Monitoring the occurrence of Southern resident killer whales, other marine mammals, and anthropogenic sound in the Pacific Northwest

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Executive Summary

Passive acoustic monitoring has been conducted along the U.S. west coast, from Central California to Cape Flattery, to monitor movements of endangered Southern resident killer whales (SRKW). Since 2008, four to seventeen Ecological Acoustic Recorders (EARs) have been deployed, depending on the year and available funding. The rate of successful data acquisition has varied each year due to fishery interactions and equipment failures. EARs were programmed to record on a 5-10% duty cycle depending on the year of deployment, resulting in 30-90 seconds of continuous recording every 300-600 seconds with a sampling rate of 25 kHz.

Data was reviewed both visually and aurally and both the biological and anthropogenic sound sources present in the frequency range monitored were classified manually.

Mid frequency active sonar (MFA) and explosive sounds were both detected in the recordings. There were 148 MFA events detected between 2011 and 2017. These events were detected at mid shelf and offshore sites more often than the nearshore sites. The number of events per year was variable, and the majority of these events occurred between February and May. This peak overlaps with the occurrence of the three killer whale communities monitored.

Explosive sounds were also more frequently detected at mid shelf and offshore sites than the nearshore sites. 3152 explosive sounds were detected on 466 days from 2011 to 2017. Most of these days had less than five explosive sounds on each day, but there are exceptions like Cape Flattery Offshore that had eight days with 100 or more explosive sounds. Explosive sounds were more common in summer months, but the peak in occurrence differed between the northern and southern sites.

The most commonly detected species were humpback whales, gray whales, sperm whales, killer whales and unidentified dolphins. The monthly occurrence of these species was variable between the years 2014 and 2017. Despite this variability some clear patterns of occurrence resulted from multiple years of acoustic monitoring from a network of recorders. For example, gray whales and humpback whales differ in their occurrence along the Washington coast. Gray whales occur year round at most nearshore sites, while humpback whale occurrence shows a strong migration signal at most sites except Cape Flattery offshore. Both Sperm whale and dolphin occurrence was low and highly variable. Northern resident killer whales (NRKW) were the most detected of the killer whales eco- types, followed by transients and SRKW. There was a peak in occurrence in spring for all three ecotypes at most sites. NRKW and transients were particularly prevalent on the Cape Flattery Offshore recorder. The highest level of MFA events overlapped with all three killer whale communities.

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Background

Estimates of cetacean abundance, density, and distribution are necessary to understanding the role of cetaceans in marine ecosystems and identifying potential anthropogenic threats to managed and endangered cetaceans. Along the U.S. west coast, cetaceans are at risk of fishery interactions, entanglement, ship strike (Douglas et al. 2008; Carretta et al. 2014b) and anthropogenic sound sources.

The U.S. Navy's Northwest Training Range Complex (NWTRC) extends 250 nautical miles offshore of the northwest coast of the continental U.S. Many cetacean species inhabit this region. These species are managed under the U.S. Marine Mammal Protection Act and include several stocks listed under the U.S. Endangered Species Act (Carretta et al. 2014a). The abundance and population density of cetaceans in the California Current off the United States Pacific Coast, including the Washington coast, has been estimated from summer and fall ship and aerial surveys (Barlow and Forney 2007; Barlow, 2010; Chandler and Calambokidis 2003). However, species distribution in this area likely changes between seasons, since many cetacean species undertake long distance annual migrations (Calambokidis 2001). Forney and Barlow (1998) found that half of the abundance estimates for species surveyed off the California coast exhibited significant differences between the winter and summer surveys, but determining cetacean seasonal distribution patterns can be difficult and cost prohibitive due to protracted periods of inclement weather, remote access, and short daylight hours.

As a part of an effort to examine year round resident killer whale movements from central California to the northwest tip of Washington State (Hanson et al. 2013), autonomous passive acoustic recorders were deployed at multiple sites spanning the Washington, Oregon, and California coasts. While the primary focus was to detect endangered Southern resident killer whales during the winter and spring months, these recorders provided near year-round monitoring of sound producing cetaceans and anthropogenic sound sources. Here we summarize the monthly occurrence of anthropogenic sounds and the most frequently detected cetacean species determined through passive acoustic monitoring: gray whales (*Eschrictius robustus*), humpback whales (*Megaptera novaengliae*), sperm whales (*Physeter macrocephalus*), killer whales (*Orcinus orca*), and unidentified dolphins

Methods

Passive Acoustic Monitoring Recorders

Since 2008, Ecological Acoustic Recorders (EARs) have been deployed by the Northwest Fisheries Science Center along the coasts of Washington, Oregon, and California to monitor the movements of Southern resident killer whales (SRKW). Details on the specifications of the EAR are provided in Lammers *et al.* (2008).

An EAR can be programmed as an event recorder or to record the full acoustic waveform on a duty cycle. In this study, EARs were programmed to record on a 5-10% duty cycle depending on the year of deployment, resulting in 30-90 seconds of continuous recording every 300-600 seconds. The duty cycle was chosen based on several factors including expected power consumption, length of deployments, and the likelihood of capturing SRKW calls. Hardware advancements allowed for longer deployments beginning in 2011, except in cases of delays in deployment schedules, mooring failures, instrument service life limitations, or fishing gear interactions. To account for the differences in duty cycle between years, we used daily vocal occurrence as our unit of measure, as in Hanson et al. (2013), which the results indicated that the decreased duty cycle did not negatively affect the monthly detection rate of resident killer whales.

The sampling rate used on all deployments was 25 kHz which provided 12.5 kHz of bandwidth. This sampling rate was chosen as a trade-off for preserving hard drive space and battery life while allowing for identification of killer whale calls.

Recorder locations

Beginning in 2008, EARs were deployed at four sites spanning the continental shelf along the Washington coast: Cape Flattery Inshore (CFI), Cape Flattery Offshore (CFO), Westport (WP), and Columbia River (CR) (Figure 1). These locations were selected based on various factors which included sites that resident killer whales had been previously sighted, sites where enhanced productivity would likely be concentrated due to bathymetric features, i.e., canyons, accessibility for mooring deployment and recovery, and to reduce the likelihood of interactions with local fisheries (Hanson et al. 2013). Recorder locations were added in following years, including in Oregon and California, with a maximum number of deployments (17) in 2015-2017 that included Juan de Fuca (JF), Cape Flattery Mid Shelf (CFM), Cape Flattery Deep (CFD), Sand Point (SP), La Push (LP), Quinault Deep (QD), Quinault Mid Shelf (QM), Quinault Inshore (QI), Westport Mid Shelf (WM), Westport Deep (WD), Willapa (WI), Columbia River South (CRS), Newport (NP), Fort Bragg (FB), and Point Reyes (PR). The additional locations were selected based on high use areas identified in the duration of occurrence model for SRKW K25 (Hanson et al. 2017) additional sites within the U.S. Navy's NWTRC W237 that included areas that the tagged SRKWs occurred infrequently in winter (mid-shelf) or not all (base of the continental slope), in order to determine if SRKWs used these areas in other seasons when satellite-linked tags were not deployed.

