Spatial and Temporal Occurrence of Killer Whale (*Orcinus orca*) Ecotypes in the Gulf of Alaska Temporary Maritime Activities Area from July 2011 to September 2019

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Gulf of Alaska transient killer whales, photo by North Gulf Oceanic Society
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A.C.R. wrote and edited the report, produced all figures, and performed killer whale ecotype identification. H.J.M., D.W.O., and J.F.P. assisted in killer whale ecotype identification. J.A.H. and S.B.P. provided supervision.

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14. ABSTRACT
Three different killer whale (*Orcinus orca*) ecotypes are known to inhabit the northeastern Pacific: residents, transients, and offshores. These ecotypes are distinguished by morphological, genetic, behavioral, and acoustic differences. Killer whales of each ecotype produce distinct, stereotypic pulsed calls that can be used as acoustic indicators of presence, making passive acoustic monitoring a useful method for assessing intraspecies differences in spatial and temporal patterns. In 2011, a passive acoustic monitoring effort was initiated in the Gulf of Alaska Temporary Maritime Activities Area (GOA TMAA) using High-frequency Acoustic Recording Packages (HARPs) to record the low-frequency soundscape and detect marine mammal and anthropogenic sounds during times of naval exercises. From 2011 to 2019, seven sites were monitored intermittently: Kenai Shelf (~200 m depth) was located on the continental shelf, offshore of Kenai Peninsula; Kodiak Shelf (~230 m depth) was located on the continental shelf, offshore of Kodiak Island; Kodiak Slope (~1,200 m depth) was located in deep water offshore of Kodiak Island; Kenai Slope (~900 m depth) was located in deep water on the continental slope; Abyssal (~4,000 m depth; hydrophone located at 1,200 m) was located in deep water beyond the continental slope; Quinn (~950 m depth) was a deep, offshore site near Quinn Seamount; Pratt (~990 m depth) was a deep, offshore site near Pratt Seamount. For this report, killer whale signals were analyzed in all collected data to determine the seasonal occurrence and distribution of different killer whale ecotypes at these sites. HARPs recorded continuously at a 200-kHz sampling rate (there was one deployment at Kenai Shelf and Quinn where a 320-kHz sampling rate was used, as well as one deployment at Kenai Shelf and Kenai Slope where a duty cycle was used). Data analysis consisted of scanning long term spectral averages for encounters of killer whale pulsed calls.

Individual calls were then examined to attribute them to specific ecotypes. In general, killer whale acoustic presence was highest at sites on the continental shelf. Although no calls were definitively matched to the resident ecotype, many calls shared aural and structural characteristics similar to known resident call types; therefore, these calls were classified as possible residents. Possible residents were detected on 59.4% of all days with killer whale acoustic presence, transients on 5.1%, and offshores on 0.9%. Possible residents were detected most often at Kenai Shelf and Kodiak Shelf, where detections occurred year-round. At Kenai Slope, acoustic presence of possible residents was seasonal, with peaks in spring and early summer. Although possible residents were less common offshore, there were detections at all sites and, at Quinn, detections occurred primarily in the spring. Transients were detected only at Kenai Shelf, Kodiak Shelf, and Kenai Slope. Detections occurred primarily in spring and summer and were most common at Kenai Shelf. All detections were of transients from the Gulf of Alaska transient population. Offshores were detected on only eight days throughout the monitoring period: two days in spring/early summer at Kenai Shelf; one day in winter and two days in spring at Kodiak Shelf; one day in winter at Quinn; two days in the fall at Pratt. At all sites there were short and faint detections that could not be attributed to an ecotype.

15. SUBJECT TERMS
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Executive Summary

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In 2011, a passive acoustic monitoring effort was initiated in the Gulf of Alaska Temporary Maritime Activities Area (GOA TMAA) using High-frequency Acoustic Recording Packages (HARPs) to record the low-frequency soundscape and detect marine mammal and anthropogenic sounds during times of naval exercises. From 2011 to 2019, seven sites were monitored intermittently: Kenai Shelf (~200 m depth) was located on the continental shelf, offshore of Kenai Peninsula; Kodiak Shelf (~230 m depth) was located on the continental shelf, offshore of Kodiak Island; Kodiak Slope (~1,200 m depth) was located in deep water offshore of Kodiak Island; Kenai Slope (~900 m depth) was located in deep water on the continental slope; Abyssal (~4,000 m depth; hydrophone located at 1,200 m) was located in deep water beyond the continental slope; Quinn (~950 m depth) was a deep, offshore site near Quinn Seamount; Pratt (~990 m depth) was a deep, offshore site near Pratt Seamount. For this report, killer whale signals were analyzed in all collected data to determine the seasonal occurrence and distribution of different killer whale ecotypes at these sites.

HARPs recorded continuously at a 200-kHz sampling rate (there was one deployment at Kenai Shelf and Quinn where a 320-kHz sampling rate was used, as well as one deployment at Kenai Shelf and Kenai Slope where a duty cycle was used). Data analysis consisted of scanning long-term spectral averages for encounters of killer whale pulsed calls. Individual calls were then examined to attribute them to specific ecotypes.

In general, killer whale acoustic presence was highest at sites on the continental shelf. Although no calls were definitively matched to the resident ecotype, many calls shared aural and structural characteristics similar to known resident call types; therefore, these calls were classified as possible residents. Possible residents were detected on 59.4% of all days with killer whale acoustic presence, transients on 5.1%, and offshores on 0.9%. Possible residents were detected most often at Kenai Shelf and Kodiak Shelf, where detections occurred year-round. At Kenai Slope, acoustic presence of possible residents was seasonal, with peaks in spring and early summer. Although possible residents were less common offshore, there were detections at all sites and, at Quinn, detections occurred primarily in the spring. Transients were detected only at Kenai Shelf, Kodiak Shelf, and Kenai Slope. Detections occurred primarily in spring and summer and were most common at Kenai Shelf. All detections were of transients from the Gulf of Alaska transient population. Offshores were detected on only eight days throughout the monitoring period: two days in spring/early summer at Kenai Shelf; one day in winter and two days in spring at Kodiak Shelf; one day in winter at Quinn; two days in the fall at Pratt. At all sites there were short and faint detections that could not be attributed to an ecotype.

Project Background:

The Navy's Gulf of Alaska Temporary Maritime Activities Area (GOA TMAA) is an area approximately 300 nautical miles (nm) long by 150 nm wide, situated south of Prince William Sound and east of Kodiak Island (Figure 1). It extends from the shallow shelf region, over the shelf break, and into deep offshore waters. The region has a subarctic climate and is a highly productive marine ecosystem as a result of upwelling linked to the counterclockwise gyre of the Alaska current.

