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Acoustic detections of North Pacific right whale *Eubalaena japonica* along the eastern Aleutian Chain and northern Gulf of Alaska, 2009–2023

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ABSTRACT: The seasonality of Critically Endangered eastern North Pacific right whales (NPRWs) *Eubalaena japonica* is poorly understood in their historical foraging grounds in eastern Aleutian Islands passes (AIPs) and the northern Gulf of Alaska (NGOA). These areas are situated between designated Critical Habitat areas in the Bering Sea and the Gulf of Alaska (GOA). Here, we report passive acoustic monitoring results for NPRWs from 6 sites — 2 in the AIPs (2009–2023) and 4 in the NGOA (2019–2023). All data (64 235 h) were manually processed for NPRW vocalizations; results are presented as daily calling activity (CA_{Daily}; the percentage of 10 min recordings per day with detections). NPRWs occurred at all sites and in the majority (84%) of sampled calendar years. Across sites, variable detections suggest seasonality in occurrence and habitat use. The presence of summer (Jun–Aug) peaks in calling at most sites indicates that these areas are contemporary feeding grounds. The greatest, most consistent CA_{Daily} occurred in the GOA right whale Critical Habitat in fall months (~Sep–Dec) concurrent with NPRW presence in the Bering Sea. The timing of overwinter (~Dec–May) detections at AIP sites relative to the Bering Sea detections supports their use as a migratory corridor. Seasonal CA_{Daily} along the GOA sites does not support an NPRW coastal migratory route, although sampling limitations may obscure underlying migratory trends. Overall, these results offer new seasonal insights into right whale occurrences in 2 key conservation areas.

KEY WORDS: Passive acoustic monitoring · Conservation · Critical Habitat · IUCN Red List · Bioacoustics · Cetaceans

1. INTRODUCTION

Understanding the conservation needs of endangered species is particularly challenging when dealing with populations that are both critically small and elusive. The genetically distinct eastern population of the North Pacific right whale (NPRW) *Eubalaena japonica* (Pastene et al. 2022) is believed to number less than 50 individuals (Wade et al. 2011b) following targeted extensive legal and illegal commercial hunting in the 19th and 20th centuries (Shelden et al. 2005, Ivashchenko & Clapham 2012, Smith et al. 2012, Ivashchenko et al. 2017). The contemporary distribution, including possible migratory routes, of this Critically Endangered (Reilly et al. 2008) population is poorly known.

The historical range of the NPRW included the Gulf of Alaska (GOA), eastern Aleutian Islands, and eastern Bering Sea (Shelden et al. 2005, Smith et al. 2012). Stomach content data from harvested whales suggest that these areas were foraging grounds (Omura 1986). Knowledge of the contemporary distribution and trophic ecology of these whales has come primarily from passive acoustic monitoring (PAM), infrequent research cruises, and opportunistic sightings. The majority of these data have been isolated to the south-

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eastern Bering Sea (SEBS; Shelden et al. 2005, Wade et al. 2006, 2011a, Munger et al. 2008, Rone et al. 2012). However, additional rare detections and observations have occurred in the GOA and around the eastern Aleutian Islands, including the heavily trafficked Unimak Pass (e.g. Mellinger et al. 2004, Shelden et al. 2005, NMFS 2006, Wade et al. 2011a, Širović et al. 2015, Ford et al. 2016, Wright et al. 2018). A lack of long-term monitoring in the GOA and eastern Aleutian Islands combined with the rarity of this population has made it difficult to describe contemporary NPRW distribution and habitat use in these waters.

Historical whaling effort in the GOA and eastern Aleutian Islands occurred predominantly from April to October (Brueggeman et al. 1986, Shelden et al. 2005, Smith et al. 2012), leaving gaps in our knowledge of the seasonality of the historical population. Contemporary effort and resulting sightings and acoustic detections in these areas have principally spanned the same period (Mellinger et al. 2004, Shelden et al. 2005, Wade et al. 2011b, Crance & Kennedy 2024, Wright et al. 2024). This seasonality aligns with PAM data from the Bering Sea feeding ground, which supports a seasonal presence that roughly spans the ice-free season in that area (~May–Dec; Munger et al. 2008, Wright et al. 2024). However, detections from long-term moored acoustic recordings and a recent observation from Unimak Pass in the eastern Aleutian Islands, suggest the intermittent presence of NPRWs in this region across seasons (Wright et al. 2018, Crance & Kennedy 2024).

Like their congeners in the North Atlantic and the southern hemisphere, NPRWs are believed to migrate seasonally from high-latitude summer feeding grounds to lower-latitude overwinter areas, which may include calving grounds (Brownell et al. 2001, Clapham et al. 2004); locations of these overwinter areas and migratory routes are still unknown. Given their proximity to the Critical Habitat of NPRW in the Bering Sea, it has been proposed that the Aleutian Islands Passes (AIPs) are part of a migratory corridor for right whales transiting from the Bering Sea in fall and spring (Clapham et al. 2004, Shelden et al. 2005, Wright et al. 2018). It is unknown whether animals take a coastal or pelagic route once entering the GOA or whether there is seasonal (northbound vs. southbound) or interannual variability (oceanographic conditions) in the route(s) taken.

Understanding the seasonal occurrence and habitat use of NPRWs in the eastern AIPs and northern GOA (NGOA) is critical, given the possible presence of feeding and migrating animals, including reproductive females (Brueggeman et al. 1986). In addition, these areas include major shipping lanes, resulting in high trans-Pacific and eastern AIP shipping traffic (Nuka Research and Planning Group 2014, Silber et al. 2021). Moreover, the National Marine Fisheries Service (NMFS) is undergoing analyses to determine whether the current NPRW Critical Habitat areas in the SEBS and southwest of Kodiak, AK, should be modified or expanded. This review is in response to a petition NMFS received (CBD & SNPRW 2022) that proposed expanding the current Critical Habitat to connect the 2 areas, thereby including both the eastern AIP and NGOA regions. Here, we report PAM data collected from long-term bottom-mounted recorders from 6 sites — 2 in the eastern AIPs and 4 in the NGOA.