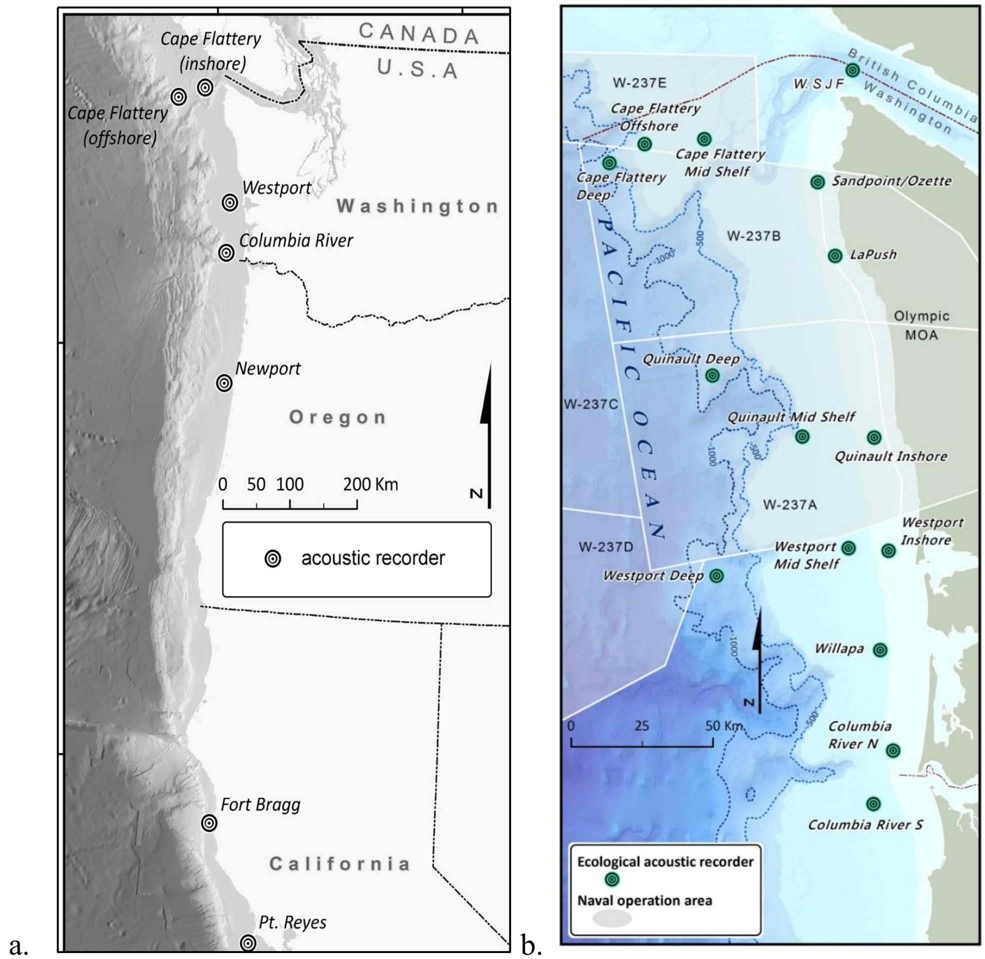

Figure 1. Locations of EARs from (a) before 2014 and (b) expanded sites from 2014- 2017.

Equipment failures, deployment delays, and interactions with local fisheries led to variable recorder effort across years. Between 2014 and 2017 recorder effort by location ranged from 69 to 1149 days. Certain locations, like CFD (n=161) and QM (n=69), were particularly vulnerable to fisheries interactions, limiting effort at these sites, while effort was highest at CR (n=1149) and CFO (n=1021). Details on deployments for each location are detailed in Table 1.

Location	Latitude/ Longitude	Dates of Recording	Sampling Rate (kHz)	Seconds on/off	Total recording time (Days)
Juan de Fuca (JF)	48.49167, -124.7833	Nov 2013- Jul 2014	25	30/600	264
		Oct 2014- Jul 2015	25	60/600	293
		Sep 2015- May 2016	25	90/600	268
Cape Flattery Inshore (CFI)	48.3338, -124.8264	Oct 2008- Feb 2009	25	30/420	145
		Sep 2010- Apr 2011	25	30/600	216
		Oct 2011- Mar 2012	25	30/600	187
		Aug 2012- Nov 2013	25	30/600	99
Cape Flattery Mid Shelf (CFM)	48.2078, -125.3480	Sep 2015- Jun 2016	25	90/600	281
		Feb 2017- Jul 2017	25	90/600	160
Cape Flattery Offshore (CFO)	48.17166, -125.6269	Oct 2008- Mar 2009	25	30/420	154
		Sep 2010- Jul 2011	25	30/600	334
		Oct 2011- Aug 2012	25	30/600	336
		Sep 2012- Sep 2013	25	30/600	371
		Nov 2013- Sep 2014	25	30/600	336
		Oct 2014- Aug 2015	25	60/600	317
		Sep 2015- May 2016	25	90/600	259
		Feb 2017- Jul 2017	25	90/600	176
Cape Flattery Deep (CFD)	48.1000, -125.7833	Feb 2017- Jul 2017	25	90/600	161
Sand Point (SP)	48.1015, -124.7941	Nov 2013- Jul 2014	25	30/600	259
		Oct 2014- Aug 2015	25	60/600	317
La Push (LP)	47.8803, -124.6809	Oct 2014- Jul 2015	25	60/600	297
		Sep 2015- Jul 2016	25	90/600	317
Quinault Deep (QD)	47.4640, -125.1964	Nov 2014- Jul 2015	25	60/600	265
		Mar 2016- Apr 2016	25	90/600	45
		Feb 2017- Jul 2017	25	90/600	159
Quinault Mid Shelf (QM)	47.3000, -124.7500	Feb 2017- Apr 2017	25	90/600	69
Quinault Inshore (QI)	47.3172, -124.4158	Nov 2014- Jul 2015	25	30/600	265
		Sep 2015- Jul 2016	25	90/600	319
		Feb 2017- Jul 2017	25	90/600	160