In 2011, a passive acoustic monitoring effort was initiated in the GOA TMAA using High-frequency Acoustic Recording Packages (HARPs) to record the low-frequency soundscape and detect marine mammal and anthropogenic sounds during times of naval exercises. From 2011 to 2019, seven sites were monitored intermittently: Kenai Shelf (~200 m depth) was located on the continental shelf, offshore of Kenai Peninsula; Kodiak Shelf (~230 m depth) was located on the continental shelf, offshore of Kodiak Island; Kodiak Slope (~1,200 m depth) was located in deep water offshore of Kodiak Island; Kenai Slope (~900 m depth) was located in deep water on the continental slope; Abyssal (~4,000 m depth; hydrophone located at 1,200 m) was located in deep water beyond the continental slope; Quinn (~950 m depth) was a deep, offshore site near Quinn Seamount; Pratt (~990 m depth) was a deep, offshore site near Pratt Seamount (Figure 1; Table 1). For this report, killer whale *(Orcinus orca)* signals were analyzed in all collected data to determine the seasonal occurrence and distribution of different killer whale ecotypes (and group or pod, if possible) at these sites.

Killer whales face threats from noise pollution, declines in prey, and bioaccumulating compounds (Matkin et al. 2008; Ward et al. 2009; Buckman et al. 2011; Joy et al. 2019; Lawson et al. 2020). To successfully conserve this important apex predator, it is essential to understand their habitat use in productive regions such as the GOA. There are three killer whale ecotypes that can be found in the GOA: residents, transients, and offshores. Because these ecotypes exhibit morphological, genetic, behavioral, and acoustic differences (Ford 1987; Bigg et al. 1990; Ford et al. 1998; Hoelzel et al. 1998; Barrett-Lennard 2000; Deecke et al. 2005; Dahlheim et al. 2008), any complete understanding of killer whale distribution must occur at the ecotype level.

In the North Pacific, residents have been relatively well studied—they prey exclusively on fish and their social structure has been well documented (Ford 1989; Bigg et al. 1990; Ford et al. 1998; Ford and Ellis 2006). However, there is still much to be learned about the year-round distribution and prey preferences of the Alaska resident population, which inhabits the GOA TMAA and surrounding waters. Transient killer whales prey primarily on marine mammals and their population structure is less well understood (Bigg et al. 1990; Ford et al. 1998). Two stocks of transient killer whales occur within or nearby the GOA TMAA: the AT1 transients, which are considered depleted under the MMPA, with only 7 animals in the current population (Muto et al. 2019), and the GOA transients. In the GOA, residents and transients are the most common ecotypes, with sightings and detections typically along the continental shelf (Consiglieri et al. 1982; Zerbini et al. 2007; Fearnbach et al. 2014; Rone et al. 2017; Olsen et al. 2018; Myers et al. 2021). Significantly less is known about the offshore ecotype as sightings are rare, but they are believed to prey on fish, primarily sharks (Ford et al. 2011; Ford et al. 2014; Matkin et al. 2018)

and are typically sighted in larger groups than the other ecotypes (Dahlheim et al. 2008). Offshores in the GOA are part of a population that ranges from California to the Aleutian Islands (Dahlheim et al. 2008; Ford et al. 2014; Schorr et al. 2022). Although sightings of offshores have typically occurred nearshore in the spring and summer (Zerbini et al. 2007; Dahlheim et al. 2008; Ford et al. 2014; Matkin et al. 2018), there have been acoustic detections of offshores near seamounts within the GOA TMAA (Rone et al. 2014), and tag data has revealed presence near the continental slope (Schorr et al. 2022).

Killer whale vocalizations consist of clicks, whistles, and pulsed calls (Ford 1989; Thomsen et al. 2001). Clicks are broadband, impulsive signals with peak energy up to 85 kHz that often occur in a series when used for echolocation, while whistles are tonal calls that have varying durations and frequencies, but typically occur from 5 to 10 kHz and are associated with social behavior (Ford 1989; Thomsen et al. 2001). Pulsed calls exhibit primary energy between 1 and 6 kHz, with harmonics occasionally >30 kHz, and a duration typically between 0.5 and 1.5 seconds (Ford 1989). They are characterized by a high repetition rate of pulsed sounds (typically 250–2000 pulses/s but can be as high as 4000/s) which results in distinctive calls that sound tonal (Ford 1989). Pulsed calls may be used for group recognition and coordination (Ford 1991; Miller 2002; Miller et al. 2004; Filatova 2020).

Each ecotype produces a distinct repertoire of pulsed calls (Ford 1991; Deecke et al. 2005). By identifying and classifying pulsed calls in passive acoustic data, it is possible to understand the acoustic presence of different ecotypes. However, there are also differences in acoustic behavior among killer whale ecotypes that must be considered when interpreting passive acoustic data. Although residents and offshores have unique call repertoires, they share similar call and echolocation rates while transients vocalize significantly less often (Barrett-Lennard et al. 1996; Deecke et al. 2005), likely due to the increased cost of vocal communication when hunting marine mammal prey that are able to hear killer whale calls from several kilometers away (Deecke et al. 2002; Deecke et al. 2005).

The aim of the current study is to provide a long-term view of the spatial and temporal distribution of killer whale ecotypes throughout the GOA TMAA, particularly in offshore waters that have not been well surveyed previously. A similar study using HARP data offshore of Washington allowed for a better understanding of killer whale distribution and provided insight into the potential population structure of transients (Rice et al. 2017). In the GOA, studies on killer whales have revealed year-round presence of residents and transients in nearshore habitats, which may shift seasonally (Durban et al. 2010; Yurk et al. 2010; Matkin et al. 2012; Fearnbach et al. 2014; Matkin et al. 2018; Olsen et al. 2018; Myers et al. 2021). Although killer whales have been detected visually and acoustically offshore (Rone et al. 2017; Rice et al. 2021), determining the extent to which each ecotype uses offshore habitats can inform future management decisions.

Methods:

Passive Acoustic Monitoring

Passive acoustic monitoring has been conducted in the Navy's Gulf of Alaska Temporary Maritime Activity Area (GOA TMAA) using High-frequency Acoustic Recording Packages (HARPs) since July 2011 (Table 1). In the GOA TMAA, HARPs were deployed in a seafloor mooring configuration with the hydrophones suspended at least 10 m above the seafloor, except for Abyssal where the seafloor was at 4,000 m and the hydrophone at 1,200 m. Each HARP hydrophone was calibrated in the laboratory and representative data loggers and hydrophones were also calibrated at the Navy's Transducer Evaluation Center facility to verify the laboratory calibrations (Wiggins and Hildebrand, 2007).

Table 1. Details of high-frequency acoustic recording package deployments including site name, latitude, longitude, depth, sampling frequency, recording duty cycle (on/off durations with "cont." denoting continuous recordings), time period analyzed, and the total number of days with recording effort.