2. METHODS

2.1. Data collection

Passive acoustic data came from an existing network of long-term passive acoustic recorders maintained by NOAA's Alaska Fisheries Science Center's Marine Mammal Laboratory (Section S1 in the Supplement at www.int-res.com/articles/suppl/n056p277_supp.pdf). We used data collected from August 2009 through September 2023 from 6 sites: 2 sites in the eastern AIPs (UM01 = in Umnak Pass and UN01 = in Unimak Pass) and 4 in the NGOA (SH01 = near the Shumagin Islands, SU01 = near Sutwik Island, BT01 = in Barnabas Trough, and SE01 = in Stevenson Entrance [to the southwest of the mouth of Cook Inlet]; Fig. 1). Sampling varied by site (Tables S1 & S2), resulting in data from 29 deployments of passive acoustic recorders (Table S3). Recording at AIP sites spans 2009 to 2023, although site UM01 did not have a recorder in the water between spring 2010 and spring 2016 (Table 1, Table S1). UN01 data include published data from 2009 to 2015 in Wright et al. (2018). NGOA sites BT01 and SH01 were first deployed in fall 2019, while sites SE01 and SU01 were first deployed in 2022 (Table 1, Table S2).

Data were collected via long-term recorders, specifically autonomous underwater recorders for acoustic listening (AURALs; Multi-Électronique) or ecological acoustic recorders (EARs; Lammers et al. 2008) (Table S3) that were attached to subsurface bottom-mounted moorings. These moorings were replaced approximately every 6 to 12 mo (Table S1). The AURAL recordings had a flat (±3 dB) frequency

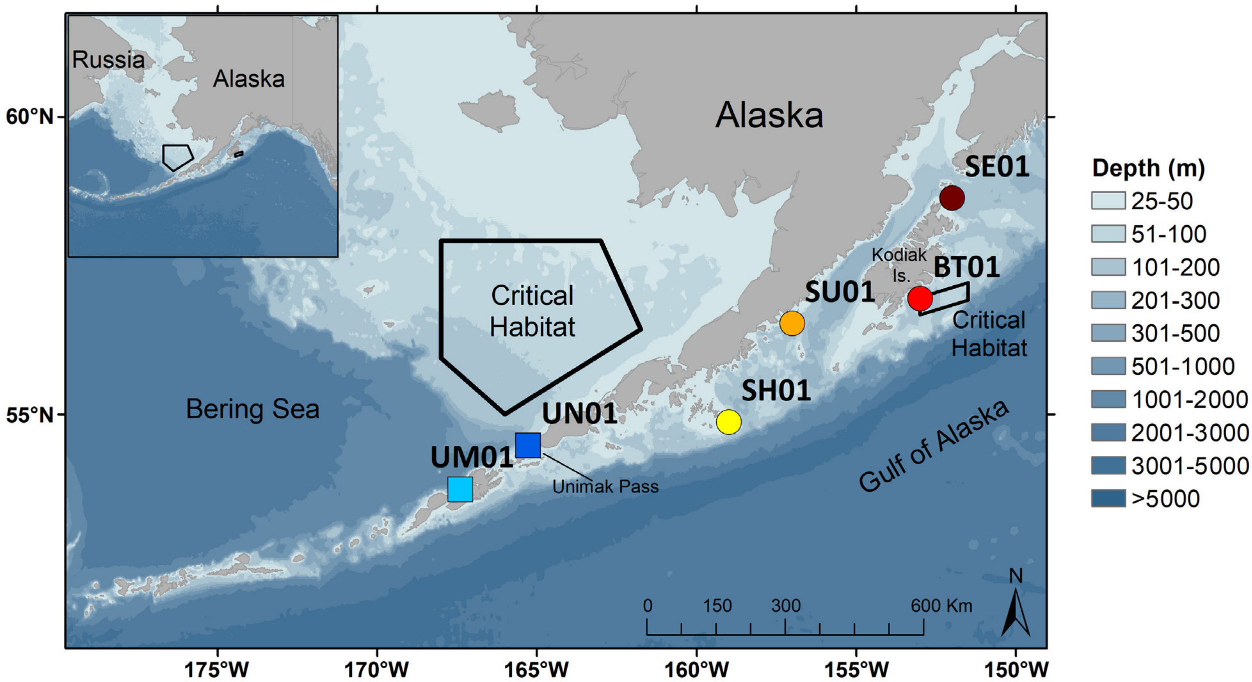

Fig. 1. Mooring sites. Symbols and colors denote region: Aleutian Islands passes (AIPs; squares) and the northern Gulf of Alaska (NGOA; circles). Black borders denote current Critical Habitat boundaries

response from 10 Hz to 7.8 kHz for the 16 kHz sampling rate and 10 Hz to 3.9 kHz for the 8 kHz sampling rate. The EAR recordings had a flat (±1.5 dB) frequency response across all frequencies for the 4 kHz sampling rate (Lammers et al. 2008). System sensitivity for the AURALs is −63.7 dB counts μPa^{-1} (−164 dB V μPa^{-1} hydrophone sensitivity, 16 dB gain, and 84.3 dB counts V^{-1}) and for the EARs is −57.6 dB (−193.5 dB V μPa^{-1} hydrophone sensitivity, 47.5 dB gain, and 88.4 dB counts V^{-1}). Dynamic range for both the AURALs and the EARs is 90 dB. AURALs have a spectral noise floor of approximately 52 to 55 dB re 1 μPa^2 Hz^{-1} (Kinda et al. 2013 and empirically derived); the spectral noise floor for the EARs is 52 to 53 dB re 1 μPa^2 Hz^{-1} (M. Castellote, University of Washington, pers. comm.). The sampling rate, duty cycle, depth, and recording period of each mooring are included in Table S3.

2.2. Processing of acoustic data

Raw data were processed by converting to .wav files (EARs only), then dividing into 10 min .wav files. Spectrograms (225 s; 0−800 Hz) were then created to allow manual analysis of all data for signal types in this frequency range,[1] including NPRW vocalizations, using the in-house MATLAB program SoundChecker (Wright et al. 2018). SoundChecker allows for visual and auditory processing of all data (Fig. S1 in Section S2); thus, NPRW vocalizations were identified at the 225 s resolution by looking at the pre-generated spectrograms of the 0−800 Hz frequency band and confirmed by listening to the call, if necessary.