Westport (WP)	46.9794, -124.4281	Oct 2008- Feb 2009	25	30/420	145
		Nov 2010- Aug 2011	25	30/600	308
		Oct 2011- Aug 2012	25	30/600	328
		Oct 2012- Jun 2013	25	30/600	222
		Oct 2013- Jan 2014	25	30/600	77
		Nov 2014- Nov 2014	25	60/600	15
		Sep 2015- Aug 2016	25	90/600	339
Westport Mid Shelf (WM)	46.9615, -124.4878	Nov 2014- Jul 2015	25	30/600	265
		Jan 2016- Sep 2016	25	90/600	243
		Sep 2016- Jun 2017	25	90/600	276
Westport Deep (WD)	46.8333, -125.0998	Mar 2016- Sep 2016	25	90/600	172
		Sep 2016- Jul 2017	25	90/600	328
Willapa (WI)	46.6515, -124.2608	Nov 2014- Jan 2015	25	60/600	72
		Sep 2016- Apr 2017	25	90/600	230
Columbia River (CR)	46.3388, -124.4170	Mar 2008- Jul 2008	25	30/300	71
		Dec 2008- Apr 2009	25	30/420	150
		Oct 2010- Sep 2011	25	30/600	336
		Oct 2011- Nov 2011	25	30/600	53
		Nov 2012- Nov 2012	25	30/600	10
		Oct 2013- Sep 2014	25	30/600	344
		Nov 2014- Sep 2015	25	60/600	310
		Jan 2016- Sep 2016	25	90/600	244
		Sep 2016- Jul 2017	25	90/600	315
Columbia River South (CRS)	46.1617, -124.2658	Oct 2013- Oct 2014	25	30/600	374
		Nov 2014- Jun 2015	25	60/600	215
Newport (NP)	44.7434, -124.2466	Feb 2011- Jul 2011	25	30/600	155
		Sep 2011- Sep 2012	25	30/600	367
		Sep 2012- Mar 2013	25	30/600	172
Fort Bragg (FB)	39.3482, -123.8843	Feb 2008- May 2008	25	30/300	100
		Dec 2010- Jul 2011	25	30/600	209
		Nov 2011- Sep 2012	25	30/600	321
		Sep 2012- Aug 2013	25	30/600	342
Point Reyes (PR)	37.9175, -123.0723	Dec 2010- Oct 2011	25	30/600	315
		Oct 2011- Sep 2012	25	30/600	324
		Sep 2012- Sep 2013	25	30/600	365

Table 1. Recorder locations and recorder effort.

Data Processing

For each deployment, all 30-90 second recordings were sorted by day (the number of files per day was determined by the duty cycle) and then concatenated and converted into .wav files using a custom script in MATLAB (MathWorks 2014).

Data Analysis

The resulting daily files were reviewed visually and aurally using the software package Triton (Scripps Institute of Oceanography 2014), and the sound sources present in the frequency range monitored were classified manually.

Since 2008, anthropogenic sound sources of interest have been noted on the initial pass through the data. Mid-frequency active sonar events and explosive sounds from 2008-2017 were further reviewed to investigate the level of exposure to SRKW.

Mid-Frequency active sonar (MFA) signals between 1 and 12 kHz were detected (Figure 2). Start and end times of each MFA sonar event were logged. MFA events were variable in duration and therefore binned into three lengths. Transient (T) events were less than 30 minutes long. Medium (M) events were greater than 30 minutes but less than two hours in duration. Long (L) events included all events over two hours in duration. MFA signals that were three hours or more apart were considered separate MFA events.

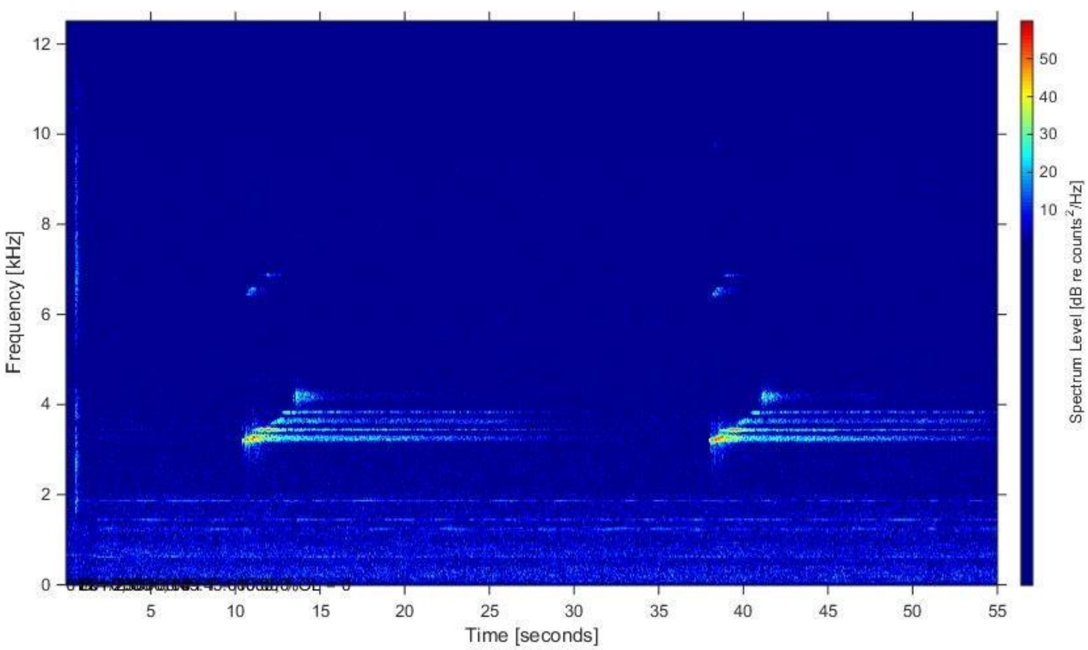

Figure 2. Example of the most frequently detected MFA signal type.

Explosive sounds were consistently identified in the data set beginning in 2011 but not attributed to a source (Figure 3), except in the case of known seismic operations in 2012. Daily occurrence of these sounds was used to look at spatial and temporal patterns. Additionally, the number of explosive sounds per day was logged and binned. In 2017 we added the time of day for these sounds to determine if they occurred more during daytime or nighttime hours.