Site	Latitude (N)	Longitude (W)	Depth (m)	Sample rate (kHz)	Duty cycle (min on/off)	Analysis Period	Effort Days
Kenai Shelf	59° 00.51'	148° 54.49'	202	200	Cont.	07/13/2011–07/31/2011	19
	59° 00.41'	148° 54.46'	203	200	10/2	05/03/2012–09/09/2012	129
	59° 00.66'	148° 54.25'	200	320	Cont.	06/06/2013–06/17/2013	11
	59° 00.61'	148° 53.96'	203	200	Cont.	09/06/2013–04/28/2014	235
	59° 00.50'	148° 54.10'	201	200	Cont.	04/29/2014–09/09/2014	133
	Total						*527*
Kodiak Shelf	57° 20.18'	150° 41.75'	234	200	Cont.	06/09/2013–06/27/2013	18
	57° 20.14'	150° 41.99'	230	200	Cont.	09/08/2013–05/01/2014	235
	57° 20.00'	150° 40.07'	232	200	Cont.	05/01/2014–09/11/2014	133
	Total						*386*
Kodiak Slope	57° 13.44'	150° 31.70'	1200	200	Cont.	04/24/2019–09/27/2019	156
Kenai Slope	58° 38.74'	148° 04.13'	1000	200	Cont.	07/13/2011–02/19/2012	222
	58° 40.28'	148° 01.25'	900	200	10/2	05/03/2012–02/12/2013	286
	58° 40.41'	148° 00.55'	877	200	Cont.	06/06/2013–09/05/2013	90
	58° 40.31'	148° 01.31'	858	200	Cont.	09/05/2013–04/28/2014	236
	58° 40.26'	148° 01.43'	914	200	Cont.	04/29/2014–09/09/2014	133
	58° 40.25'	148° 01.46'	900	200	Cont.	09/09/2014–05/01/2015	234
	58° 39.32'	148° 05.48'	929	200	Cont.	05/01/2015–09/06/2015[a]	108
	58° 40.17'	148° 01.50'	874	200	Cont.	04/30/2017–09/12/2017	135
	58° 40.22'	148° 01.62'	900	200	Cont.	09/14/2017–06/16/2018	275
	58° 40.18'	148° 05.57'	972	200	Cont.	04/25/2019–09/27/2019	155
	Total						*1874*
Abyssal	57° 30.82'	146° 30.05'	1200[b]	200	Cont.	04/29/2017–09/13/2017	137
Quinn	56° 20.34'	145° 11.18'	930	320	Cont.	06/10/2013–09/11/2013	93
	56° 20.36'	145° 11.24'	930	200	Cont.	09/11/2013–04/16/2014	217
	56° 20.48'	145° 10.99'	900	200	Cont.	09/10/2014–05/02/2015	233
	56° 20.44'	145° 11.11'	994	200	Cont.	05/02/2015–08/18/2015	108
	56° 20.39'	145° 11.11'	964	200	Cont.	04/30/2017–09/13/2017	137
	Total						*788*
Pratt	56° 14.61'	142° 45.44'	989	200	Cont.	09/09/2012–06/10/2013	275
	56° 14.64'	142° 45.43'	987	200	Cont.	06/11/2013–08/20/2013	70
	56° 14.58'	142° 45.41'	988	200	Cont.	09/03/2013–03/21/2014	199
	56° 14.60'	142° 45.46'	987	200	Cont.	04/30/2014–09/10/2014	133
	Total						*677*
	Total all sites						*4545*

[a] There was a gap in this deployment from approximately July 21, 2015 until August 10, 2015, due to an instrument hard drive failure.
[b] Seafloor depth at this site was approximately 4,000 m but the hydrophone was located at 1,200 m.

The seven sites monitored spanned the continental shelf (sites Kenai Shelf and Kodiak Shelf), the continental slope (sites Kodiak Slope and Kenai Slope), deep, offshore water (site Abyssal), and offshore seamounts (sites Quinn and Pratt; Figure 1). Kenai Shelf was monitored intermittently from July 2011 to September 2014, Kodiak Shelf almost continuously from June

2013 to September 2014, Kodiak Slope from April to September 2019, Kenai Slope intermittently from July 2011 to September 2019, Abyssal from April to September 2017, Quinn intermittently from June 2013 to September 2017, and Pratt almost continuously from September 2012 to September 2014 (Table 1).

Each HARP sampled continuously at 200 kHz except for one deployment each at Kenai Shelf and Kenai Slope, where a duty cycle was used, and one deployment each at Kenai Shelf and Quinn, which were sampled at 320 kHz (Table 1). Duty-cycled deployments recorded for 10 minutes on and 2 minutes off. There were 4,545 days of recording effort overall (Table 1). Kenai Slope had the highest number of days with recording effort (1,874 days) while Abyssal had the lowest (137 days).

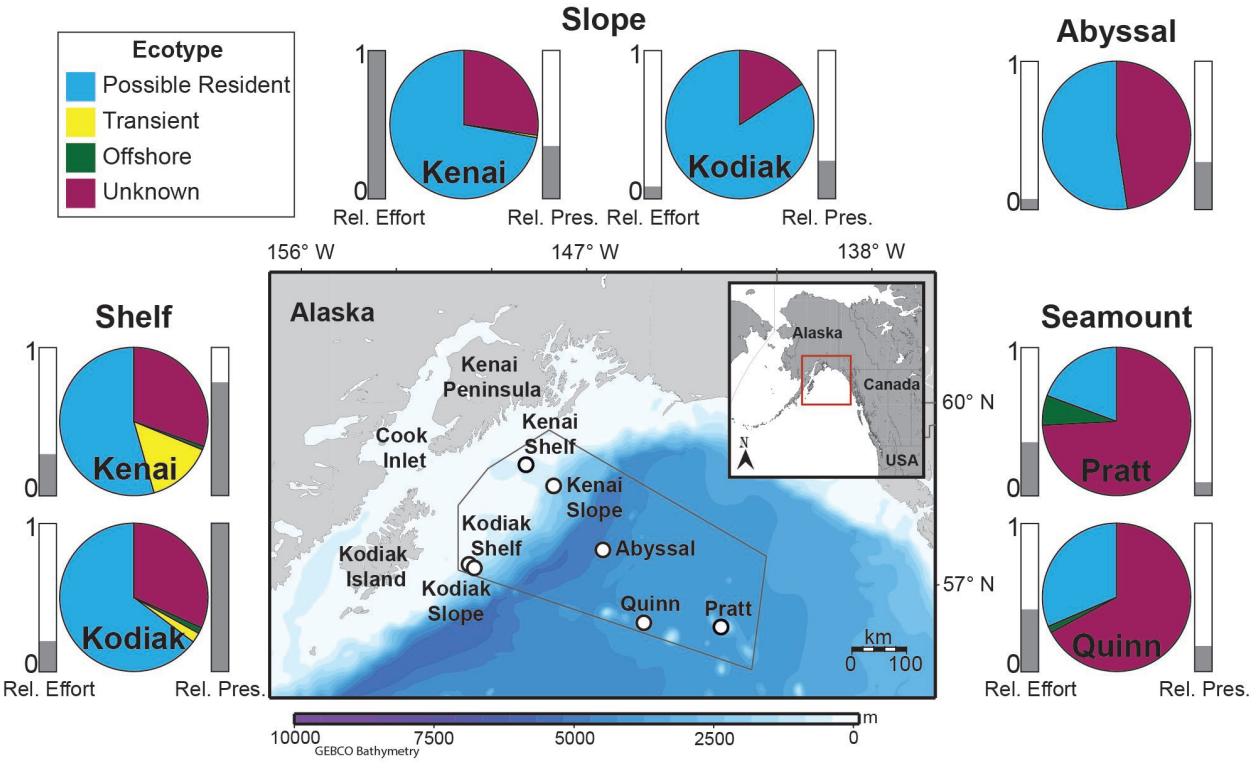

Figure 1. Relative daily acoustic presence of killer whale ecotypes (pie charts; possible resident in blue, transient in yellow, offshore in green, and unknown in magenta) at High Frequency Acoustic Recording Package (HARP) locations (white circles) in the Gulf of Alaska from July 2011 to September 2019. Recording effort varied at each site (Table 1); the relative detection effort (number of days with recording effort) is displayed on the left and overall relative presence (number of days with killer whale acoustic presence, adjusted for effort) on the right. Kenai Slope had the highest effort (1,874 days; Rel. Effort of 1) and Kodiak Shelf had the highest presence (47.9% of days; Rel. Pres. of 1). Map color bar shows depth in meters. The red box in the inset map of northwest USA and Canada indicates the study site. Map generated using Maptool, a product of seaturtle.org.