NPRWs were identified using the 2 primary call types attributed to NPRWs: upcalls and gunshot calls (McDonald & Moore 2002, Crance et al. 2017, 2019, Wright et al. 2018; Fig. 2). NPRW upcalls are frequency-modulated upsweeps predominantly between 80−160 Hz and 1−1.5 s that occur in bouts of irregular spacing (McDonald & Moore 2002). NPRW gunshot calls are short (<1 s) broadband impulsive calls that can occur in pattern to create song (Crance et al. 2017, 2019).

Humpback whales produce upsweeps similar to the NPRW upcall (Thompson et al. 1986), and bowhead whales produce similar upsweeps and gunshot calls (Würsig & Clark 1993). Although the spatial range

[1]Six possible species — NPRW, bowhead whale *Balaena mysticetus*, humpback whale *Megaptera novaeangliae*, gray whale *Eschrichtius robustus*, walrus *Odobenus rosmarus divergens*, minke whale *Balaenoptera acutorostrata*; 3 additional biological sounds — double knocks, unidentified pinniped calls, and gunshot calls; 2 anthropogenic sounds — vessel and seismic airgun

Table 1. Number of days with North Pacific right whale (NPRW) vocalizations detected/annual effort (e.g. no. of days with recordings), the annual percentage of days (PoD; %) with NPRW calls (parentheses), and the range of sampling by calendar year (square brackets) for each site (Fig. 1). Also shown are the overall total days with calls/days with recordings and the PoD (parentheses) by site (square brackets = no. of calendar years sampled) as well as the mean daily calling activity (mean CA_{Daily}) (95% bootstrapped CI) for days with >0% CA_{Daily}

	UM01	UN01	SH01	SU01	BT01	SE01
2009	10/169 (6) [Jul–Dec]	8/150 (5) [Aug–Dec]				
2010	0/22 (0) [Jan]	3/213 (1) [Jan–Aug]				
2011		0/114 (0) [Sep–Dec]				
2012		4/366 (1) [Jan–Dec]				
2013		5/360 (1) [Jan–Dec]				
2014		6/365 (2) [Jan–Dec]				
2015		12/365 (3) [Jan–Dec]				
2016	35/232 (15) [May–Dec]	11/365 (3) [Jan–Dec]				
2017	4/365 (1) [Jan–Dec]	0/281 (0) [Jan–Oct]				
2018	1/348 (<1) [Jan–Dec]	1/91 (1) [Oct–Dec]				
2019	21/243 (9) [May–Dec]	9/365 (3) [Jan–Dec]	0/91 (0) [Oct–Dec]		35/90 (39) [Oct–Dec]	
2020	21/320 (7) [Jan–Nov]	10/366 (3) [Jan–Dec]	3/366 (1) [Jan–Dec]		34/366 (9) [Jan–Dec]	
2021	10/230 (4) [May–Dec]	13/365 (4) [Jan–Dec]	48/312 (15) [Jan–Nov]		0/228 (0) [Jan–Aug]	
2022	0/166 (0) [Jan–Jun]	15/355 (4) [Jan–Dec]	8/121 (7) [Sep–Dec]	1/93 (1) [Sep–Dec]	109/122 (89) [Sep–Dec]	1/93 (1) [Sep–Dec]
2023		1/114 (<1) [Jan–Apr]	8/229 (3) [Jan–Aug]	2/187 (1) [Jan–Jul]	24/228 (11) [Jan–Aug]	8/220 (4) [Jan–Aug]
Total	102/2095 (5) [9 yr]	98/4,235 (2) [15 yr]	67/1119 (6) [5 yr]	3/280 (1) [2 yr]	202/1034 (20) [5 yr]	9/313 (3) [2 yr]
Mean CA_{Daily}	4.8 [4.1–6.0]	4.4 [3.5–5.5]	5.3 [4.3–6.5]	2.5 [2.5–2.6]	15.9 [13.6–18.1]	4.5 [2.5–7.9]

and timing of humpback whales overlap with our study region, bowhead whales occur north of our study area (Calambokidis et al. 2001, Citta et al. 2015). We used call characteristics (e.g. fundamental frequency, call interval and duration, variability in call type, and patterning) and contextual clues (e.g. season, known spatial range, bout characteristics, association with conspecific sounds, and proximity to non-conspecific sounds) to identify NPRWs from other species.

For each spectrogram, the analyst can mark yes, no, or maybe for a signal type. Marking yes for a given signal type indicates at least 1 call that could be confidentially attributed to that signal type was present in the 225 s spectrogram window, while maybe indicates at least 1 possible sound of a given signal type was present, and no indicates the absence of a given signal type (Wright et al. 2018). This paper only presents yes detections of NPRW vocalizations.

2.3. Analytical methods: Daily calling activity

Data were collected on a duty cycle (i.e. the recorder was not recording continuously and instead cycled on and off for designated periods each day), which varied among sites (Table S2). Therefore, the individual 225 s spectrograms were collated to the 10 min resolution and converted to a metric normalized for daily effort, termed daily calling activity (CA_{Daily}; %):

$$CA_{Daily} = \frac{\#\,\text{yes 10 min sound clips d}^{-1}}{\#\,\text{total 10 min sound clips d}^{-1}} \quad (1)$$

i.e. the daily percentage of 10 min sound clips with yes detections (Wright et al. 2018). Note that CA_{Daily} is not a measure of the number of individual animals or individual calls nor a direct measure of habitat use, as animals could be present but not calling.

2.4. Spatial NPRW occurrence patterns

Calling occurrence by site was computed by calculating mean CA_{Daily} as well as the percentage of days (PoD) with NPRW calls (i.e. no. of days with CA_{Daily} > 0/no. of days sampled) for each site. Mean CA_{Daily} estimates include the bootstrapped 95% CI instead of SD or SE, given the small sample size and presence of outliers at some sites. We calculated the bootstrapped 95% CI using 1000 bootstrap samples with replacement in the R package 'boot' (Davison & Hinkley 1997, Canty & Ripley 2022).