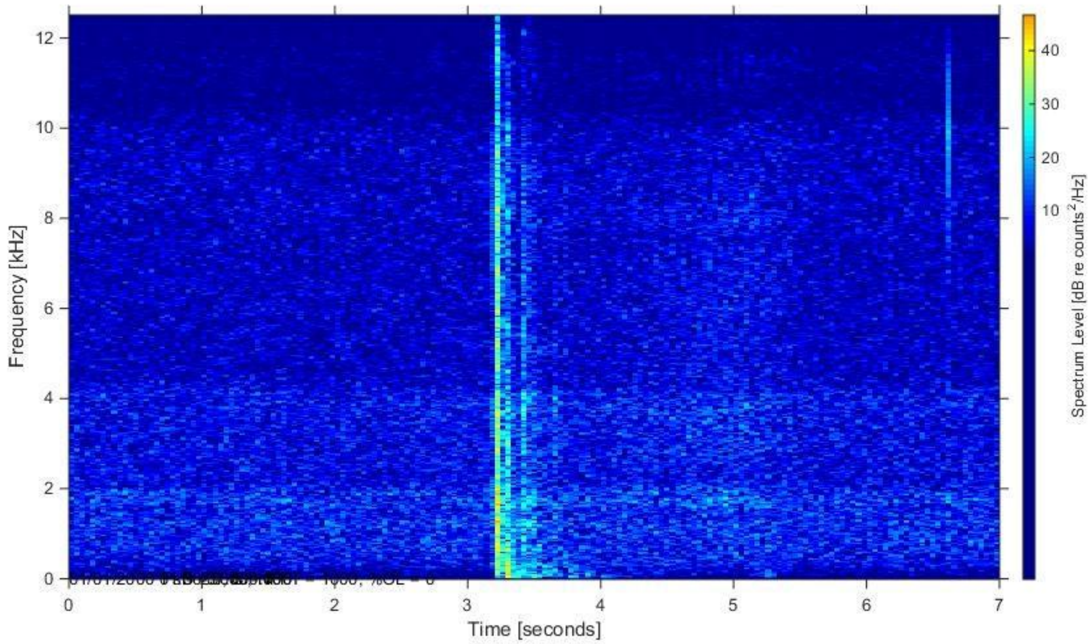

Figure 3. Example of explosive sounds detected.

Biological sounds were compared to previously published descriptions of species-specific call and click types (Table 2). The restricted bandwidth (12.5 kHz) limited which species we were reliably able to detect and identify. Therefore, odontocete sounds above 12.5 kHz and mysticete sounds below 500Hz were not included in this analysis. Those .wav files containing killer whale sounds were further reviewed, and discrete calls were compared to a catalog of pod and community specific dialects to determine the killer whale ecotype, community and pod, if possible (Ford 1987).

For the years 2014-2017, when recorder effort was highest, the daily occurrence of the monitored species was summarized by month for each recorder location. Boxplots were used to represent the number of days per month that each species was detected. Horizontal lines within the boxes indicate the median, box boundaries indicate the 25th (lower boundary) and 75th (upper boundary) percentiles, and vertical lines indicate minimum and maximum values.

Species	Sound type	Description	References
Gray whale	M1 call, M3 call	M1 – series of knocks; dominant sound type in breeding lagoons; comprises about half of the repertoire during migration M3-simply structured low frequency sound; only makes up 7% of repertoire in the breeding lagoons, but increases to over 50% during migration	Dahlheim 1987 Crane and Lashkari 1996
Humpback whale	Social sounds (non-song), song	Social sounds – produced by males and females; “grunts”, “wops” and “moans”; associated with feeding grounds, but also heard during migration and infrequently on breeding grounds Song- produced by males; associated with breeding grounds; complex and structured series of vocalizations	Au et al. 2006 Stimpert et al. 2011
Sperm whale	Usual clicks, slow clicks (rare)	Usual clicks - broadband clicks with an interclick interval of 0.5-1 second; long-range echolocation Slow clicks – broadband clicks with an interclick of greater than 1 second	Jaquet et al. 2001 Weilgard & Whitehead 1988
Killer whale	Pulsed calls, clicks, whistles	Pulsed calls – stereotyped broadband calls; ecotype, community, and pod specific; group cohesion Clicks – short duration, broadband; echolocation Whistles – nonpulsed or continuous tones with average bandwidth of 4.5 kHz; close-range motivational sounds	Ford 1989 Barrett-Lennard et al. 1996 Thomsen et al. 2001 Foote & Nystuen 2008

Table 2. Sound types for species monitored.

Results- Anthropogenic sound sources

MFA

MFA was detected at only 13 of the 19 sites: CFI, CFM, CFO, CFD, JF, QM, QD, WM, WD, CR, NP, PR, and FB. At all sites, MFA events were rare (Figure 4). At nearshore sites these events were detected on less than 1% of days, while they were detected at mid shelf and offshore sites on 3-8% of days.

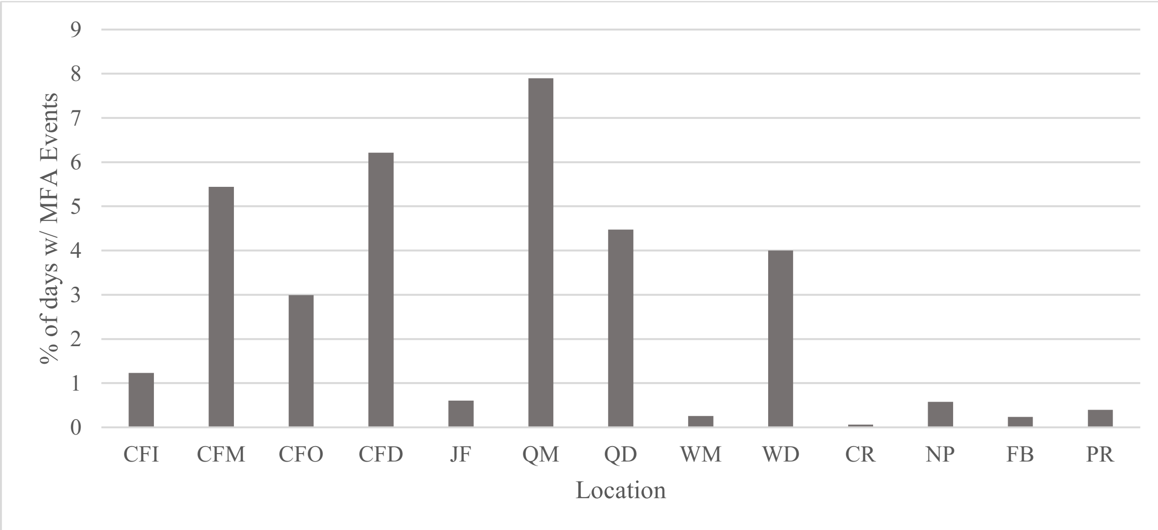

Figure 4. Percent of days monitored with MFA events detected by location.