Data Analysis

Before analysis, data were decimated by a factor of 20 for more effective scanning up to 5 kHz (8 kHz for deployments that were sampled at 320 kHz). Long-term spectral averages (LTSAs) were created using a 5-s time average and a 10-Hz resolution and were scanned by an analyst for killer whale whistles and pulsed calls using *Triton*, custom MATLAB (MathWorks, Natick, MA) software (Wiggins and Hildebrand 2007). When a potential killer whale signal was identified in the LTSA, a 30-s long spectrogram (1000-point FFT length, 90% overlap) was examined to confirm that the calls belonged to killer whales. Calls were logged as encounters, where each encounter was bounded by at least 15 min of recording that did not contain any calls. The use of a 15 min separation between encounters is conservative and resulting encounter durations should be considered minimums.

Ecotype Identification

Each encounter was later examined for pulsed calls which, when found, were scrutinized in a 30-s spectrogram window in order to visually and aurally identify call types that could be used to distinguish between different ecotypes. An encounter was only classified to ecotype level if calls from the encounter could be positively matched to existing call repertoires. Resident and transient call types were identified using a digitized call catalog made from recordings provided by H. Myers (North Gulf Oceanic Society, unpublished data). These call types were from previously published call catalogs (Yurk et al. 2002; Saulitis et al. 2005; Yurk et al. 2010; Myers et al. 2021) and from vessel surveys with resident killer whales (North Gulf Oceanic Society, unpublished data). Resident and transient encounters were confirmed by H. Myers and D. Olsen. Offshore encounters were confirmed by J. Pilkington by matching calls to a digitized call catalog of offshore calls made from field recordings taken during encounters with photo-identified offshore killer whales (DFO Cetacean Research Program, unpublished data). Encounters that could not be identified to the ecotype level were labeled unknown. Unknown encounters were typically short in duration and contained short and faint calls that were not suitable for making ecotype identifications.

Results:

Killer whales were detected at all seven recording locations and overall 32% of days with recording effort had killer whale acoustic presence (either possible resident, transient, offshore, or unknown). The percent of days with acoustic presence varied across sites: Kodiak Shelf and Kenai Shelf had the highest percent of days with killer whale acoustic presence (47.9% and 36.6%, respectively), while Quinn and Pratt had the lowest (8.2% and 4.3%, respectively). In general, acoustic presence was highest on the continental shelf and during the summer, although each ecotype had unique spatial and temporal distributions.

There were no definitive matches to previously recorded Alaska resident call types. However, there were many calls that shared aural and structural similarities with resident call types. These similarities, noted by multiple analysts, along with the consistent occurrence of these calls in the

recordings, led us to classify such encounters as possible residents. At this time, classifying these calls as resident would be premature without definitive call type matches, particularly due to the occurrence of these calls at sites farther offshore than resident killer whales are known to travel (Olsen et al. 2018). Resident killer whale call repertoires typically contain variants, or subtypes, of a given call type. These call subtypes are produced by different pods within an acoustic clan and are characterized by variations in call elements or contours (Ford 1989; Yurk et al. 2002). It is possible that some of the calls recorded in this study represent subtypes of Alaska resident calls, though concurrent visual identification and acoustic recordings would be required to confirm this theory. The calls used for ecotype classification are available on Dryad (Rice et al. 2022) and we hope to eventually make a definitive ecotype classification for these encounters. It is worth noting that these calls also did not match the known call repertoires for the southern and northern resident killer whale populations.

Possible Residents

- Possible resident was the most common ecotype classification.
- Acoustic presence was highest at sites on the continental shelf and lowest at the offshore seamounts (Figure 2).
- Encounters occurred on 59.4% of the total days with killer whale acoustic presence.
- At Kenai Shelf and Kodiak Shelf, detections occurred year-round. At Kenai Slope, detections occurred primarily during spring and early summer. Although there was a lower number of encounters at the seamounts, at Quinn, detections occurred primarily in spring/early summer (Figure 2).
- Relative daily acoustic presence of possible residents ranged from 19.4% at Pratt to 84.2% at Kodiak Slope.
- Possible residents had the highest relative presence at all sites, except for the offshore seamounts, where the majority of encounters could not be identified (Figure 1).
- Median encounter duration was 1.3 h, which was the highest of all ecotypes, and ranged from 3.6 s to 14.3 h (Figure 3). Broken down by site, encounter duration was highest at Kodiak Slope (3 h) and lowest at Abyssal and Pratt (0.5 h).

