluga presence in both the bay and the river on multiple months, primarily from September to April (**Figure 5**). Belugas were detected in the river on September 8th 2021 prior to detection in the bay. The last day of detections in 2021 in the river was November 13th, then detections were only in the bay from November 18th 2021 to April 1st 2022. In April 3rd belugas were detected in both sites until last detections on April 12th in the bay and April 17th in the river. Detection periods in the bay reached the maxima of 24 h per day, and 13 h in the river. Periods not sampled due to issues described in previous sections were September 2021 and October 2022 at the bay, and mid-January 2021 to end of March 2022 at the river. Feeding behavior was detected multiple times, with maximum occurrence in September and October of both years, and low but consistent occurrence through the month of November 2021 and the month of January 2022. Humpback whales were detected only on May 25th in the Tuxedni Bay. Orca were also detected only in the Bay on 2 days in January, 2 days in May, 2 days in June, and one day in July, with a maximum of 5 hours/day. Harbor porpoise were detected on an almost daily basis from September 30th 2021 until January 3rd and from February 12th until May 24th, with up to 18 hours/day.

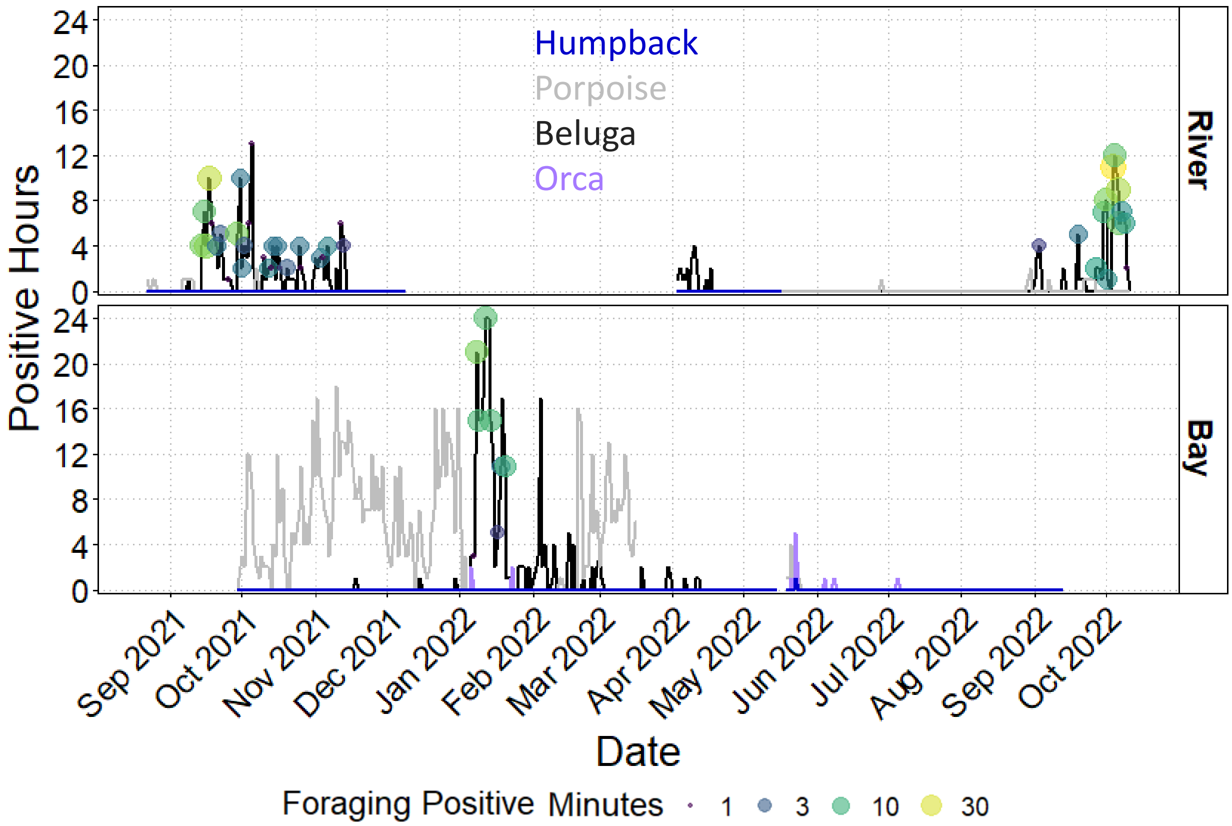

Figure 5: Detection positive hours for humpback whale, harbor porpoise, beluga and orca at Tuxedni Bay and River. Gaps in the line series denote no sampling effort. Beluga feeding behavior as positive minutes per day are denoted as circles in the beluga line series.

When comparing positive hours by species and location, Chinitna Bay yielded the highest number of positive hours (2368) primarily driven by harbor porpoise, humpback, and orca presence, followed by Tuxedni Bay (1158) driven by harbor porpoise and beluga presence, followed by Tuxedni River (290) driven by beluga presence, and finally Chinitna River (52) driven by beluga and porpoise presence (**Figure 6**).

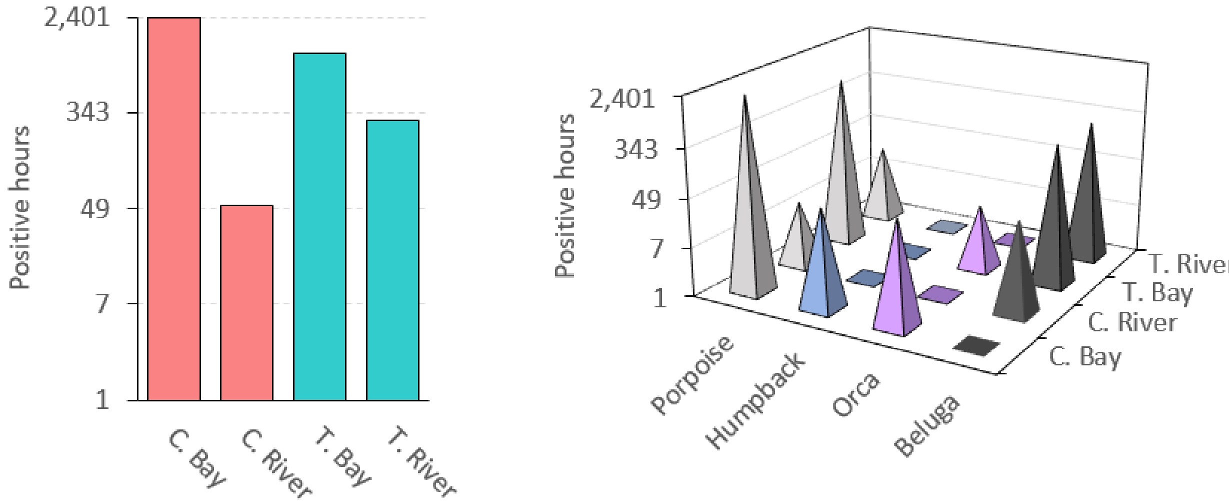

Figure 6: Left panel – total number of detection positive hours per study site, and right panel – distribution of detection positive hours per species and site.