There were 148 MFA events detected between 2011 and 2017 (this includes events that were heard at multiple sites in 2017). The majority of these events were transient in length (n=64) while there were 49 medium length events and 35 long events (Figure. 5). The most frequently detected MFA signal was 3-4 kHz

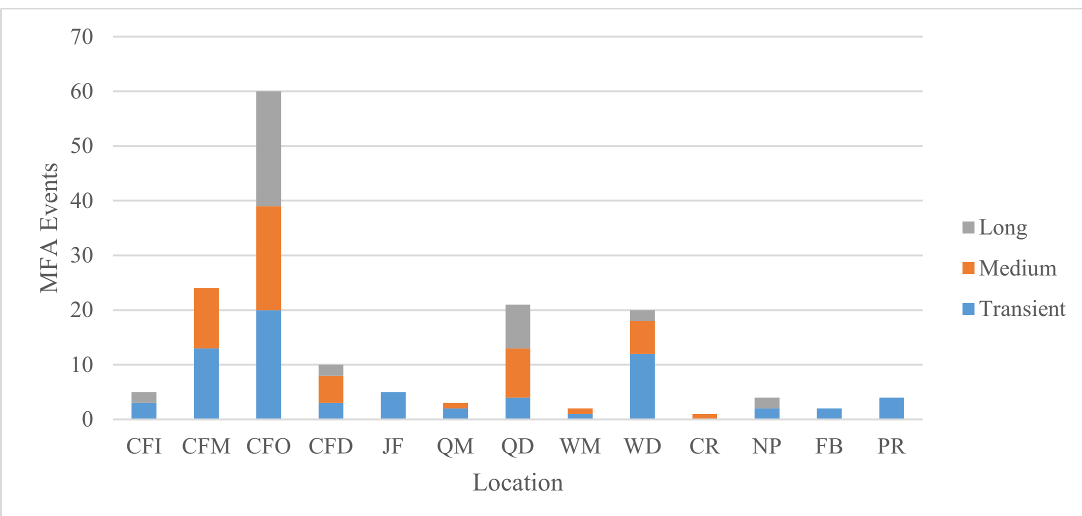

Figure 5. Locations of MFA events by event length.

The number of days that MFA was detected was variable from year to year. The most MFA events were in 2016 and 2017, which may be a result of the additions of the mid shelf and deep recorder locations. It was detected in 2011 (6 days), 2012 (11 days), 2013 (14 days), 2014 (11 days), 2015 (8 days), 2016 (24 days) and 2017 (13 days), with multiple events on some days. In all years except 2017, it was rare to detect MFA on multiple recorders on a given day. In 2017, on eight days, MFA events were heard on 3-6 recorders, which may be in part due to the higher proportion of medium and long events detected (Figure 6a).

Close to half of the MFA events were at CFO (n=60). There were detections at this location in every year monitored (Figure 6), and this is in part due to the consistent monitoring at this location. The number of MFA events detected at CFO did not follow the same pattern of yearly occurrence at all sites.

(a) (b)

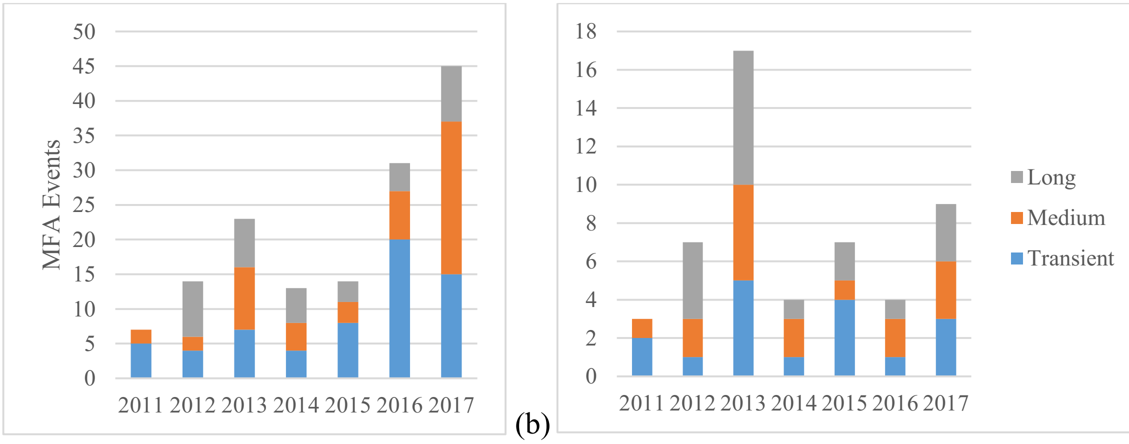

Figure 6. (a) Yearly occurrence of MFA events at all sites and (b) at only CFO

MFA events occurred in every month of the year, with the majority of events occurring between February and May (Figure 7).

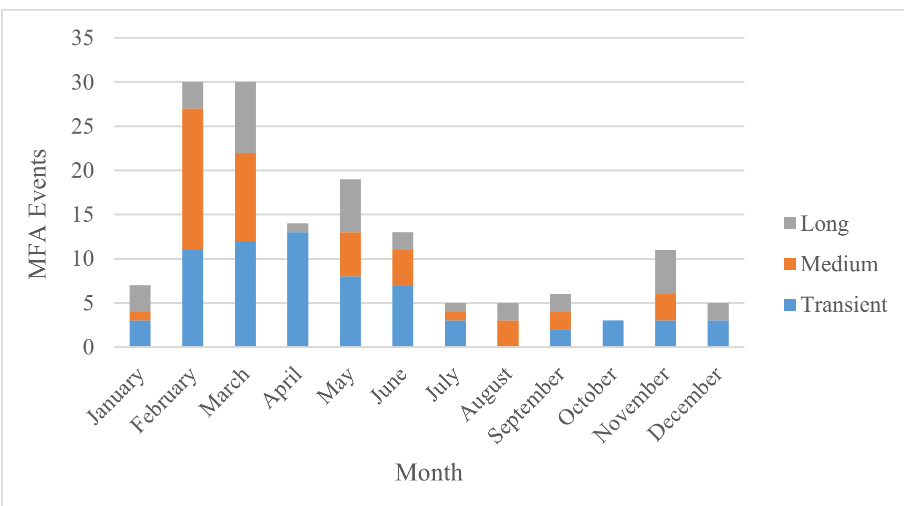

Figure 7. Monthly occurrence of MFA events.

Explosive sounds

Between 2011 and 2017, 3152 explosive sounds were detected on 466 days. The percent of days monitored at each site with explosive sounds ranged from less than 1% to 19% (Figure 8). Half of these days were at CFO (n=231). Less than five explosive sounds were heard on most of these days (Figure 9), but there were eight days at CFO with 100 or more of these sounds.