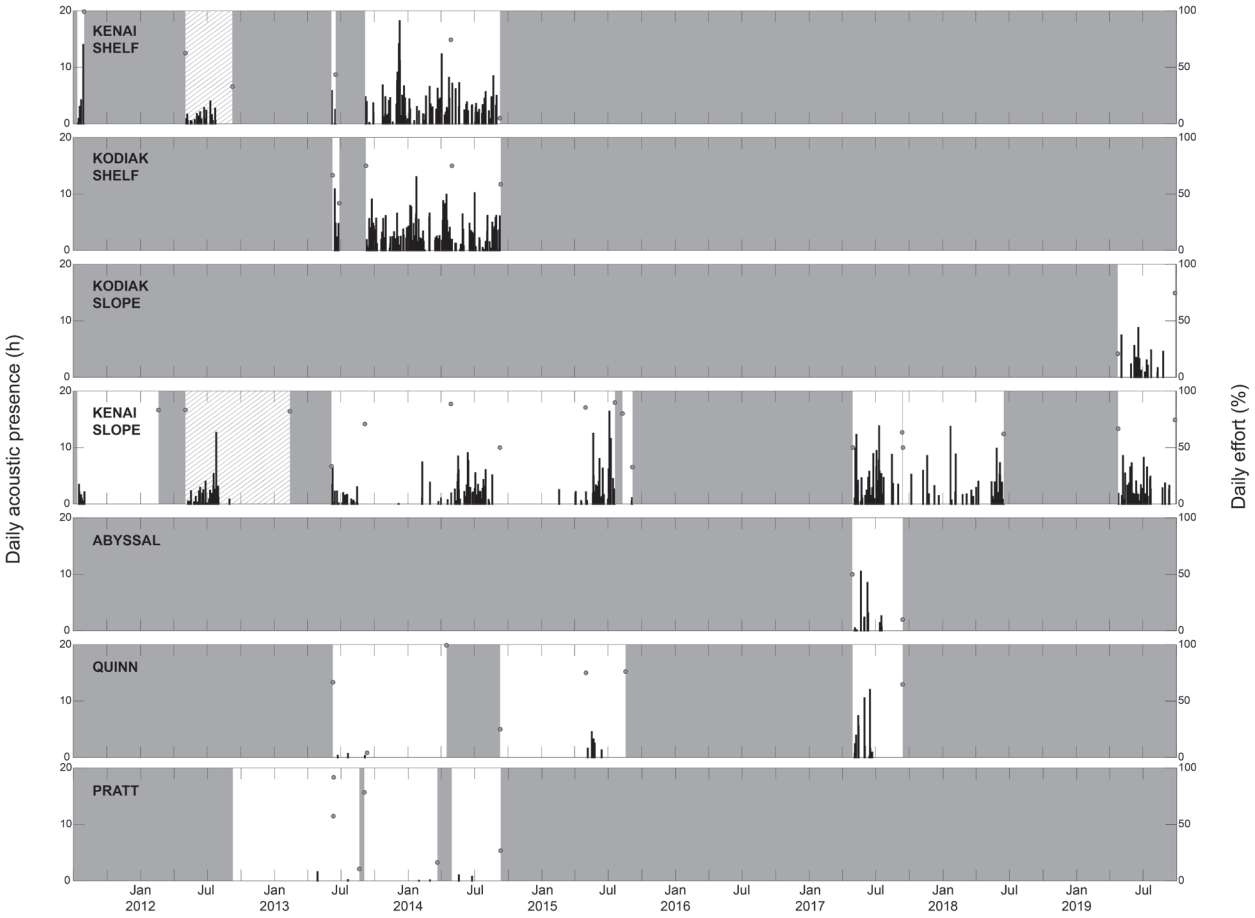

Figure 2. Daily acoustic presence (black bars) of possible resident killer whales at seven recording locations (Kenai Shelf, Kodiak Shelf, Kodiak Slope, Kenai Slope, Abyssal, Quinn, and Pratt) in the Gulf of Alaska from July 2011 to September 2019. Grey dots represent the percent of recording effort each day for days with < 100% recording effort. Gray hatching at Kenai Shelf and Kenai Slope represents that a duty cycle with used in those deployments (Table 1). Gray shading represents periods with no recording effort.

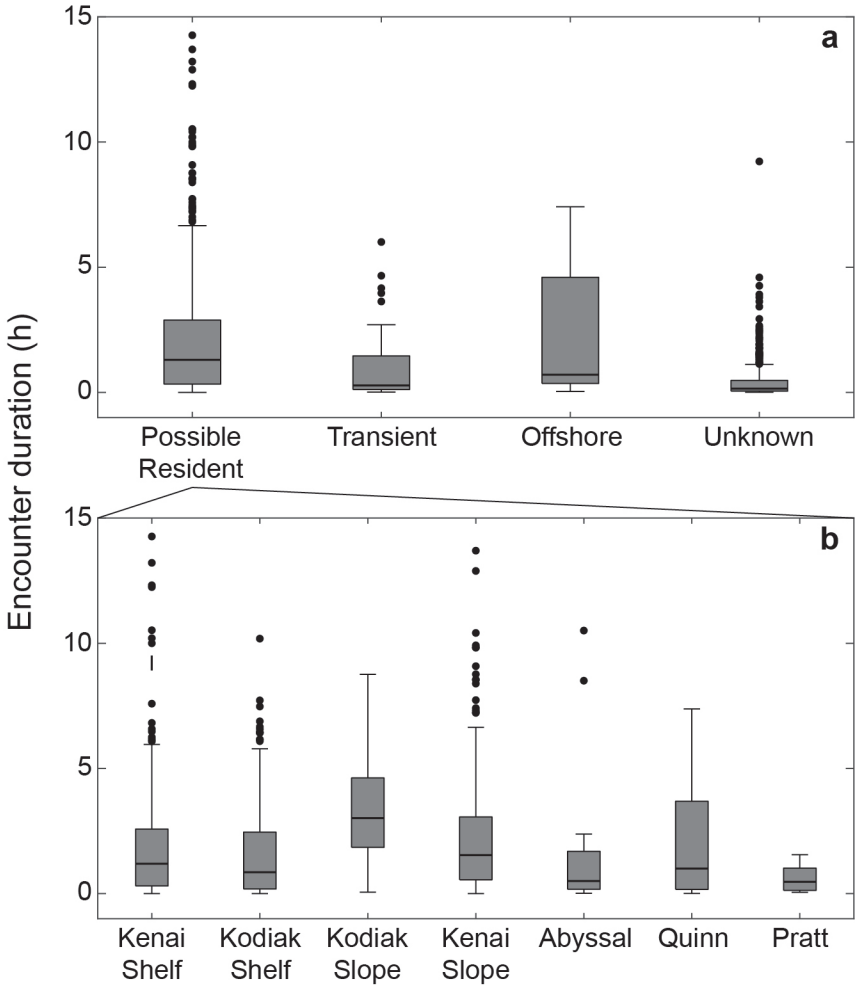

Figure 3. Encounter duration, in hours, (**a**) combined across all sites for possible residents (n=839), transients (n=60), offshores (n=8), and unknowns (n=403) and (**b**) for possible residents at Kenai Shelf (n=179), Kodiak Island (n=266), Kodiak Slope (n=17), Kenai Slope (n=321), Abyssal (n=19), Quinn (n=31), and Pratt (n=6). Black lines indicate the median; bottom and top edges of the grey boxes represent the lower (25%) and upper (75%) quartiles, respectively; whiskers show maximum and minimum values; black circles represent outliers. Encounters from duty-cycled deployments are not included.

Transients

- Transients were encountered only at Kenai Shelf, Kodiak Shelf, and Kenai Slope, with most detections occurring at Kenai Shelf in 2014 (Figure 4).
- All detections were of GOA transients; there were no detections of AT1 transients during the monitoring period.
- Encounters occurred on 5.1% of the total days with killer whale acoustic presence.
- At Kenai Shelf in 2014, transients were detected sporadically, year-round, but were most common in the spring and summer (Figure 4).
- Relative daily acoustic presence was 14.5% at Kenai Shelf, 2.2% at Kodiak Shelf, and 0.6% at Kenai Slope (Figure 1).

- Median encounter duration was 0.3 h and ranged from 36 s to 6 h (Figure 3a). Encounter duration was not examined on a per-site basis due to the low number of transient encounters at Kodiak Shelf and Kenai Slope.
- There was one day at Kenai Shelf (November 10, 2013) with an encounter that contained both residents and transients.