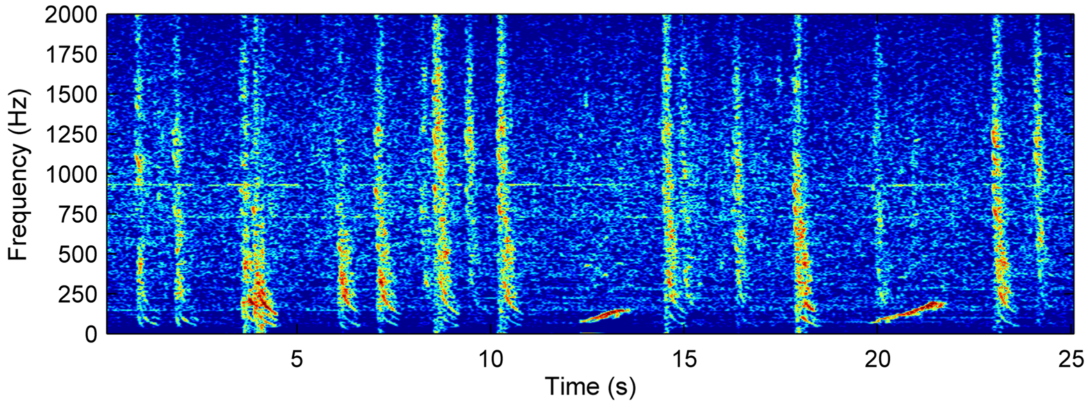

Fig. 2. Spectrogram of North Pacific right whale upcalls (12 s, 20 s) and gunshot calls (0–10 s, 15–25 s) within the Bering Sea right whale Critical Habitat on 28 July 2009. The spectrogram used a Hamming window and has a fast Fourier transform length of 512 and a 95% overlap. Color denotes relative amplitude (red being highest) of signal

2.5. Seasonal NPRW occurrence patterns

2.5.1. Month and year comparisons: All data

To compare seasonal trends in calling occurrence over the study area, all available data were used to compute calling occurrence for month and year by site by calculating the number of days and PoD with NPRW calls. These metrics are qualitative, as the number of days the recorders were collecting data was not consistent across sites and years, given funding constraints and recorder malfunctions; thus, gaps in the time series exist for each site (Table S1).

2.5.2. Annual differences by site: Period of consistent recording

We quantitatively tested for differences in NPRW CA_{Daily} at each site using a subset of the total dataset, termed the period of consistent recording. The period of consistent recording was defined as the maximal date range of consecutively sampled days in a calendar year for a given site. To allow for statistical analysis, all years included in the analysis at each site contained at least 3 days with NPRW vocalizations during the period of consistent recording (Table 1, Section S3 in the Supplement). SH01 and SE01 were excluded because they did not contain at least 3 days with NPRW vocalizations in at least 2 years (Table 1). Thus, 4 sites were included in the statistical analysis (UM01, UN01, SH01, and BT01), which had the following period of consistent recording: UM01 = 15 July to 15 November for years 2009, 2016, 2017, and 2019–2021; UN01 = 1 January to 31 December for years 2012–2016 and 2019–2022; SH01 = 1 January to 17 August for years 2020, 2021, and 2023; and BT01 = 1 January to 16 August for years 2020 and 2023 (Table 1).

Interannual comparisons of these site-specific periods for CA_{Daily} were made using Bayesian ANOVA models ($ANOVA_B$) and *t*-tests ($t\text{-test}_B$), given the small number of detections and recording years for each site and the presence of outliers. Tests were run in R statistical software (R Core Team 2023) using the package 'brms' (Bürkner 2017, 2018, 2021). Each model consisted of 3 chains that ran for 100 000 iterations and was thinned by 100 in a Gaussian framework with identity links for mu and sigma using default priors of the package (improper flat prior from the Stan package for sigma and a uniform flat prior from negative infinity to infinity for beta). Post hoc analysis consisted of estimating the probability of difference between recording years using model predictions. Significant differences in post hoc analyses assumed a difference ≥95%.

3. RESULTS

3.1. Spatial NPRW occurrence patterns

Seasonality of detections in both the AIPs and the NGOA offers insight into NPRW occurrence in these areas. NPRW vocalizations were detected on at least 1 d at each site, occurring in the majority of sampled calendar years across the study (84%; Table 1); no calls were recorded at UM01 in 2010 and 2022, UN01 in 2011 and 2017, SH01 in 2019, and BT01 in 2021 (Table 1, Fig. 3). By site, CA_{Daily} was greatest at site BT01 (72.5%) followed by UN01 (40%), while similar maximum CA_{Daily} occurred at UM01 (26.5%), SE01 (17.5%), and SH01 (27.5%; Fig. 3).