Tuxedni anthropogenic noise

A total of 505 anthropogenic noise events were identified in Tuxedni Bay for the period sampled with the recorder (345 days, September 29th 2021 to May 15th 2022, and May 19th 2022 to September 13th 2022), with 4 sources of noise (**Table 2**). Commercial ship noise was the most prevalent anthropogenic contributor, and overall anthropogenic noise was present 14.2% of the time (**Figure 7**).

Table 2: Descriptive results for anthropogenic noise events identified in Tuxedni Bay, Cook Inlet, Alaska.

	Commercial ship	**Ship generator**	**Outboard**	**Aircraft**
%	13.2	0.7	0.3	0.01
Total (minutes)	65,446.5	3,382.6	1,598.7	10.9
Total events	406	28	54	17
Events/day	1.2	0.1	0.2	0.05
Average duration (minutes)	161.2	120.8	14.0	0.6
1 x SD	334.2	124.4	36.2	0.3

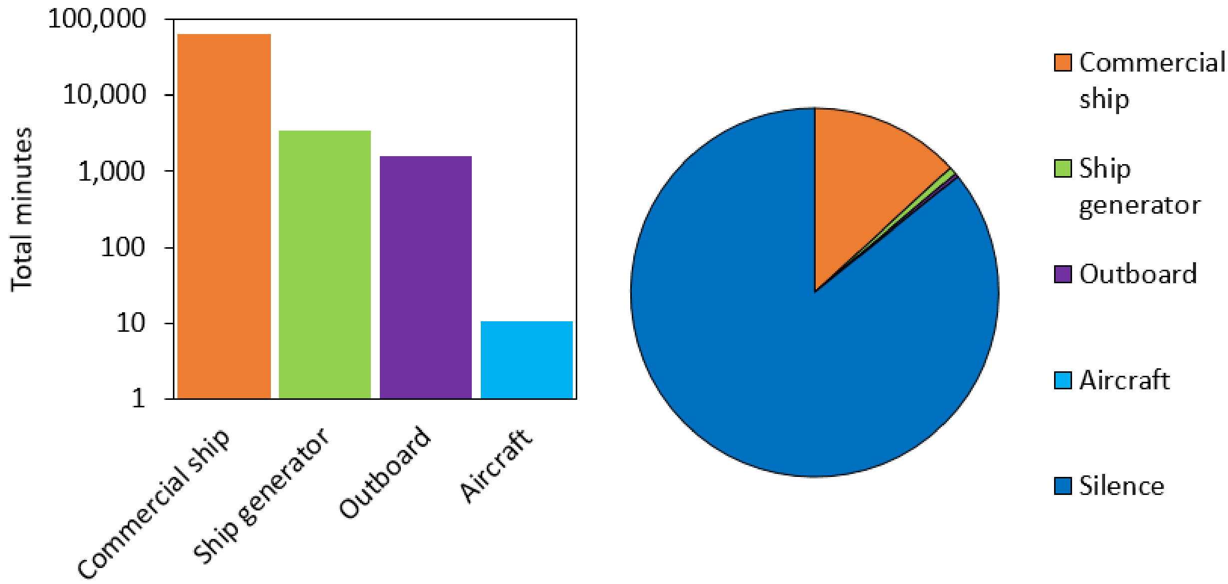

Figure 7: Left – Bar diagram with total number of minutes per noise class, and right – pie chart with percent of time for each noise class and silence (period with no evident contribution form anthropogenic sources) for Tuxedni Bay, Cook Inlet, Alaska.

Received levels of anthropogenic sources ranged 102 to 138 dB, with outboard motor and ship generator as the highest amplitude classes (**Figure 4**). The SPL for quiet periods ranged from 85 to 93 dB with a mean of 88 dB (1 x SD 3.2 dB), which is 9 dB lower than Chinitna Bay.

Tuxedni River was very quiet, with only one aircraft event identified in the sampled period (268 days, August 22nd 2021 to May 5th 2022) which lasted 53 s with a received level of 116 dB.

Relationship between beluga acoustic presence and tide period

Beluga acoustic detections in both river locations occurred in their majority during the ebbing tidal period, however the detections in Tuxedni Bay were distributed between the ebbing and flooding periods (**Figure 8**).

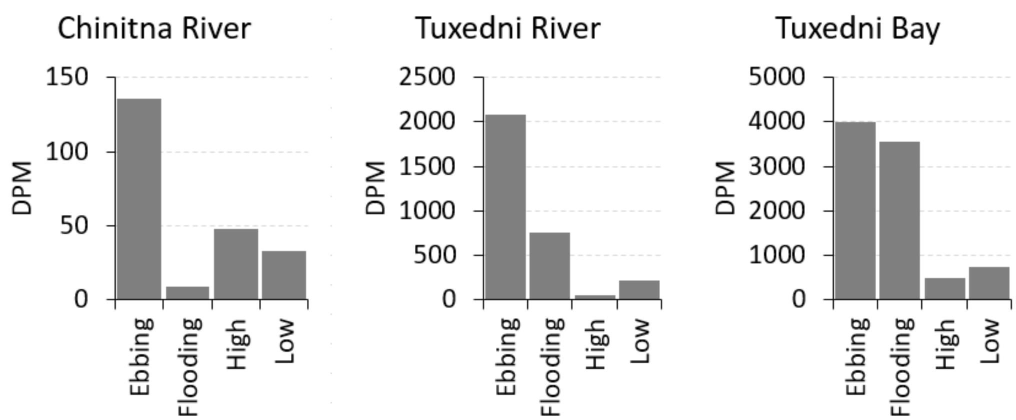

Figure 8: Tidal period distribution of beluga acoustic detections in DPM for the three sites where depth data was available, Chinitna River, Tuxedni River and Tuxedni Bay, Cook Inlet, AK.