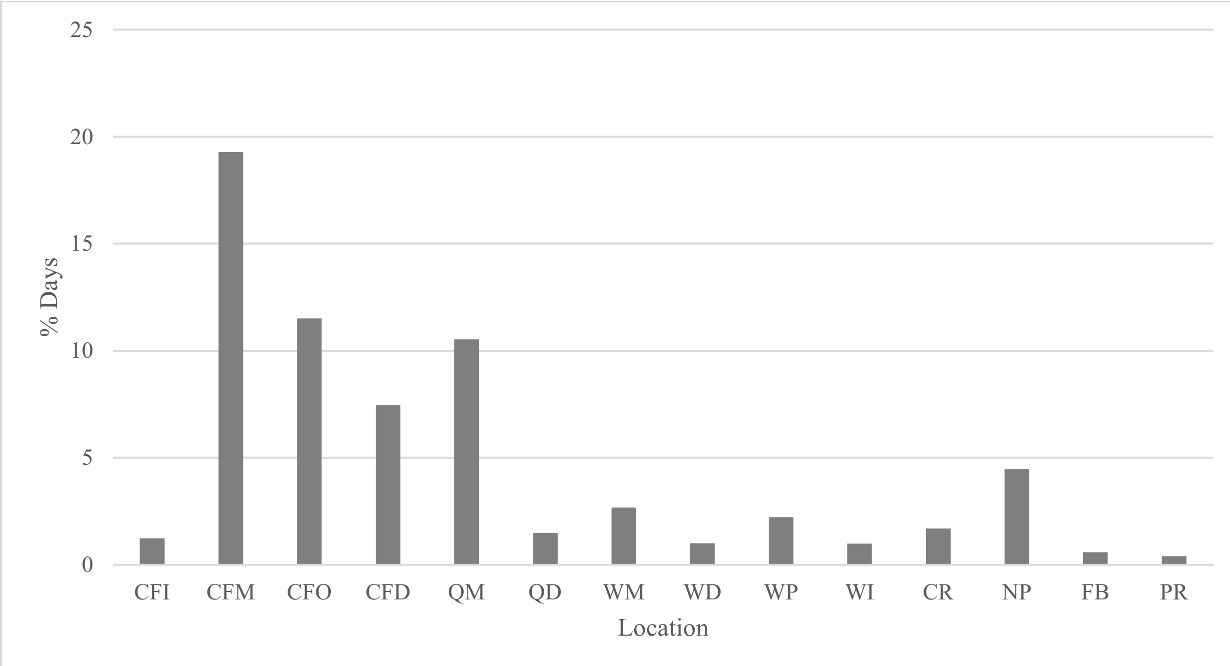

Figure 8. Percent of days monitored with explosive sounds detected by location.

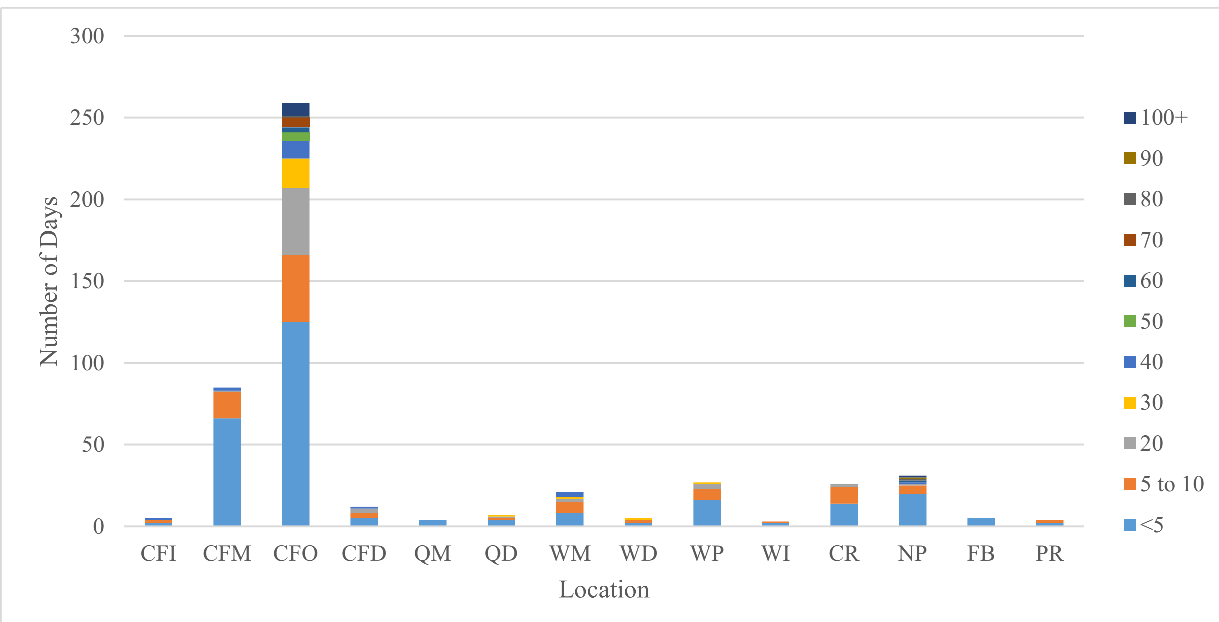

Figure 9. Number of explosive sounds per day by location.

Explosive sounds were detected at 14 of the 19 sites: CFI, CFM, CFO, CFD, QM, QD, WP, WM, WD, CR, CRS, NP, PR, and FB. These sounds were much more commonly heard at the sites north of Westport, than those from Westport south or in California (Figure 10).

Explosive sounds were heard in all months of the year, but seasonal occurrence differed by area. At the northern sites, the most days with explosive sounds were between May and July. At the southern sites, there were fewer days with these sounds than the northern sites for most months of the year with the peak occurrence in July.

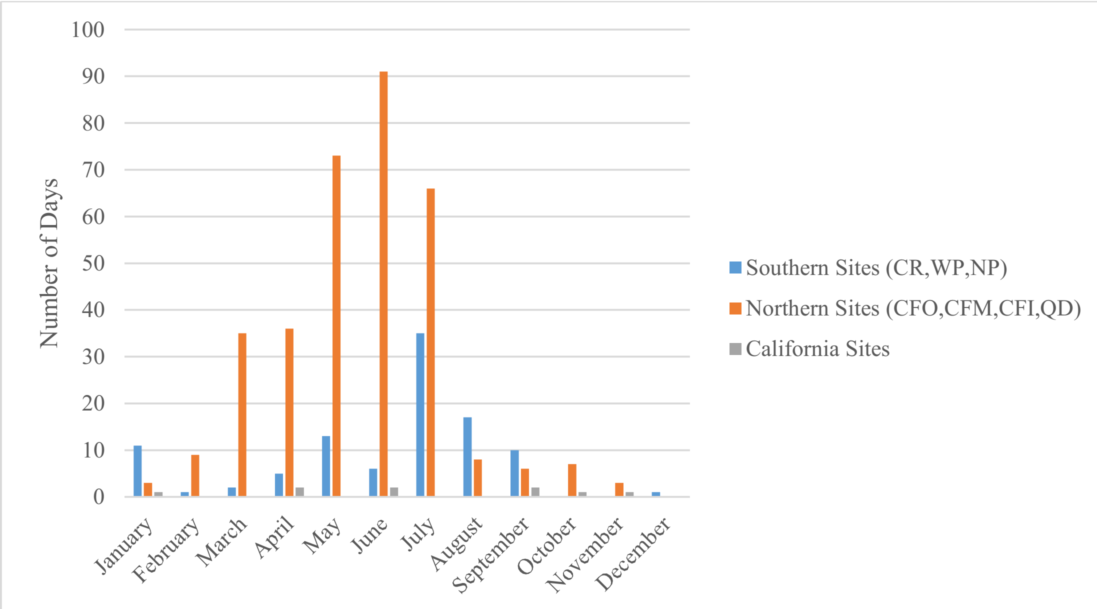

Figure 10. Monthly number of days that explosive sounds were heard.