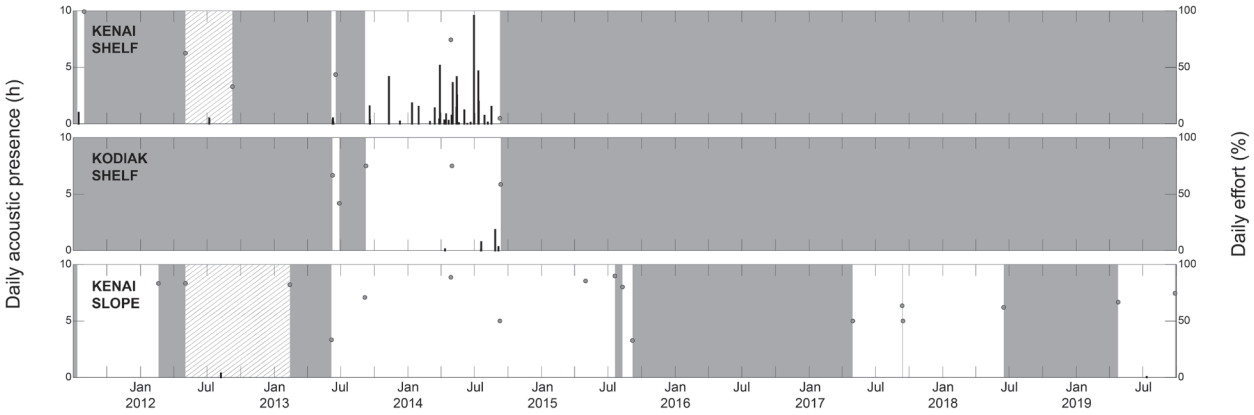

Figure 4. Daily acoustic presence (black bars) of transient killer whales at three recording locations (Kenai Shelf, Kodiak Shelf, and Kenai Slope) in the Gulf of Alaska from July 2011 to September 2019. Grey dots represent the percent of recording effort each day for days with < 100% recording effort. Gray hatching at Kenai Shelf represents that a duty cycle with used in the deployment (Table 1). Gray shading represents periods with no recording effort.

Offshores

- Offshores were the least commonly detected ecotype.
- Encounters occurred on 0.9% of the total days with killer whale acoustic presence.
- There were eight days with encounters (Figure 5):
    - Kenai Shelf:
        - June 12, 2013
        - March 3, 2014
    - Kodiak Shelf:
        - January 4, 2014
        - May 13-14, 2014
    - Quinn:
        - December 3, 2014
    - Pratt:
        - October 2, 2012
        - November 13, 2013
- Encounters occurred sporadically throughout the year with no clear seasonal pattern.
- Relative daily acoustic presence was 0.8% at Kenai Shelf, 1.3% at Kodiak Shelf, 1.4% at Quinn, and 6.5% at Pratt (Figure 1).
- Median encounter duration was 0.7 h and ranged from 2.4 min to 7.4 h (Figure 3a). Offshore encounter duration was not examined on a per-site basis due to the low number of offshore encounters overall.

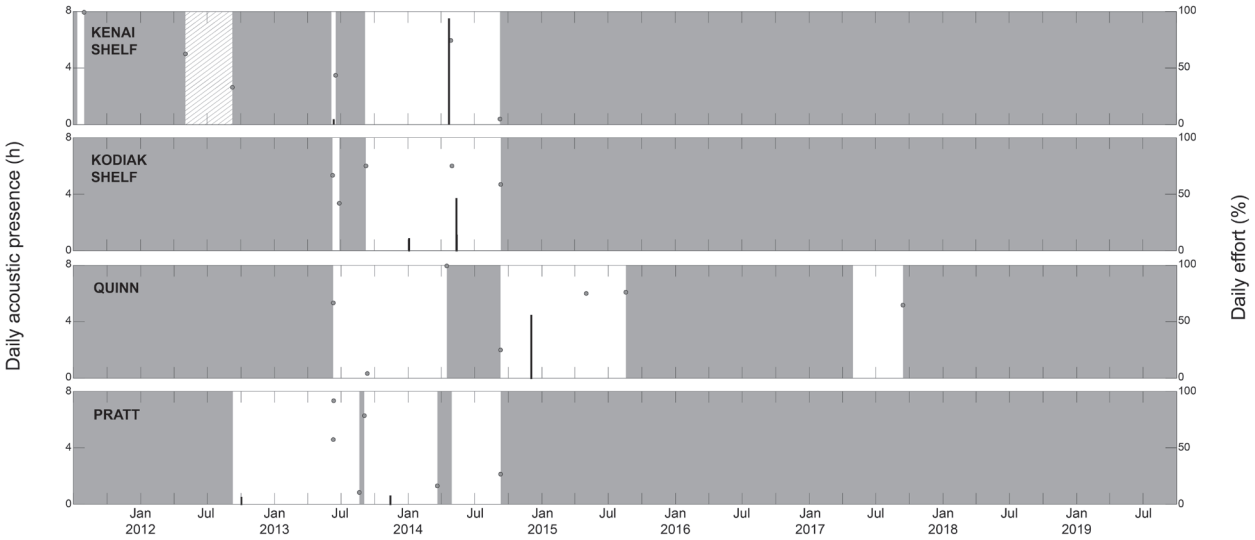

Figure 5. Daily acoustic presence (black bars) of offshore killer whales at four recording locations (Kenai Shelf, Kodiak Shelf, Quinn, and Pratt) in the Gulf of Alaska from July 2011 to September 2019. Grey dots represent the percent of recording effort each day for days with < 100% recording effort. Gray hatching at Kenai Shelf represents that a duty cycle with used in the deployment (Table 1). Gray shading represents periods with no recording effort.

Unknowns

- Encounters that could not be identified to ecotype were common across all sites.
- These encounters were often short and primarily contained short, faint, and nondescript calls, making them unsuitable for ecotype identification.
- Encounters occurred on 34.5% of the total days with killer whale acoustic presence.
- Encounters peaked during spring and early summer at Kenai Slope but occurred year-round at all other sites (Figure 6).
- Relative daily acoustic presence ranged from 15.8% at Kodiak Slope to 44.2% at Pratt (Figure 1).
- Median encounter duration was 0.1 h and ranged from 18 s to 9.2 h (Figure 3a). Broken down by site, median encounter duration was highest at Kodiak Slope (2.5 h) and lowest at the continental shelf sites (0.1 h).