The contingency table and χ^2 test results yielded a highly significant relationship between acoustic beluga presence and tidal period both for the overall results, χ^2 (6, N =12,097, p < .001, and independently for each of the 3 study sites where depth data was available (**Table 3**). Beluga DPM were not randomly distributed across the 4 tidal periods in any of the 3 study sites where depth data was available.

Table 3: Contingency table and χ2 results for beluga acoustic detections (in DPM) and the 4 tidal periods for each study site where depth was available.

Area		Ebbing	Flooding	High	Low	χ2
Tuxedni River	Obs	2084	754	49	218	df=6; N=13,962
	Exp	1593	1108	7900	256	p < 0.01
Chinitna River	Obs	136	9	48	33	df=6; N=1016
	Exp	116	81	575	19	p < 0.01
Tuxedni Bay	Obs	3986	3555	478	747	df=6; N=39,418
	Exp	4497	3129	22303	723	p < 0.01

The relationship of beluga DPM with depth was very different between the three sites. For the river sites, the majority of the beluga detections occurred at the shallowest end of the depth range (**Figure 9**). For Chinitna River this relationship was extreme, with most detections falling in the 0-0.5 m depth range. For Tuxedni River, detections were spread in the 0 - 2.5 m range, although the higher proportion of detections fell into the 0-0.5 m depth. For Tuxedni Bay, beluga detections were distributed along a wider range of depths, with the majority between 12 and 16.5 m depth.

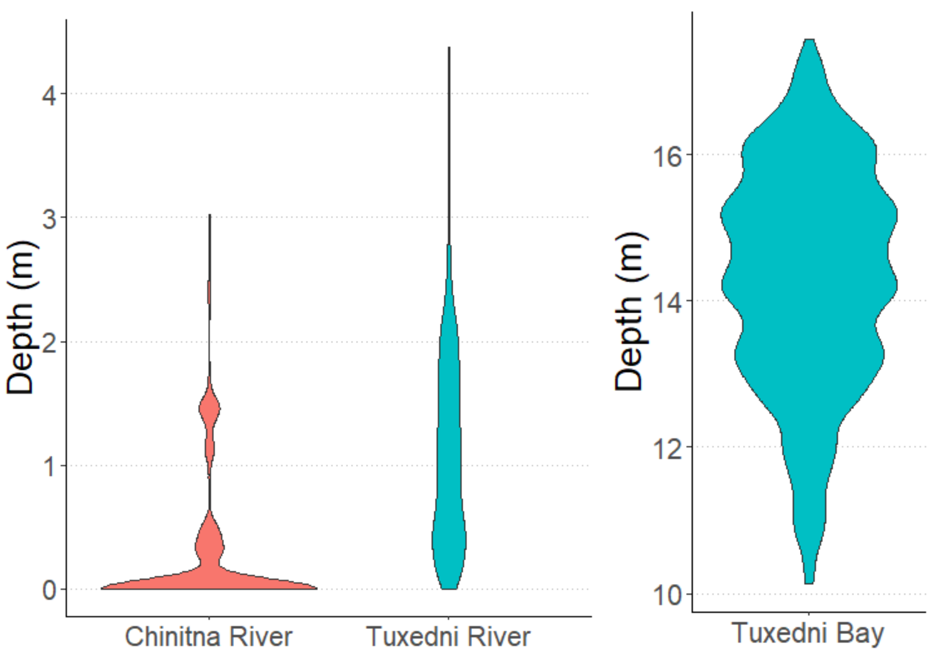

Figure 9: Violin plot outlines illustrating kernel probability density (i.e. the width of the color area represents the proportion of the data located there) of beluga acoustic detections in DPM and depth at the time of each detection, for the three areas where depth data was available, Chinitna River, Tuxedni River and Tuxedni Bay, Cook Inlet, AK. Note Tuxedni Bay data ranged deeper in depth and therefore is plotted independently of the river data.

Anthropogenic noise disturbance

The predominant anthropogenic noise sources identified in the data are commercial ship, ship generator, outboard motor, and for Chinitna Bay the class unknown (**Figure 3** and **Figure 7**). The aircraft class, although identified in 3 of the 4 areas, was less prevalent and occurred in small numbers, and therefore is not included in this analysis. Because the river data from both bays yielded very few anthropogenic noise events, only the bay data is considered in this analysis.

All three anthropogenic noise sources evaluated for the potential to mask beluga hearing exceeded hearing thresholds at or below the band centered at 500 Hz (**Figure 10**). Maximum composite, maximum and median TOLs exceeded beluga hearing thresholds in all cases except the median for outboard noise in Chinitna Bay, which only partially exceeded hearing thresholds for some frequency bands above 600 Hz. In absence of anthropogenic noise, beluga hearing is limited by background noise in Chinitna Bay at frequency bands above 400 Hz, and in Tuxedni Bay at bands above 800 Hz (quiet TOLs exceed hearing thresholds at and beyond these frequencies, therefore beluga cannot hear signals within that frequency range unless they are of higher amplitude than the background noise in quiet conditions). However, anthropogenic noise can further limit beluga hearing in lower frequency bands and for a much higher magnitude. For example, commercial ship noise in Tuxedni Bay will limit beluga hearing starting at 250 Hz for median levels, and 170 Hz for the maximum composite level, and while background noise would barely affect hearing at the band centered at 800 Hz, median levels for commercial ship noise will bump hearing thresholds by ~20 dB, and the maximum composite level by ~43 dB.