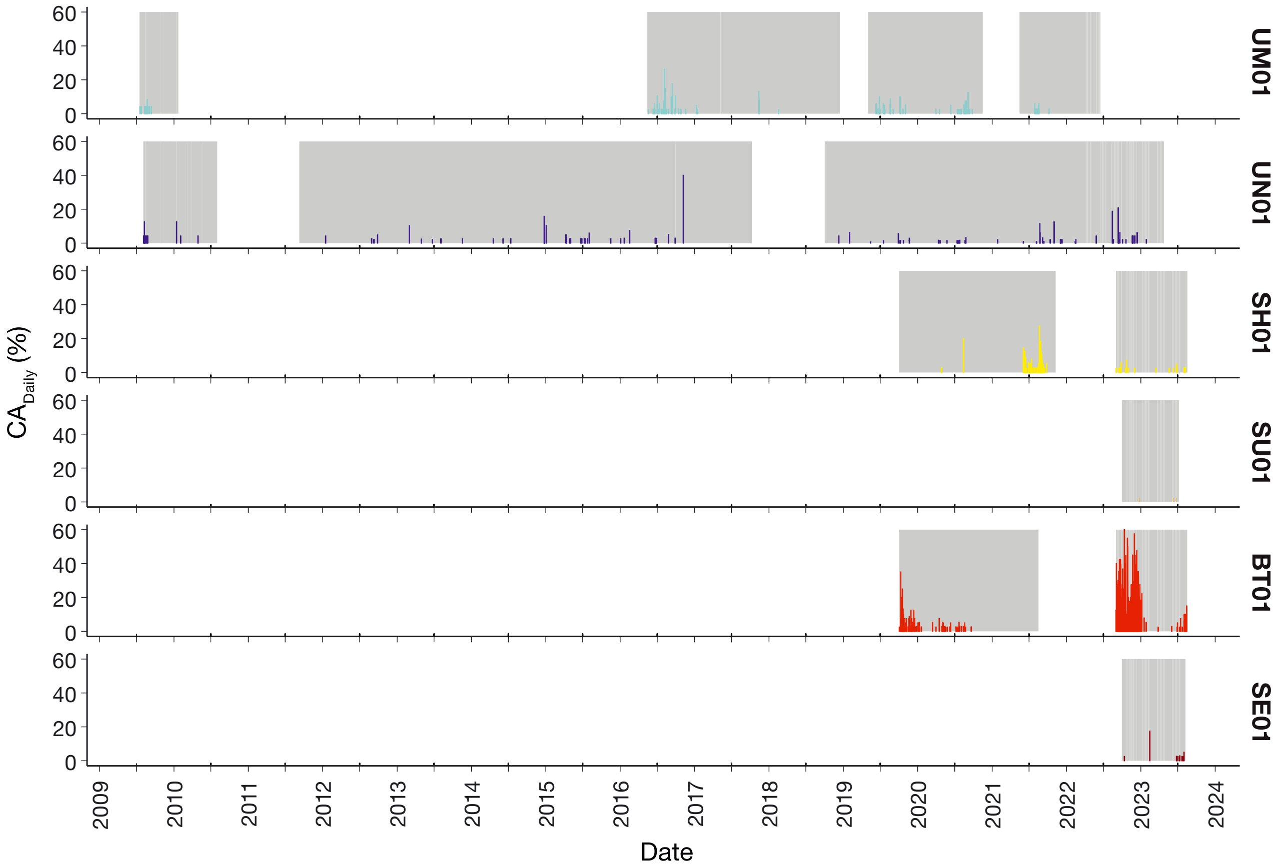

Fig. 3. Daily calling activity (CA_{Daily}; %) of North Pacific right whale vocalizations by site (row; Fig. 1), 2009 to 2023. Days with sampling denoted by gray background

Across the study period, mean CA_{Daily} and PoD varied among sites (Table 1, Section S3 in the Supplement). Although effort was greatest at UN01, both overall PoD and mean CA_{Daily} were highest at site BT01 followed by SH01. For the 2 AIP sites, despite differing effort, mean CA_{Daily} was similar, while PoD was approximately twice as high at UM01. Calls were recorded on the fewest days at SU01 (3 days) followed by SE01 (9 days), the 2 moorings with only 1 deployment (Table 1).

3.2. Seasonal NPRW occurrence patterns

3.2.1. Month and year comparisons: All data

Monthly PoD followed a Gaussian shape that peaked during summer months (Jun–Aug) across the majority of sampled years (Fig. 4). Site BT01 peaked between September and October for the majority of years with fall sampling. Seasonality of CA_{Daily} followed a similar trend at all sites except UN01 (Fig. 3), although calls were detected most consistently at UN01 in August (8 of 12 sampled years). Similar seasonal trends in monthly PoD were observed for each site when averaged across months (Fig. 5a).

Calls were detected outside of the summer period of June through August across all sites (Figs. 4 & 5a). For UN01, calls were observed at least once in each month over the study period from 2009 to 2023; this included detections in 50% of sampled years in November and January; between 30 and 45% of years in December, February, and April; and 8% of sampled years in March. For UM01 and BT01, calls were observed over the study for at least 1 d in all months except December and February, respectively. In addition, SH01 had at least 1 d with calls in all months except January and February. Moreover, calls were heard for 1 d during this period at SU01 (Dec 2022) and SE01 (Feb 2023) (Figs. 4 & 5a).

For both regions, calls were detected across mooring site within the same months. For the AIP sites, calls were recorded in the same months in 2009 (Aug), 2016 (Jun, Aug, Sep, Nov), 2019 (Jul, Sep, Oct), 2020

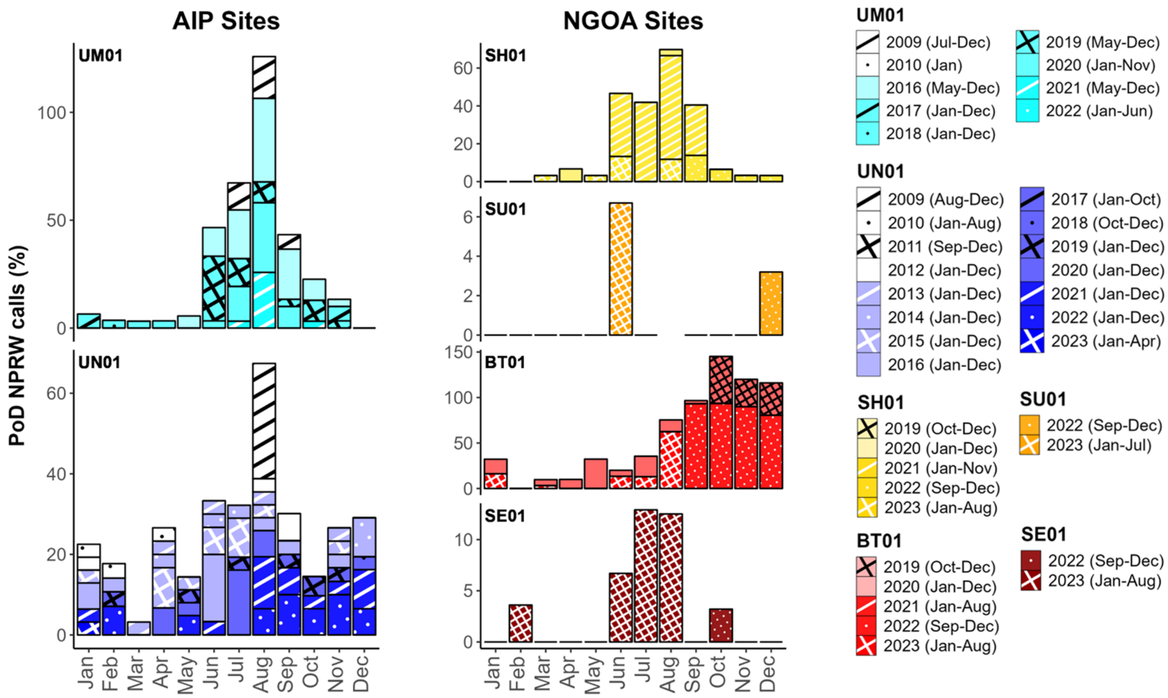

Fig. 4. Percentage of days (PoD) with North Pacific right whale (NPRW) calls by month and site (color; Fig. 1) for each calendar year (shaded bar and pattern), 2009 to 2023. Patterns repeat every 4 yr, and stacked columns are read top down starting from 2009 and ending with 2023. Note the difference in *y*-axis across station, and note that not all days were recording at each site and year (e.g. northern Gulf of Alaska [NGOA] sampling started in 2019; Table 1, Table S3). PoD values are provided in Section S3 in the Supplement. AIP: Aleutian Islands pass

(Apr, Jul, Aug), and 2021 (Aug, Oct; Figs. 3 & 4). Calls were heard across all 4 NGOA sites in June 2023 and at 3 of the 4 sites in October 2022, December 2022, and August 2023 (Figs. 3 & 4).