In 2017 there were 1459 explosive sounds. 69.5% of these were during daytime hours, while 30.5% were during the night. At all locations except WM these sounds were more common during the day (Figure 11). At WM, the number of sounds during the day (n=80) and night (n=75) were nearly equal. As in most years monitored, 70% of the explosive sounds heard in 2017 were at the CFO site. Daytime explosive sounds were more common in all months except in April (Figure 12).

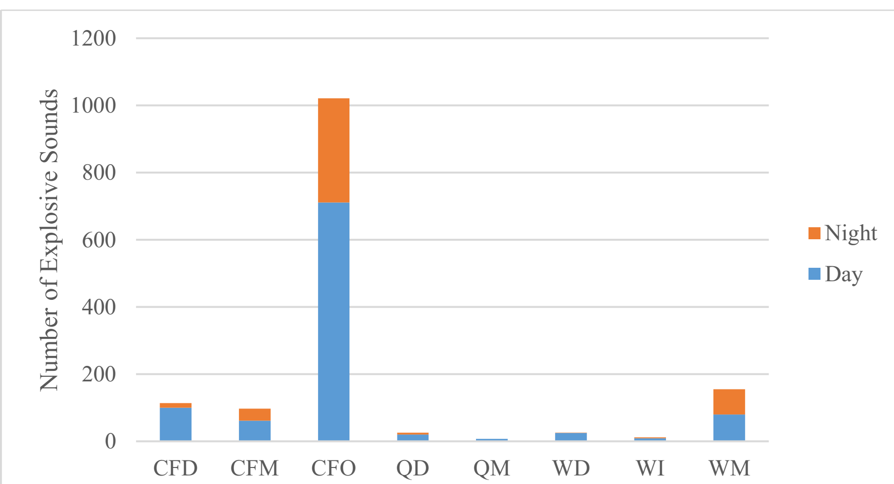

Figure 11. Day versus nighttime number of explosive sounds by location.

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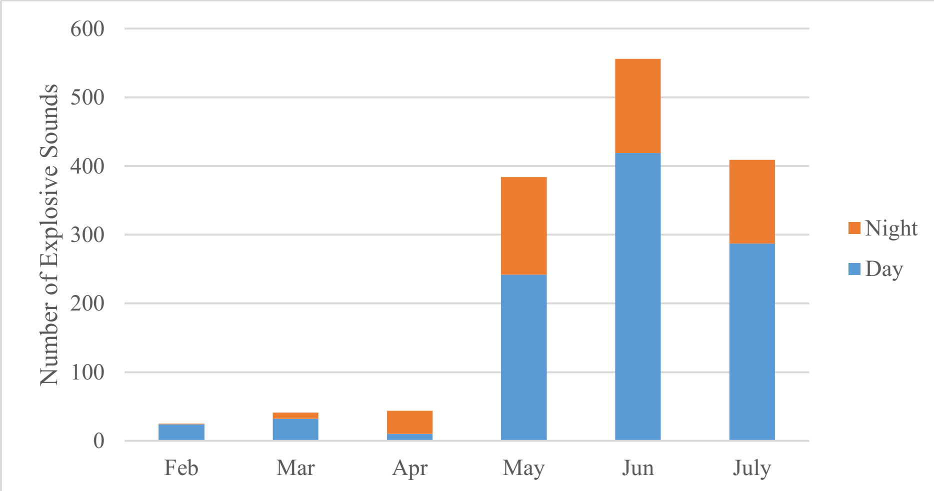


Figure 12. Day versus nighttime number of explosive sounds by month.

Results- Biological sound sources

Humpback whales

Most sites showed a strong migration signal with the highest occurrence in fall and early winter (Figure 13). Two exceptions were LP and CFO. Both these sites had higher occurrence in May, June and July than any other sites. Southern sites had lower occurrence than the more northern sites, but all sites showed quite a bit of annual variability.

Gray whales

Gray whale occurrence was nearly year round at most inshore sites (Figure 14). The mid shelf and deep sites generally had lower occurrence with more year to year variability. A migration signal was not evident at any of the sites. CFD and CRS has the lowest occurrence.

Sperm whales

Sperm whale occurrence was low and variable at most sites (Figure 15). Except for QI, occurrence was higher at offshore and deep sites than the mid shelf and nearshore sites.

Dolphins

Dolphin occurrence was highest at deep sites, followed by the mid-shelf sites, and the lowest occurrence was at the nearshore sites (Figure 16). At the three deep sites, there was a peak in occurrence in month of June. CFO, LP, and WM showed quite a bit of year to year variability.

Killer whales

Killer whale occurrence was low and highly variable, both monthly and annually, at all sites except CFO (Figure 17). At CFO there were peaks in occurrence in March/April and August/September

Figure 13. Number of days humpback whales were detected at each location are on the Y axis. Horizontal lines within the boxes indicate the median, box boundaries indicate the 25th (lower boundary) and 75th (upper boundary) percentiles, and vertical lines indicate minimum and maximum values.

Figure 14. Number of days gray whales were detected at each location are on the Y axis. Horizontal lines within the boxes indicate the median, box boundaries indicate the 25th (lower boundary) and 75th (upper boundary) percentiles, and vertical lines indicate minimum and maximum values.

Figure 15. Number of days sperm whales were detected at each location are on the Y axis. Horizontal lines within the boxes indicate the median, box boundaries indicate the 25th (lower boundary) and 75th (upper boundary) percentiles, and vertical lines indicate minimum and maximum values.