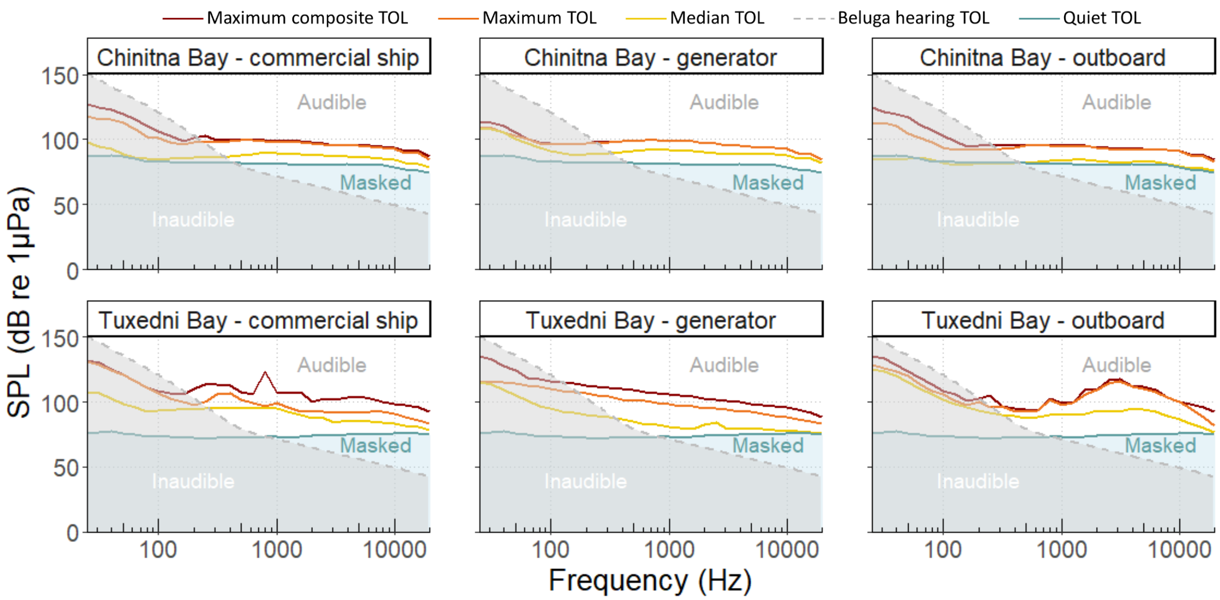

Figure 10: TOL for the maximum composite, maximum event, median, and quiet conditions grouped by area and anthropogenic noise class, as well as minimum beluga hearing thresholds. Grey area will be inaudible for beluga, white area will be audible, and light blue will be the naturally masked area in quiet conditions for each bay. The respective anthropogenic noise source and levels will mask any white area below the red, orange and yellow lines.

The TOLs from commercial ship and generator noise are relatively similar within bays, and of higher general amplitude in Tuxedni Bay than Chinitna Bay (**Figure 4**). Outboard motor noise band levels are also higher in Tuxedni Bay, in particular for the range 1 to 20 kHz, and while all three TOL metrics are above quiet levels in Tuxedni Bay, the median levels in Chinitna Bay are barely discernable from quiet levels.

Results for evaluating the amount of temporal overlap between beluga acoustic encounters and anthropogenic noise occurrence was limited to the periods when sound recordings were available at each location. A total of 239 beluga encounters were obtained, of which 37 (15.5%) were overlapped by anthropogenic noise. The overlap in all 37 encounters was caused by commercial ship noise, and one encounter also included aircraft noise. This temporal overlap ranged from just a few minutes to the entire duration of the encounter. The distribution of temporal overlap by anthropogenic noise for all encounters is shown in **Figure 9**.

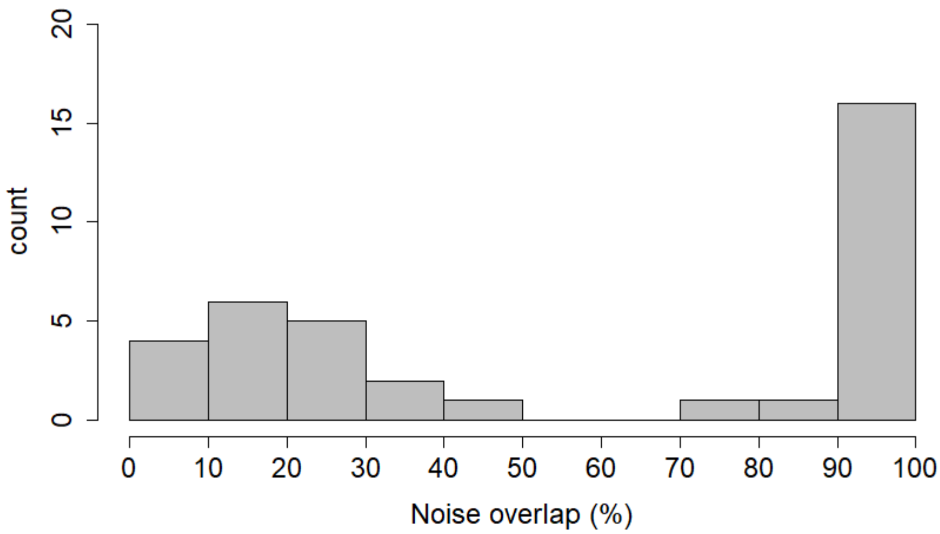

Figure 11: Percent of temporal overlap between co-occurring beluga acoustic encounters and anthropogenic noise events for Tuxedni Bay, Cook Inlet, for the period September 29th 2021 to May 15th 2022.

Discussion

Successful sampling despite data gaps

This work documented the seasonal presence of several cetaceans, the foraging occurrence of beluga, and the sources and levels of anthropogenic noise contributing to the soundscapes of the two areas of the west coast of LCI. The study however suffered significant data gaps due to equipment malfunction, ice entrapment, equipment destruction by wildlife interaction, and theft of data cards after collection. Ice entrapment is difficult to avoid in a subarctic environment, in especially if instruments are periodically exposed to the air. However, if silos are deployed lower in the intertidal zone, reducing air exposure periods and the risk ice formation, it is possible this could be mitigated. The challenge with this sampling approach is that there needs to be a balance between how far down the intertidal zone instruments can be deployed, and what available tidal windows that location provides to access the instruments for servicing and recovery. Because both sites in the Tuxedni and Chinitna rivers had never previously been sampled, and no river discharge data exists, we opted for a conservative balance, where instruments were deployed several feet above the ambient river level at a negative low tide. This approach ensured access to the instruments during all discharge conditions and relatively mild low tide cycles. We believe one sound recorder was destroyed by a sea otter (*Enhydra lutris*) and another by a brown bear (*Ursus arctos*). Future deployments in areas of high sea otter density, such as Chinitna Bay (Gerlach-Miller et al., 2018), should protect the hydrophones and flow shields or replace the ABS hydrophone guards in mud silos with metal guards, although these could interfere with signal reception.