Annual variability in calling was also observed. Averaged across month, the highest annual mean PoD occurred at NGOA site BT01 in 2022 (89.3%) followed by BT01 in 2019 (38.9%) and SH01 in 2021 (15.4%); no calls were observed at BT01 in 2021 (Fig. 5b). Annual mean PoD of the remaining NGOA sites was low and similar, 0.7 to 1.0% for SU01 and 1.0 to 3.6% for SE01 (Fig. 5b). The highest annual PoD at AIP sites occurred at UM01 in 2016 (15.1%) followed by UM01 in 2019 (8.6%). Similar PoD was observed across sampled years with detections at UN01 (0.9–5.3%; Fig. 5b), although the months with detections varied over the study period (Table 1).

3.2.2. Annual differences by site: Period of consistent recording

Significant differences in mean CA_{Daily} for the period of consistent recording were observed at each site (Fig. 6, Table 2, Section S4 in the Supplement). For UM01, mean CA_{Daily} was significantly greater in 2016 than in 2020 and 2021. For UN01, both 2014 and 2016 were significantly greater than 2019 and 2020, while 2022 was significantly greater than 2020. For SH01, 2020 was significantly greater than 2021 and 2023. For BT01, 2020 was significantly less than 2023 (Table 2).

4. DISCUSSION

Our results provide new insight into the seasonal occurrence of NPRWs in the eastern AIPs and NGOA. NPRWs were detected at all sites, supporting their contemporary presence in both of these areas. The overall low and variable CA_{Daily} and PoD across sites suggest intermittent occurrence in these waters, aligning with prior studies (Shelden et al. 2005, Wade et al. 2011a, Wright et al. 2018). Nevertheless, their detection in the majority of sampled years across deployments confirms consistent low-level presence across the study period. Averaged over the study, the finding of PoD greater than zero for the majority of months at each site supports NPRW presence across all seasons. It is important to note that calls may have

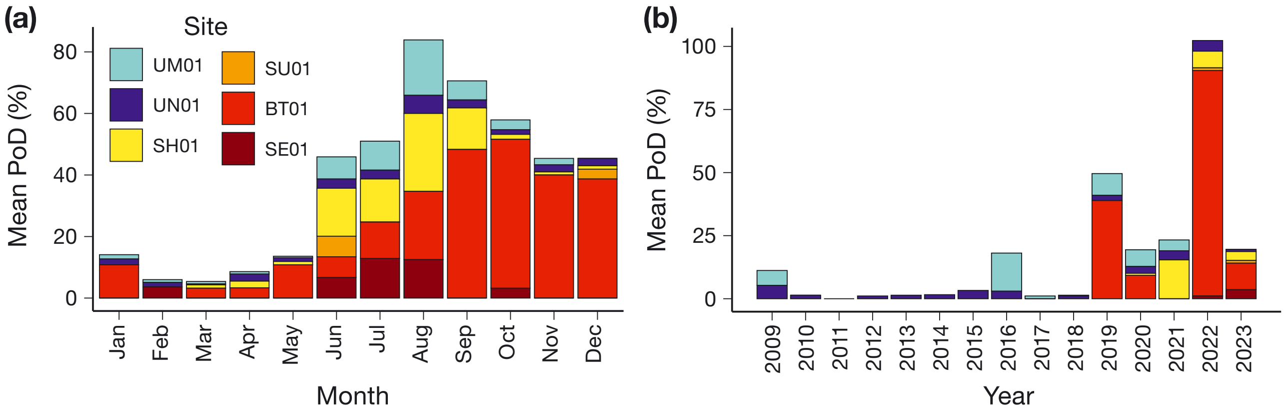

Fig. 5. Mean percentage of days (PoD; no. of days with vocalizations/no. of days with recordings) with North Pacific right whale calls by (a) month (Jan–Dec) and (b) calendar year (2009–2023) by site (colored bar; Fig. 1). Note that not all days were recording at each site and year (Table 1, Table S3). Mean PoD values are provided in Section S3 in the Supplement