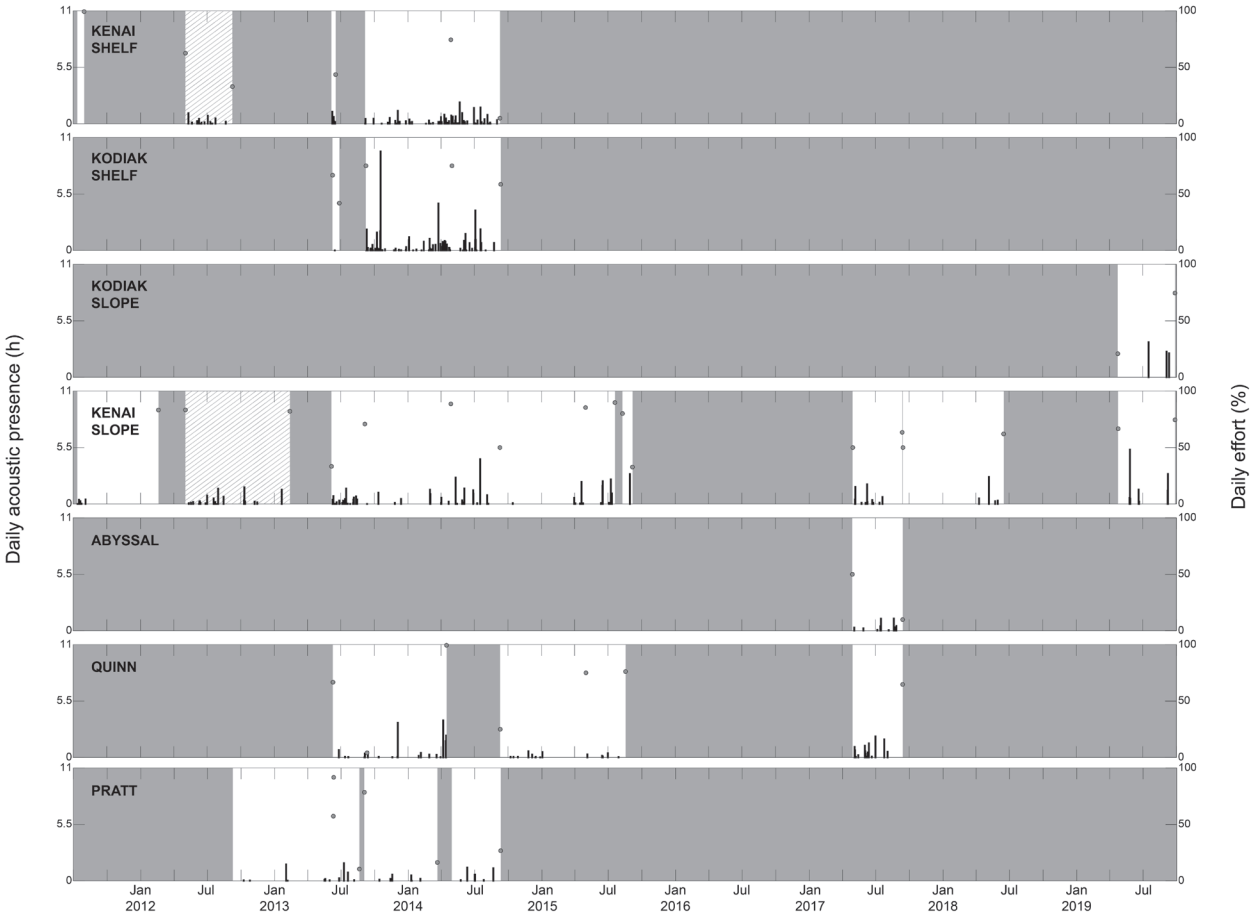

Figure 6. Daily acoustic presence (black bars) of unknown killer whales at seven recording locations (Kenai Shelf, Kodiak Shelf, Kodiak Slope, Kenai Slope, Abyssal, Quinn, and Pratt) in the Gulf of Alaska from July 2011 to September 2019. Grey dots represent the percent of recording effort each day for days with < 100% recording effort. Gray hatching at Kenai Shelf and Kenai Slope represents that a duty cycle with used in those deployments (Table 1). Gray shading represents periods with no recording effort.

Discussion:

Killer whales were present year-round in the GOA and were most common on the continental shelf. Possible resident was the most common ecotype classification, followed by transient, and then offshore. Detections of possible residents occurred year-round at the continental shelf, primarily during summer at the slope, and primarily during spring at Quinn, while for transients and offshores, detections were more sporadic and did not show any definitive seasonal pattern.

Encounters that were labeled unknown were common at all sites, and so the daily acoustic presence of each ecotype is likely higher than shown here. Some unknown encounters contained calls that matched or shared close similarities with calls from unidentified killer whales in outer coast and offshore waters of British Columbia (J. Pilkington, pers. comm.). It is also possible that some of the unknown encounters could be attributed to killer whale populations from

neighboring regions, such as residents or transients from the eastern and central Aleutian Islands or transients from the West Coast stock. Further scrutiny of calls would be required to determine if this may be the case. The presence of any of these populations in the GOA would be noteworthy in better establishing the range of these populations, but the low number of unknown encounters that may be attributable to these populations does not suggest any extended presence in the region. The year-round presence of unknown encounters on the continental shelf, as well as seasonal presence on the continental slope, correspond with the acoustic presence of possible residents. It is possible that many of the unknown encounters with poor sample quality (faint calls and short-duration encounters) are residents.

The detection range of killer whale calls varies with instrument location, season, background noise level, and call type (Miller 2006; Holt et al. 2011; Riera et al. 2013). Calculating detection ranges for the locations used in this study was not possible, primarily because call source levels and calling depth are currently unknown for these populations. Offshore of Washington State, detection ranges of 5–16 km have been calculated for residents (Miller 2006; Riera et al. 2013). These ranges show some seasonal variation, with a decrease in detection range during winter (Riera et al. 2013). In our study, detection ranges are likely higher at the offshore sites, where the recorders were located at greater depths (i.e., Kenai Slope, Kodiak Slope, Abyssal, Quinn, and Pratt). This increased detection range could also explain the increased relative presence of encounters that could not be attributed to an ecotype at the offshores sites, if faint calls from distant killer whales were more likely to be picked up at these sites. It is important to consider the influence that spatial and temporal differences have on detection ranges when interpreting passive acoustic results.

Possible Residents

The lack of matches between previously recorded Alaska resident calls and the calls recorded in this study was unexpected. For calls that were noted to have aural and structural similarities to known Alaska resident calls, a label of "possible resident" was assigned.

Detections of possible residents were highest at the sites on the continental shelf (Figure 2), where Alaska residents are most commonly found based on previous findings from visual surveys and satellite tags (Zerbini et al. 2007; Fearnbach et al. 2014; Olsen et al. 2018). However, satellite-tagged individuals occasionally traveled out to and along the continental slope (Olsen et al. 2018). The acoustic presence of possible residents at the continental slope documented here was higher than might have been expected from resident tag data. Additionally, the acoustic presence of possible residents at offshore sites was unexpected, as tag data did not indicate that residents travelled so far offshore (Olsen et al. 2018). The detections of possible residents occurred seasonally in both cases, with most detections at the continental slope occurring in the spring and early summer, and during spring at Quinn seamount (Figure 2).

The repeated occurrence of calls classified as possible resident, their presence on the continental shelf year-round, and their similarities with known Alaska resident calls led analysts to initially believe these calls were Alaska residents. However, the lack of definitive call type matches to known Alaska resident calls as well as the occasional occurrence of these calls at sites farther offshore led to the designation of "possible resident". Although we cannot yet definitely classify

these detections as residents, it is possible that these detections are representative of infrequently encountered Alaska resident pods for which acoustic recordings and tag data are limited.

Alaska residents prey primarily upon Chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), and chum (*O. keta*) salmon (Saulitis et al. 2000; Matkin et al. 2018). In the Kenai Fjords, residents consume different proportions of these species, following shifts in abundance from spring to fall: Chinook are the primary prey in May and June, chum in July and August, and coho in September (Matkin et al. 2018). It has been hypothesized that Pacific herring (*Clupea pallasii*) aggregations that overwinter on the continental shelf (Bishop and Eiler 2018) may attract Pacific salmon species, allowing residents to forage successfully throughout the winter (Olsen et al. 2018; Myers et al. 2021). This seasonal flexibility in diet could explain the year-round detections of possible residents on the continental shelf. Seasonal dietary changes have also been observed for resident killer whales offshore of Washington State and British Columbia (Ford and Ellis 2006; Hanson et al. 2010; Ford et al. 2016; Hanson et al. 2021). Meanwhile, seasonal presence on the continental slope and further offshore could indicate predation on salmon stocks undertaking migrations to the northwest or southeast or those overwintering offshore (Seeb et al. 2004; Larson et al. 2013; Urawa et al. 2016). These patterns could also be related to the differences in core use areas exhibited by different resident pods (Olsen et al. 2018).