Chinitna Bay

Differences in cetacean presence between the two study areas are evident (**Figure 6**). Chinitna (bay and river) hosted higher cetacean presence overall than Tuxedni (bay and river). Harbor porpoise totaled 2265 detection positive hours in Chinitna vs. 894 in Tuxedni. Humpback whale presence was almost exclusive to Chinitna Bay, and orcas were predominant in Chinitna Bay. However, beluga seemed to prefer Tuxedni, totaling 540 detection positive hours vs. 38 in Chinitna. Predation pressure likely played a role in the differences observed for beluga presence between the two areas. In particular, it is interesting to note that beluga were never detected in Chinitna Bay, but 38 positive hours were obtained in Chinitna River distributed over 21 different days (**Figure 2**). Beluga most likely snuck in and out of the river undetected by the mooring located 2.4 km from shore at the north end of the bay entrance. Beluga calls would have been detected at that distance (Lammers et al., 2013), thus it is assumed that belugas were acoustically cryptic while transiting this area. This quiet condition has been described as anti-predation behavior reflecting an awareness of predation risk in their habitat (Castellote et al., 2022). Access in and out of the river via deeper waters of the central bay, south of the mooring site and outside the detection range, is unlikely as it is known that beluga exhibit a strong antipredator response by fleeing to shallow coastal waters when predation risk is perceived (Huntington, 2000; Lydersen et al., 2001; Westdal, 2016). This acoustically elusive behavior was also apparent in September 2022 when belugas accessed Tuxedni River without detection in the bay (**Figure 5**). Although, in mid-November 2021, belugas left Tuxedni River and within 4 days they were detected in the bay, as well as in April 2022 detections in the bay were followed by river detections 3 days later. These results suggest that, at least for areas in LCI where orca presence is more common than in the upper inlet, acoustic monitoring results should not be extrapolated to wider general areas, and fine scale spatial sampling should be implemented. For example, if our results from the moorings in the bays were to be used to inform on beluga presence in the general area of Tuxedni and Chinitna bays, one could easily conclude that beluga did not use Chinitna Bay and miss the 21 days of presence reported by the silos in the river (**Figure 2**). Similarly, beluga presence in Tuxedni Bay would be limited to December to April, when results from the river silo shows abundant occurrence in September to November (**Figure 5**).

Beluga detection periods in Chinitna River were shorter than in Tuxedni River, and feeding was not detected. This suggests beluga might use that area of the river as a corridor to access prey further up river. Quite often (12 of 21 events) detections occurred isolated to one single hour of the day, suggesting that belugas were detected only when traveling the river in one direction, upriver or downriver. It could be that belugas were silent and non-echolocating while transiting through the sampled area, resulting in missed presence. Such transit without detectable echolocation has been observed in Eagle River, in UCI, where biologists on Joint Base Elmendorf Richardson (JBER) report a missed detection rate of up to 33% for whales moving up and down the river past multiple F-POD acoustic monitoring stations (C. Garner, unpublished).

Additionally, the depth data reflects a possible effect by deploying the silos several feet above the ambient river level, likely allowing whales to cross the monitored river section during early flood and late ebb, when the instruments were "off effort" (i.e. out of the water). Most detections occur when the whales are exiting the river, during the ebbing tidal period. For Chinitna River, because the proportion of detections during flood tide was minimal (**Figure 8**) and most detections occurred within the 0 to 0.5 m in depth (**Figure 9**), this suggests most whales entering the river were already up river from our monitoring station by the time the hydrophones got submerged during the flood tides. Similarly, we only acoustically captured the presence of the early belugas transiting back towards the bay in the ebb tides, and more whales could have continued to cross this area in a downstream direction once hydrophones were exposed to the air.

It is interesting to note that a short beluga detection was obtained in Chinitna river on June 5th 2022. This matches the sporadic sightings of single whales or small groups in this region of LCI from surveys 30+ years ago (Shelden et al., 2016), but not from contemporary surveys. Aerial surveys run in June have focused on areas where there are large concentrations of whales in UCI to obtain beluga estimates of abundance and have not had beluga sightings in the LCI since 2001 (Hobbs et al., 2000; Rugh et al., 2005a). Since then, belugas are typically concentrated in dense groups only across a fairly limited range of UCI at the mouths of rivers and in shallow waters; their presence coincides with the spawning migration of anadromous fish into these rivers and streams, however, survey tracks do not cover the lower inlet (i.e., Goetz et al., 2023). Even though this was a single event, it is significant as it suggests there might still be a wider spatial distribution in early summer than recent accounts, and highlights the practicality of acoustic monitoring. Furthermore, the detections in December 2021 occurred with 6/10th to 8/10th sea ice concentration in the tidally-influenced reaches of the head of the bay and river, and in February 2022 with 5/10th to 7/10th (National Weather Service Alaska Sea Ice Program) throughout the entire Chinitna area, which would have made satellite imagery analysis or aerial survey effort too challenging for beluga monitoring.

Orca were detected in the Chinitna Bay area on 29 days from February to May and in September and December. Orca were detected once in the river on September 20th 2021 within 17 hours of beluga detections. Also, orca were detected in the bay and beluga in the river on February 5th 2022. Although not all orca detections could be assigned to a specific ecotype, the majority were determined to be marine mammal-eating (transients), including the two encounters described above. Beluga predation by transient orca has been reported before in Chinitna Bay (Shelden et al., 2003). Our data cannot confirm if beluga are using the Chinitna River as refugia against orca predation, but the several observations discussed here are suggestive of this hypothesis. First, it is surprising that none of the beluga detections in the river were associated with feeding behavior. While this could indicate that this reach of the river is used primarily to access upstream foraging grounds, a more parsimonious explanation could be that beluga use the river to escape predation, by maintaining a depth too shallow for orcas to access (i.e., February 5th 2022 detections). Second, the data indicate that beluga were aware of the predation risk in Chinitna, given their acoustically cryptic behavior and presumed preference for near-shore habitat. This also would explain why we potentially missed beluga presence as they transited through in quiet mode. And third, we documented concurrent (same-day) beluga-orca presence twice within our sampled periods, on September 20th 2021, and February 5th 2022. Furthermore, the September orca detection occurred within the Chinitna river, suggesting orca awareness of and potential search for beluga within the river.