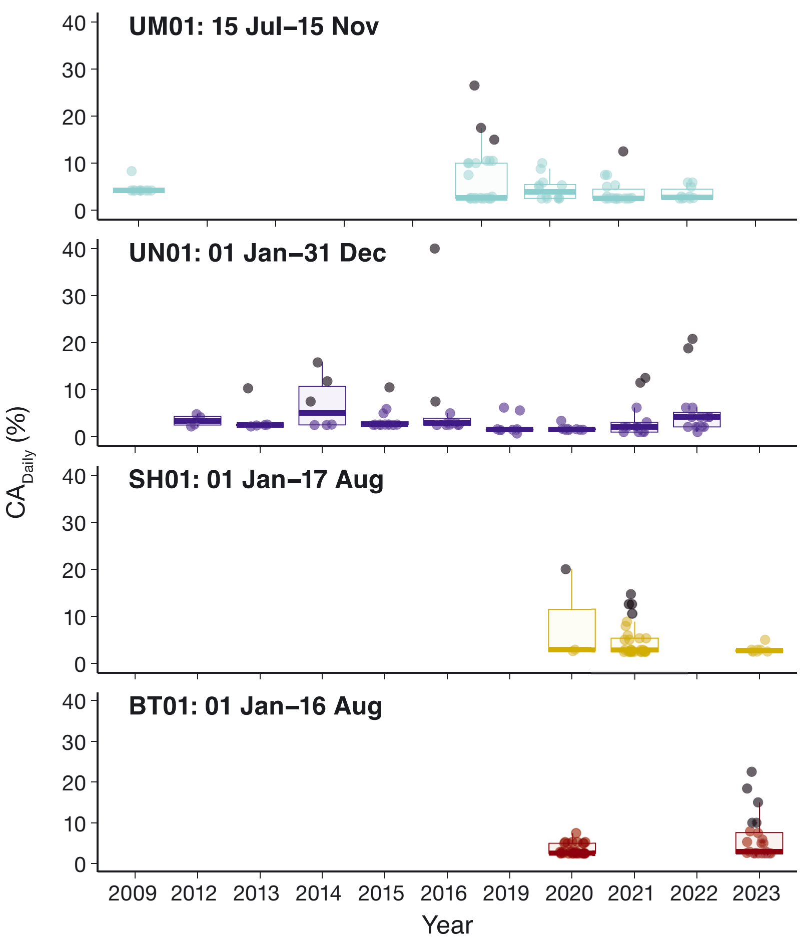

Fig. 6. North Pacific right whale (NPRW) daily calling activity (CA_{Daily}; %) for days with >0% CA_{Daily} by site (colors; Fig. 1) and year for the period of consistent recording for sites included in the statistical analysis of annual differences by site (UM01, UN01, SH01, BT01). SH01 and SE01 were excluded because they did not contain at least 3 days with NPRW vocalizations in at least 2 years (Table 1). Each box represents the interquartile range (IQR), with the median indicated by a horizontal line inside the box. Whiskers extend to 1.5 times the IQR. Raw data points are overlaid using jittered points to provide a comprehensive view of the distribution within each group. Gray dots denote outliers

been missed due to non-continuous sampling (duty cycle; Wright et al. 2018), behavior of the animals (i.e. choosing not to vocalize or reducing calling/falling silent in the presence of vessel noise), or external acoustic factors, such as calls being masked by high levels of vessel noise at some stations (Parks et al. 2007). Thus, our results provide a conservative estimate of NPRW occurrence in these areas.

4.1. Contemporary feeding grounds

Seasonality of detections in both the AIPs and NGOA provides evidence that these areas are contemporary foraging grounds of NPRWs. Peak calling from July to October at sites UM01, SH01, BT01, and SE01 across most sampled years aligns with historical data (Shelden et al. 2005) and acoustic detections in the Bering Sea Critical Habitat (Wright et al. 2024). Right whales are zooplanktivores of euphausiids and large-bodied copepods (Omura et al.1969, Baumgartner et al. 2013), and seabird communities in the eastern Aleutian Islands have historically been dominated by planktivorous species in this region (Jahncke et al. 2005, Renner et al. 2008). Barnabas Trough, which includes the area of BT01, is a known euphausiid hotspot (Simonsen et al. 2016), and NPRWs have been sighted in this region in

Table 2. Probability in difference (%) of North Pacific right whale mean daily calling activity by pairwise recording year (see Subsection 2.5.2) for sites UM01, UN01, SH01, and BT01 (see Fig. 1). Table should be read column to row (e.g. first cell indicates probability 2009 > 2016). *Significant difference, defined as ≥95% difference. Note that 95–100% and 0–5% both denote 95% difference between the pair. (–) denotes years with acoustic recordings that were not included in the analysis

		2009	2012	2013	2014	2015	2016	2019	2020	2021
UM01	2016	10					–	–	–	
	2019	49					92	–	–	
	2020	66					99*	67	–	
	2021	73					97*	67	59	
UN01	2013		44	–	–	–	–	–	–	–
	2014		14	17	–	–	–	–	–	–
	2015		46	54	89	–	–	–	–	–
	2016		16	54	58	09	–	–	–	–
	2019		63	71	95*	71	96*	–	–	–
	2020		71	78	97*	80	98*	60	–	–
	2021		48	55	90	50	91	29	19	–
	2022		24	28	71	18	69	07	04*	18
SH01	2021								94*	–
	2023								98*	89
BT01	2023								01*	

areas with the highest density of zooplankton (Wade et al. 2011a). Further, the entire shelf area to the south of Kodiak Island, which includes Barnabas Trough, has been named a Biologically Important Area for feeding for NPRWs (Wild et al. 2023). The acoustic detection of NPRWs across most months and greatest PoD across site and year at BT01 further support this as an important area for this species.

4.2. Migration

Detections from December to May across sites support the hypothesis of seasonal migration, given the timing of NPRW presence on the Bering Sea feeding ground (May–Dec; Munger et al. 2008, Wright et al. 2018, 2024). Within the AIP sites, calling was more consistently observed between December and May at site UN01 within Unimak Pass, while infrequent detections occurred during winter months at UM01. NPRW detections at UN01 are thought to reflect transiting animals, potentially timed to tidal cycles (Wright et al. 2018). The consistency of detections at UN01 further supports the importance of this pass as a transit corridor between the GOA and Bering Sea across seasons. Although concurrent sampling at both AIP sites was limited between December and May, detections of NPRWs occurred at both sites in November 2019 and April 2020. This finding tentatively supports the hypothesis that animals may use more than 1 AIP during a single migratory season.

Seasonal patterns were also observed at the NGOA sites. At BT01, detections spanned from September through January and included March detections in 2 of the 3 sampled years, aligning with potential fall and spring migration periods. In contrast, detections at SH01 and SE01 were limited to February through April, while SU01 only recorded winter detections in December. We had hypothesized that migration might occur in a staggered manner along the NGOA sites. Specifically, NPRWs may migrate from the Bering Sea through the Aleutian passes and follow a coastal migratory route along the GOA in late fall, reversing this route in the spring, which would be reflected as similar-sized seasonal cohorts of CA_{Daily} in the data. However, this hypothesis was not strongly supported by our data.

Inconsistencies in winter call timing at BT01 and the lack of consistently high CA_{Daily} values across NGOA sites suggest that nearshore waters along the NGOA coastline between Unimak Pass and Kodiak, AK, may not serve as a dependable migratory corridor. Several limitations may have influenced these results. NPRW rarity and the non-continuous (duty cycle) nature of the data collection could have led to missed detections. Additionally, the inability to detect non-calling whales and the potential effects of high vessel traffic in the region on NPRW calling rates (Parks et al. 2007, Nuka Research and Planning Group 2014, Silber et al. 2021) likely impacted our observations. Furthermore, sites SU01 and SE01 only had 1 deployment during the study period. Additional years of data collection at these sites and along the NGOA slope are necessary to describe seasonal patterns in this area with greater confidence.