Encounter duration of possible residents (Figure 3a) fell within the range of previous findings for residents (Riera et al. 2019). The increased encounter duration at Kodiak Slope (Figure 4b) may indicate that the whales are spending more time in this area. Behavior cannot necessarily be inferred from the amount of acoustic presence, but greater encounter durations do suggest that the vocalizing animals are not quickly transiting through the area and may be spending time foraging or socializing (Riera et al. 2019).

Transients

GOA transients were primarily detected at Kenai Shelf (Figure 4) and were not detected at any offshore sites. Previous sightings and detections of GOA transients have typically occurred closer to shore than the continental shelf sites monitored here (Zerbini et al. 2007; Durban et al. 2010; Matkin et al. 2012; Myers et al. 2021), though surveys were biased towards nearshore habitats. Tag data revealed that GOA transients travel along the coast with occasional trips farther out onto the continental shelf (Matkin et al. 2012). In one year of data (September 6, 2013–September 9, 2014), GOA transients were detected at the continental shelf sites on 36 days (Figure 4). This is comparable to 41 days of detections over a one-year period (June 1, 2019–May 31, 2020) at sites near the primary entrances to Prince William Sound (Myers et al. 2021) and reveals that GOA transients may utilize more of the continental shelf than indicated from previous studies.

Transient vocalization rates are highest when engaging in social behavior following predation (Baird and Dill 1995; Deecke et al. 2005; Riesch and Deecke 2011), meaning that the peak in GOA transient detections during spring and summer at Kenai Shelf may indicate successful foraging. Nearshore, GOA transients have been observed preying primarily upon Steller sea lions (*Eumetopias jubatus*; Saulitis et al. 2000; Maniscalco et al. 2007; Matkin et al. 2018), although observations of predation on Dall's porpoises have increased in recent years (Matkin et al. 2018). The seasonal acoustic presence of GOA transients observed here matches the general seasonal

presence of Steller sea lions at rookeries, where presence increases in June and decreases throughout the fall (Maniscalco et al. 2007). However, although Steller sea lions occasionally transit further out on the continental shelf, they predominantly inhabit nearshore areas where their rookeries are located (Lander et al. 2009; Bishop et al. 2018), indicating that GOA transients are likely preying upon other species in our study area. Possibilities include gray whales (*Eschrichtius robustus*) and northern fur seals (*Callorhinus ursinus*), which both migrate north through the Gulf of Alaska in the spring (Kenyon and Wilke 1953; Bigg 1990; Matkin et al. 2007; Barrett-Lennard et al. 2011).

Another population of transients, the AT1s, also inhabit the GOA but are known to show high site fidelity to Prince William Sound and the Kenai Fjords (Matkin et al. 2012). This population was severely depleted by the *Exxon Valdez* oil spill in 1989 and is expected to go extinct (Matkin et al. 2018). Although not unexpected, there were no detections of this transient population in the recordings for this study.

Passive acoustic results always represent the minimum of a species' presence because animals are not vocalizing constantly. This is particularly relevant for transient killer whales, which are known to vocalize less frequently than other ecotypes (Barrett-Lennard et al. 1996; Deecke et al. 2005; Saulitis et al. 2005; Riesch and Deecke 2011). When transients do produce the pulsed calls used for ecotype classification in this study, most often after a kill, the call rate is lower than observed in other ecotypes (Deecke et al. 2005; Riesch and Deecke 2011). As expected, we found that the median length of GOA transient acoustic encounters was shorter than that of the other ecotypes (Figure 3a). While passive acoustic monitoring can indicate habitat use for transients, acoustic presence should be used to complement results from other survey methods, as opposed to as the sole measure of the ecotype's presence in a region.

Offshores

The GOA falls within the wide range of the North Pacific offshore killer whale population, but sightings are rare and have typically occurred during spring and summer (Zerbini et al. 2007; Dahlheim et al. 2008; Ford et al. 2014; Matkin et al. 2018). The paucity of sightings in the region has often been attributed to survey effort being biased towards nearshore habitats and summer months, when survey conditions are more suitable. Near Washington State and Vancouver Island, BC, tagged offshores often traveled along the continental slope, where one of their known prey species, the Pacific sleeper shark (*Somniosus pacificus*), is often found (Ford et al. 2011; Ford et al. 2014; Schorr et al. 2022). However, there have also been acoustic detections farther offshore, at Bowie Seamount (DFO Cetacean Research Program, unpublished data), and in a survey covering the GATMAA, offshores were acoustically detected near offshore seamounts (Rone et al. 2014), indicating the population does occupy waters farther from shore. Therefore, it seemed probable that by acoustically monitoring sites along the continental slope and further offshore, it would be possible to get a better understanding of offshore distribution in the GOA. However, detections of offshores were low across all sites (Figure 5) and there were no confirmed offshore detections on the continental slope, even though Kenai Slope had the highest recording effort. It is unclear whether the lack of offshore detections is indicative of sparse presence in the region or if it indicates that the recording locations used did not successfully cover the preferred habitat of offshores in the GOA. A recent study using satellite tags found that as offshores traveled north they moved towards progressively shallower water (Schorr et al.

2022). Of the few detections of offshores in this study, the majority did occur at sites on the continental shelf (Figure 5). However, in a year of recording at nearshore sites in the GOA, offshores were detected on only 1 day (Myers et al. 2021), indicating that the use of recording locations closer to shore may not have resulted in increased detections of offshores.

Conclusions:

Killer whales range more extensively in the GOA than once assumed. Understanding the habitat use of killer whale ecotypes within a region is necessary for successful species management, as the *Exxon Valdez* oil spill demonstrated the lasting and irreversible impact one environmental disaster can have on killer whales in the GOA (Matkin et al. 2018). Killer whales face negative impacts from the bioaccumulation of contaminants, reductions in prey availability, and reductions in foraging opportunities due to increased noise levels from shipping activity (Buckman et al. 2011; Joy et al. 2019; Lawson et al. 2020). The continental shelf appears to be an important habitat for GOA transients in the spring and summer, and potentially for Alaska residents year-round. While offshores were not detected as often as other ecotypes, this area may still constitute important habitat. The small population size of offshores (Ford et al. 2014), combined with the fact that they often travel in large groups (Dahlheim et al. 2008), means that a large proportion of the offshore population could be impacted by an acute anthropogenic event. Reducing anthropogenic noise in key areas may positively impact killer whale foraging success (Joy et al. 2019). The occurrence of anthropogenic activities in offshore areas may pose less of an immediate threat to killer whale populations, particularly in winter when killer whale presence was lowest. Based on our passive acoustic detections, avoiding potentially harmful activities during the summer along the continental slope and during spring farther offshore may have the greatest ecological benefit for killer whales in the GOA.

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