Transient orca are notoriously cryptic when in hunting mode, emitting few, very brief echolocation emissions-often composed of just single and double clicks-to avoid detection by targeted marine mammals (Guinet, 1992; Barrett-Lennard et al., 1996; Castellote et al., 2022). For this reason, it should be noted that, in this study, acoustic presence of transient orca in Chinitna and Tuxedni areas is likely underestimated.

Humpback whales were detected on 17 days in Chinitna Bay up to 9 hours per day in December, January, April and May. Song (Jan), feeding (Apr), and social (Apr-May) signals were identified. Six of the 17 days of humpback presence overlapped with orca detections. Accounts of orca predation on humpback whales in Alaska are rare but there are observed summer attacks in LCI to sub-adults and cow/calf pairs, as well as carcasses of sub-adults that have been found with evidence of orca predation and consumption (Shelden et al., 2003; Saulitis et al., 2015).

Harbor porpoise were present in Chinitna Bay almost daily except for the period from January 4th - 24th which corresponded with a period of 8/10th to 10/10th sea ice concentration levels, the highest of all winter for Chinitna Bay (National Weather Service Alaska Sea Ice Program). Ice displacement has been described for this species in the UCI (Castellote et al., 2016), therefore we assume this was also the case in Chinitna Bay.

Tuxedni Bay

Beluga foraging behavior was identified in the Tuxedni area (bay and river) primarily in two periods, September-October, and January. Interestingly, beluga presence was still very high in February and, to a lesser extent, in March and April but foraging behavior was not identified. Fall foraging occurred in the river and winter foraging in the bay. For both periods, feeding events reached up to 37 minutes per day, which is a high value compared to other important foraging areas monitored acoustically with the same methodology (Castellote et al., 2020; Castellote et al., 2021). Beluga presence in winter in the bay reached 24 hours for two consecutive days. This level of concentrated acoustic presence has only been observed in the Susitna delta in June when beluga concentrate in this area preying on a high concentration of adult migrating salmon on their way to their spawning rivers (Castellote et al., 2021). Limited knowledge is available on potential prey targeted by beluga in the Tuxedni Bay area in fall and winter. Coho salmon have been documented in Tuxedni River but no information is available on the timing of that run (Barclay and Habicht, 2019). However, a coho salmon spawning run is known to occur in the nearby Crescent River (**Figure 1**) from mid-August extending into October, and it is not clear how far into the fall this run continues as coho typically have a long river entry pattern (Tarbox, 1988). This timing of the coho spawning run can partially explain the presence of feeding beluga in fall at Tuxedni River, if a similar run occurs there. Summer surveys for fish in the Tuxedni area have identified a rich diversity of forage fish, in particular herring (*Clupea pallasii*), capelin (*Mallotus villosus*) (but these spawn in April-May and are believed to migrate offshore in winter), Pacific sand lance (*Ammodytes hexapterus*) which spawn in fall and winter, and longfin smelt (*Spirinchus thaleichthys*) which have been observed returning to Kenai River in late November through early December (Marston and Frothingham, 2022). Other species include Pacific sandfish (*Trichodon trichodon*), Pacifc lamprey (*Lampetra tridentata*), snake prickleback (*Lumpenus sagitta*), Pacific cod (*Gadus macrocephalus*), Alaska Pollock (*Gadus chalcogrammussculpins*), dolly varden (*Salvelinus malma*), sculpins (Cottoidea), flat fishes, and crangonid and pandalid shrimp (Fechhelm et al., 1999; Robards et al., 1999; Speckman et al., 2005; Arimitsu et al., 2021). Tanner (*Chionoecetes bairdi*), dungeness *(Cancer magister)* and to a much lesser degree, red king crab (*Paralithodes camtschaticus*) are also present in the area although due to low survey estimates of abundance, commercial fisheries for tanner and king crab have been closed in the Cook Inlet Area since 1995 and for dungeness since 1991 (Rumble et al. 2020, Booz and Dickson 2023). Noncommercial fishing for king and dungeness crab (sport and subsistence) has been closed in the Cook Inlet Area since 1985 and 1998 respectively. The noncommercial fisheries for tanner crab have had periodic closures since 1989 (Booz and Dickson 2023). Most recently, a restricted, limited noncommercial (sport and subsistence) tanner crab fishery was opened by the State starting in the 2017/18 seasons from fall through early spring (Booz and Dickson 2023). The majority of the effort and harvest (over 90%) is in Kachemak Bay on the east side of LCI which is consistent with historical records (Rumble et al. 2020, Booz and Dickson 2023). Due to low numbers, there appears to be no fishing on the west side of LCI for tanner crab even though the noncommercial fishery remains open (Holly Dickson, ADFG, pers. comm, December 21 2023). Many of these species have been identified as part of the diet of Cook inlet beluga (Quakenbush et al., 2015), thus the Tuxedni area should be considered an important fall/winter foraging ground. No other winter foraging ground has been described yet for Cook Inlet beluga. Further research in identifying fall and winter beluga prey communities in this area should be prioritized. Population modeling efforts on Cook Inlet beluga highlight how survival and resilience against disturbed environments are influenced by winter energy intake (McHuron et al., 2023). Therefore, understanding what prey is targeted by beluga in this area, and evaluating the trend of these prey assemblages are critical actions to facilitate proper management for the recovery of this endangered population.