Non-exclusively, an alternate hypothesis to explain the lack of a detected coastal migratory signal between the 2 regions is that certain individuals within the population may not seasonally leave the feeding grounds in some years. Seabird community data suggest sustained euphausiid levels in the AIP region across seasons (Renner et al. 2008). These findings imply that prey availability may support right whales in this area during the winter months. Two right whales were observed in February 2022 northeast of Unimak Pass exhibiting behavior consistent with skim feeding (Crance & Kennedy 2024). Similarly, detections at SE01 in February and across most winter months at BT01 could reflect individuals that forgo migration during particular years (Mussoline et al. 2012, Gowan et al. 2019). Complementary data methods (e.g. visual surveys, prey sampling) are needed to discern drivers of habitat use in this area.

A subsequent hypothesis to explain the lack of a detected coastal migratory signal is that NPRWs in the Bering Sea and GOA may represent 2 distinct subpopulations. Despite over 40 yr of photo-identification efforts and genetic sampling, no matches have been documented between individuals in these regions (Wade et al. 2006, 2011b, Crance & Kennedy 2024). However, it is important to note that this remains a hypothesis, as the lack of matches could also result from the extreme rarity of these animals and the limited availability of data. Furthermore, even if right whales in the GOA represent a distinct population, a coastal migratory signal across the NGOA sites (e.g. SH01 to BT01) would still be expected and was not observed in our data.

4.3. Variability in detections

Interannual variability in detections was observed at both the Aleutian Islands and NGOA sites. AIP sites exhibited significantly higher CA_{Daily} and elevated monthly PoD during 2016, which coincided with an extreme marine heatwave in the Northeast Pacific, nicknamed the Blob, which had cascading impacts on trophic dynamics in the region (Bond et al. 2015, Cavole et al. 2016, Di Lorenzo & Mantua 2016, Hobday et al. 2018, Yang et al. 2019). A notable spike in PoD at UN01 in June 2016 compared with other sampled years may indicate an increased number of animals passing through the area. This combined with the higher detections at UM01 from July to September 2016 suggests an increased presence in the AIPs during this period. Notably, the highest June PoD at UM01 occurred in 2019, another year with a substantial heatwave in the region (Amaya et al. 2020, Barkhordarian et al. 2022).

These increased detections also coincided with years characterized by reduced ice extent and warmer bottom temperatures in the whales' Bering Sea Critical Habitat (Duffy-Anderson et al. 2017). Warmer conditions have been associated with a decreased abundance of calanoid copepods — a primary prey species for NPRWs — on the Bering shelf (Kimmel et al. 2018, 2023, Wright et al. 2024). This could have also influenced foraging behavior, with animals feeding more frequently outside their presumed core feeding areas during these warm periods. A broader distribution of right whales during warm conditions aligns with observations from satellite tags (Zerbini et al. 2015) and stable isotope analysis of right whale skin biopsies (Wright et al. 2025). Nevertheless, detections within the AIPs varied during the 2014–2016 and 2019 heatwaves, suggesting that it is likely a combination of factors that impact the ecosystem, which in turn influence right whale behavior and distribution in this area (Litzow et al. 2020).

Variability among NGOA sites may also reflect residency or behavioral differences in NPRWs. At SH01, NPRWs were consistently detected in August, supporting this area as a contemporary feeding ground. Significantly higher CA_{Daily} occurred in 2020, which was primarily driven by a single day of elevated calling activity in August. In contrast, PoD was markedly greater during this period in the other sampled years. Although our data cannot determine the number of animals or underlying behaviors, the difference between concentrated detections over a short period of time versus smaller bouts of detections extending over a longer period suggests a potential shift in movement and residency patterns over the study period.

Notably, right whale calls were absent at BT01 in 2021, standing in stark contrast to detections in other sampled years. During this same summer, calls were consistently recorded at SH01, hinting at a possible redistribution of right whales within the NGOA, potentially driven by foraging dynamics. These observations, along with the intermittent detections at SU01 and SE01, highlight the need for expanded monitoring in this region to better understand the drivers of right whale occurrence.

4.4. Recommendations

To further resolve seasonal NPRW distribution, migration, and drivers of habitat use, we recommend continued monitoring at all 6 sites reported here as well as expansion of monitoring further west in the Aleutian Chain, south of the AIPs into the NGOA, and between the AIP area and the Bering Sea Critical Habitat (Jahncke et al. 2005, Shelden et al. 2005, Wright et al. 2024). We also recommend investigation into implementation of a year-round real-time monitoring system within Unimak Pass, such as is being currently done for the Endangered North Atlantic right whale *Eubalaena glacialis* (Baumgartner et al. 2019), given the demonstrated importance of this area as a migration corridor, its year-round right whale presence, and the high volume of vessel traffic. Additionally, we recommend implementing seasonal multidisciplinary monitoring efforts (e.g. vessel and aerial surveys, oceanographic and prey surveys, drone surveys) in regions with consistent summer detections (BT01, UM01, and SH01) to complement the PAM data to discern abundance, habitat use, and drivers of habitat use in these areas.

5. CONCLUSIONS

NPRW vocalizations were detected in the eastern AIPs between 2009 and 2023 and the NGOA between 2019 and 2023. Overall low and intermittent detections across site and season support infrequent but consistent NPRW occurrence during possible migratory periods (Dec–May) as well feeding periods when NPRW are detected consistently in the Bering Sea (May–Dec; Wright et al. 2024). Timing of the acoustic detections suggests that multiple Aleutian passes may be migratory routes with variable summer occurrence that could be linked to temperature shifts. Inconsistent timing and occurrence of NPRW calling at NGOA sites during the proposed migratory window, December to May, casts doubt that NPRWs consistently follow a coastal migratory route once entering the GOA, but sampling length (1 deployment at some sites) and bias (duty cycle) combined with the whale's rarity could be masking underlying trends. Together, our results support the utility of PAM in monitoring NPRWs and the need for continued PAM in both the AIP and NGOA areas to further describe seasonality and understand drivers of NPRW occurrence in this area.

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