Similarly to Chinitna River, in Tuxedni River, belugas were detected primarily during the ebbing tidal period (**Figure 8**). Therefore, we can also assume that belugas detected here were on their way back to the bay after their incursion into the river with the flooding tidal period. The proportion of detections during the flooding period is slightly larger than in Chinitna River, and the distribution of these detections is more spread across depth (**Figure 9**), suggesting the silos in this study site were placed a bit lower in the intertidal zone, which in turn allowed a more complete capture of the beluga presence when transiting this part of the river both during the flooding in an upstream direction and the ebbing in a downstream direction. The Tuxedni Bay depth data shows a more balanced proportion of beluga detections between the ebbing and the flooding tidal periods (**Figure 8**) and detections are well distributed across the range of depths reported (**Figure 9**), suggesting that beluga have less of a preference for a tidal stage when using the bay as compared to the river. The χ^2 test results in Table 3 confirm depth is not independent of beluga presence in the bay, but that might just be caused by the low number of beluga detections occurring during the low and high slack periods.

Our Tuxedni River instruments were entrapped in ice from December 12th until April 2nd, drastically attenuating sound sensing, therefore absence of beluga presence in the river within this period cannot be confirmed. But some interesting observations can still be described. Beluga use of Tuxedni River ended on November 13th 2021 (30 days prior to instruments icing) and sea ice formation in the bay-head and river started on November 17th 2021 (2/10th to 4/10th sea ice concentration, National Weather Service Alaska Sea Ice Program). First detections in the bay occurred on November 18^{th} 2021, highlighting how beluga moved out of the river and into the bay at the onset of sea ice formation. However, first spring detections in the river occurred on April 3^{rd} 2022 (1 day after instruments thawed) when sea ice concentration in the river and bay-head was at $7/10^{th}$ to $9/10^{th}$ (National Weather Service Alaska Sea Ice Program). Beluga detections continued to occur almost on a daily basis for 1 to 4 h per day until April 17^{th}, the last day of spring detections in this site. Sea ice concentration remained at $7/10^{th}$ to $9/10^{th}$ until break up on April 20^{th} (National Weather Service Alaska Sea Ice Program), suggesting beluga used the river and head-bay under heavy sea ice coverage. This differing relationship with ice in fall and spring suggests beluga are driven in and out of the river by something else than just ice presence, which is one more reason to further research winter prey availability and prey preferences in this area of their critical habitat.

Results from this study increase our knowledge on the seasonal occurrence of beluga in this region of the lower inlet. Until now, based on aerial surveys in 2018, 2019, 2021 and 2023, beluga occurrence was documented in Tuxedni in September, March and April (NMFS, unpublished), and based on previous acoustic monitoring (2009-2011), beluga occurrence in Tuxedni Bay was limited to January-April with significant inter-annual variation (Castellote et al., 2020). These new acoustic results, incorporating sampling in the bay-head through the use of silos, strengthen our knowledge of beluga use of this habitat, and further support the importance of the Tuxedni Bay and river area as beluga habitat from September to April.

Humpback whales were only detected in Tuxedni Bay on May 23^{rd} 2022 for a period of 5 hours, consisting of social signals. This species is seasonally observed in the lower inlet, and rarely seen further north than the latitude of Chinitna Bay (i.e., Rugh et al., 2005b). Rip tides, higher turbidity and more estuarine conditions further north in the inlet might not be preferred by this species.

Orca were detected on 7 days in Tuxedni Bay in January, and May to July, for up to 5 hours per day. Although beluga were not detected when orca calls were identified in May to July, spatio-temporal overlap of these 2 species occurred in January, when beluga presence was at its highest. On January 6th 2022, a spike of transient orca calls, often overlapped indicating multiple individuals were vocalizing, coincided within a 29 minute window with beluga calls, and on January 23rd 2022 another spike of transient orca calls were detected 31 minutes after beluga calls. Although successful beluga kills cannot be confirmed with just this data, it is known that transient orca only show significant amounts of vocal behavior after a marine mammal kill (Guinet, 1992; Deecke et al., 2005; Guinet et al., 2006). A review of orca and Cook Inlet beluga interactions by Shelden et al. (2003) describes how most observed interactions occurred in the upper Inlet, from May to September, and roughly estimated 1 beluga predation per year from accounts between 1985 and 2002. The authors discuss how this is probably a function of observational effort and likely underrepresenting predation rates. The National Marine Fisheries Service Cook Inlet Beluga Recovery Plan (NMFS, 2016) states that the loss of more than one beluga whale annually due to predation could impede recovery. Our results with orca visiting this beluga hotspot area in winter at least 2 times, and both overlapping spatio-temporally with beluga, indicate predation might be occurring more often than previously determined.

Anthropogenic noise

Commercial ships were clearly the dominant anthropogenic source of noise in both Tuxedni Bay and Chinitna Bay, similarly to other areas of upper Cook Inlet (Castellote et al., 2019), but here the levels reported are much lower, both in terms of prevalence and SPLs. For example, 0.4 and 1.5 ship events per day were identified in Chinitna Bay and Tuxedni Bay respectively and with mean SPL values of 109 dB and 115 dB, compared to 12 events per day and a mean SPL of 120 dB near Fire Island in upper Cook Inlet (**Figure 1**) (Castellote et al., 2019). Ship generators were the second most common source of noise for both bays, and this source is likely directly related to commercial ship noise, as it is probably caused by vessels anchored or idling within acoustic range of the moored instruments. Together they account for 99% of all anthropogenic noise in Tuxedni Bay and 88% for Chinitna Bay (**Figure 3** and **Figure 5**). An ‘unknown’ class was included in Chinitna Bay, accounting for 10.8% of all anthropogenic noise, which encompassed low frequency impulsive sounds identified over 7 days from September 29th to October 7^{th,} 2021. This impulsive noise appeared in sequences of approximately 3.4 hours in duration (**Figure 3**), with impulses at 1 s intervals, which very precisely matches what has been described acoustically for in water impact pile driving operations (Dahl, 2015). Neither NMFS (https://www.fisheries.noaa.gov/resource/tool-app/environmental-consultation-organizer-eco) nor the U.S. Army Corps of Engineers (USACE; https://permits.ops.usace.army.mil/orm-public#) have any record of pile driving in Chinitna Bay at that time, therefore this activity likely occurred unpermitted. Had the entity pile driving obtained a required USACE permit the Action Agency would have also needed to then undergo a consultation with NMFS under Section Seven of the Endangered Species Act (ESA). As part of that process mitigation measures (i.e. temporal, spatial) to avoid harm to ESA listed species, like CIB, are requested as part of the permitting process. It is concerning an event with a similar sound profile as a pile driving operation was identified in Chinitna Bay in September-October 2021 without any USACE permit or ESA consultation.

Commercial ship noise likely involves traffic coming in and out of the Port of Alaska (Anchorage), Port of Nikiski, and Port of Homer, with shipping lanes roughly 18 nautical miles from the Tuxedni Bay mooring and 20 nautical miles from the Chinitna mooring. Also, commercial fishing vessels operate, seasonally, closer to the sampled areas predominately out of the port of Kenai and Homer on the east side of LCI. For example, by August 15, the drift gillnet fleet is restricted to fishing in areas on the west side of LCI adjacent to Chinitna Bay (NMFS, 2023). Some vessel and generator noise might be related to this fleet using Chinitna Bay or Tuxedni Bay as protected overnight anchoring. Interestingly, the prevalence of commercial ship noise in Tuxedni Bay is more than twice the one in Chinitna Bay (13.2% vs. 5.5%, **Figure 3** and **Figure 7**) and with higher SPLs (7.6 dB difference in median, **Figure 4**), but it is not clear what vessel presence might be driving these differences. Sport fishing, razor clam charters, and ecotourism boat-based tours to Chinitna and Tuxedni from Homer operate seasonally. Also, remote lodges and private cabins also generate traffic, although most of it is by small plane. This local activity would be captured by the outboard motor source rather than the commercial ship noise class as most charter vessels for sport fishing, clam digging, or bear viewing have smaller motors for propulsion ran at higher rpm than larger commercial vessels.

Other identified sources of anthropogenic noise for both areas were outboard and aircraft. For both areas the prevalence of these sources was minimal, below 0.3% (**Figure 3** and **Figure 7**). Despite the higher prevalence for commercial ship and generator noise, both areas remain among the quietest and most pristine soundscapes of all the quantified locations in Cook Inlet. Tuxedni

Bay sustained 85.8% of time with no evident sources of anthropogenic noise, and Chinitna a 93.5%. Their respective mean quiet SPL values of 96.6 dB for Chinitna and 88 dB for Tuxedni (**Figure 4**) are below the mean values from all other reported sites in Cook Inlet (Castellote et al., 2019).

A key question to understand the potential for beluga disturbance by the anthropogenic sources of noise detected in the study areas is to assess if these are heard by beluga at the levels reported from our data. The three main sources of noise (commercial ship, generator, and outboard motor) exceeded beluga hearing thresholds in both bays for median and maximum TOLs, and in some instances by large differences (**Figure 10**). Thus, it must be assumed that beluga were impacted by masked hearing and reduced communication space during the majority of the noise events identified in our data. Masking was evaluated up to 24 kHz due to the sampling rate used in our instruments, and while these sources of noise can extend beyond this limit, all the key acoustic components of beluga communication are occurring within that frequency limit, except for echolocation signals (Brewer et al., 2023). Based on our results, we believe that belugas in our study area are negatively affected by the current level and type of anthropogenic noise in that their communication and passive listening for acoustic cues (i.e. prey or predator signals) are disrupted. While the magnitude of the masking evaluated in our comparison is very elevated in terms of frequency range and excess dB, only a small percent (15.5%) of beluga encounters were masked by noise, and by only the commercial ship noise class (except one encounter which also included aircraft noise). This is due to the relatively low prevalence of anthropogenic noise in both areas compared to other parts of Cook Inlet. This low level of overlap could reduce the concern for potential negative effects by acoustic disturbance. However, it is interesting to note that half of the beluga encounters masked by noise were affected in its totality (100% noise overlap, **Figure 11**), suggesting that any future increase in shipping activity in the area could quickly escalate the potential negative effects of masking, unless restricted to the season where beluga presence is minimal or absent (May to August). It is currently very difficult to evaluate population consequences for this or any other level of acoustic masking in marine mammals (Erbe et al., 2016). But recent work has demonstrated how cetacean species exhibiting costly antipredator responses (i.e., fleeing and cessation of feeding) also have stronger behavioral reactions to anthropogenic noise (Miller et al., 2022). Similar to predation risk, disturbance stimuli can indirectly affect fitness and population dynamics via the energetic and lost opportunity costs of risk avoidance (Frid and Dill, 2002). Cetacean species that rely upon crypsis and escape antipredator behaviors, such as beluga, will be most sensitive to disturbance by anthropogenic noise, especially when in areas with increased predation (Miller et al., 2022). Therefore, if these adaptive responses known to occur on CIB are also triggered by the exposure of anthropogenic noise sources, even if in this case for a relatively low amount of time, there is potential for negative effects beyond acoustic masking. Additionally, the quiet environments of Tuxedni and Chinitna may indicate that beluga (and other cetaceans) are more behaviorally responsive to anthropogenic noise in these pristine areas than in more industrialized areas due to the novelty of the stimuli (Sih, 2013; Wensveen et al., 2019). This may have consequences to CIB recovery if future industrial activities bring novel sources of noise to these areas of noise refuge.

Tuxedni Bay, in fall to spring, qualifies for what has been termed as an “opportunity site” — important habitats with low ship noise (Williams et al., 2015). This term derives from incorporating ocean noise into spatial planning and swapping the aim of the analysis: rather than identifying areas of important habitat with high ship noise requiring mitigation, here conservation gain is facilitated by identifying opportunities to protect important habitat that happen to be currently quiet. The conservation task may simply involve maintaining the acoustic status quo of this habitat. Few other areas of the CIB critical habitat can be designated this way due to the spatial overlap between anthropogenic activities (or the noise generated by these) and the habitat importance to beluga. And, while important foraging grounds are recognized in the UCI during the ice-free season (NMFS, 2008), no winter foraging grounds are known except the one proposed in this study for Tuxedni Bay.

Spatio-temporal restrictions of noise generating activities offer one of the most effective means of protecting cetaceans and their habitats from the cumulative and synergistic effects of noise as well as from other anthropogenic stressors (Castellote, 2007; Dolman, 2007; Nowacek, 2013; Chou et al., 2021). For this, and the above discussed reasons, we suggest a seasonal restriction for high noise producing anthropogenic activities, such as seismic surveys or in water pile driving operations, in and adjacent to Tuxedni Bay from September 1st to May 15th when beluga are present in this habitat.

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