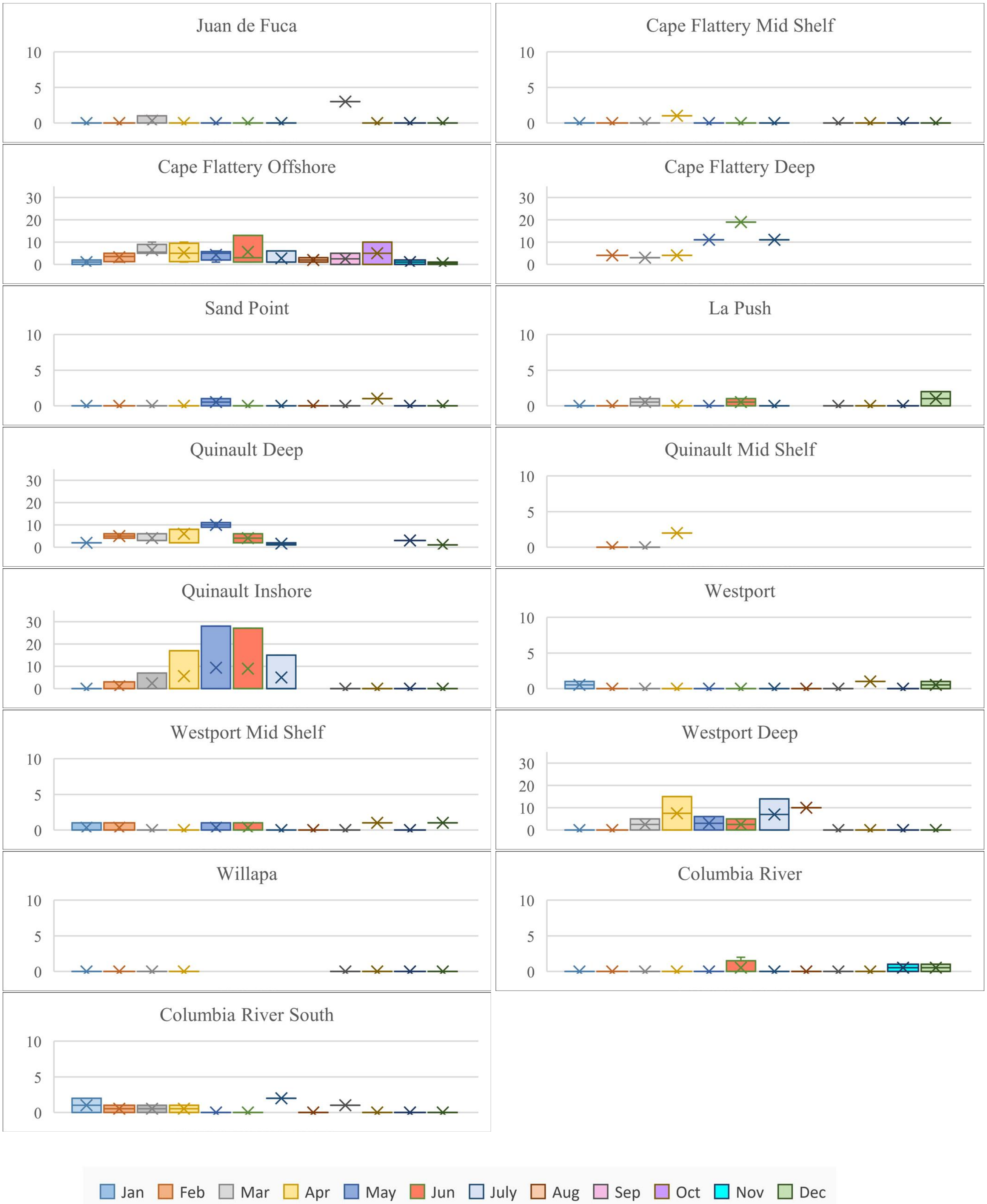


Figure 16. Number of days dolphins were detected at each location are on the Y axis. Horizontal lines within the boxes indicate the median, box boundaries indicate the 25th (lower boundary) and 75th (upper boundary) percentiles, and vertical lines indicate minimum and maximum values.

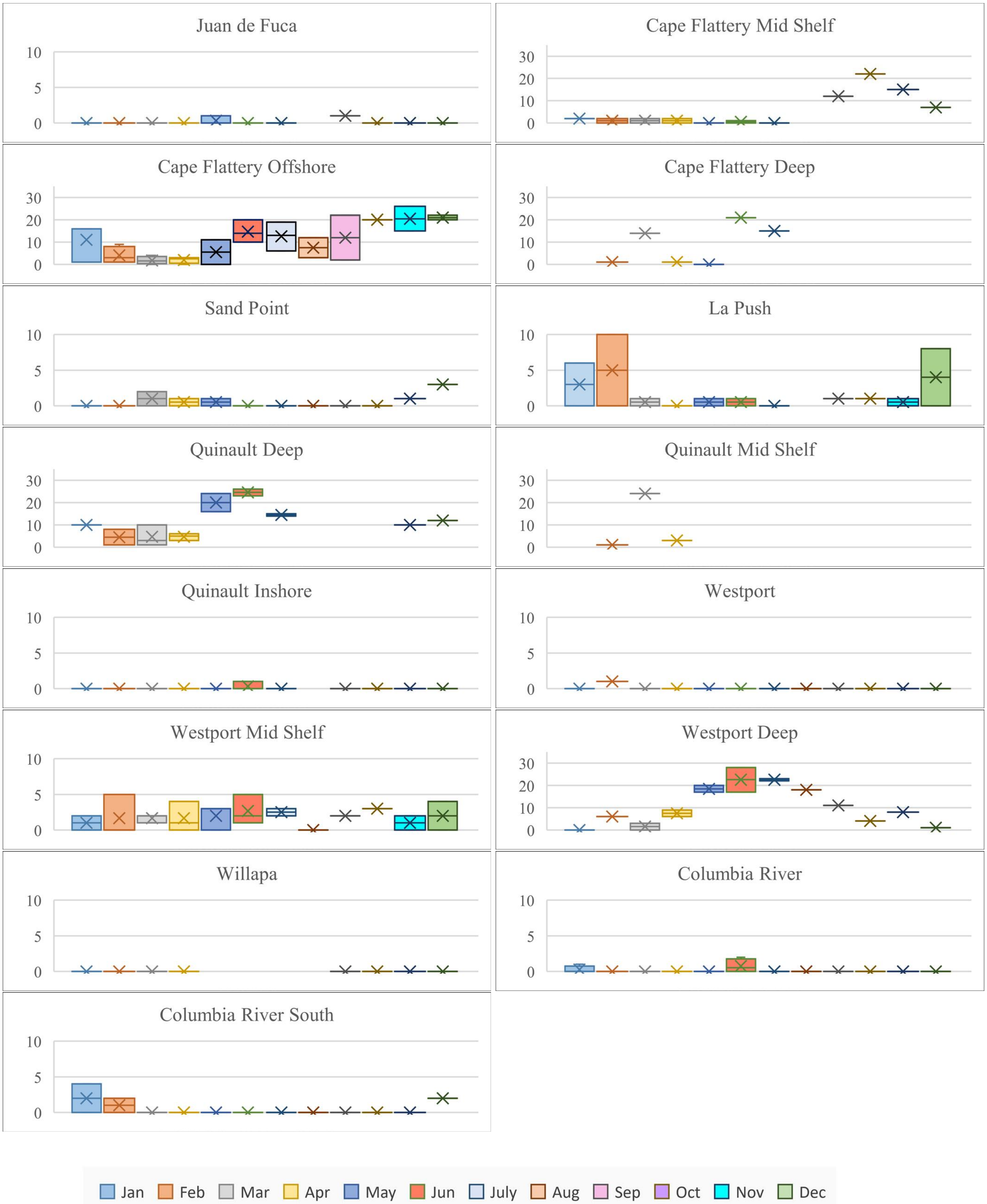
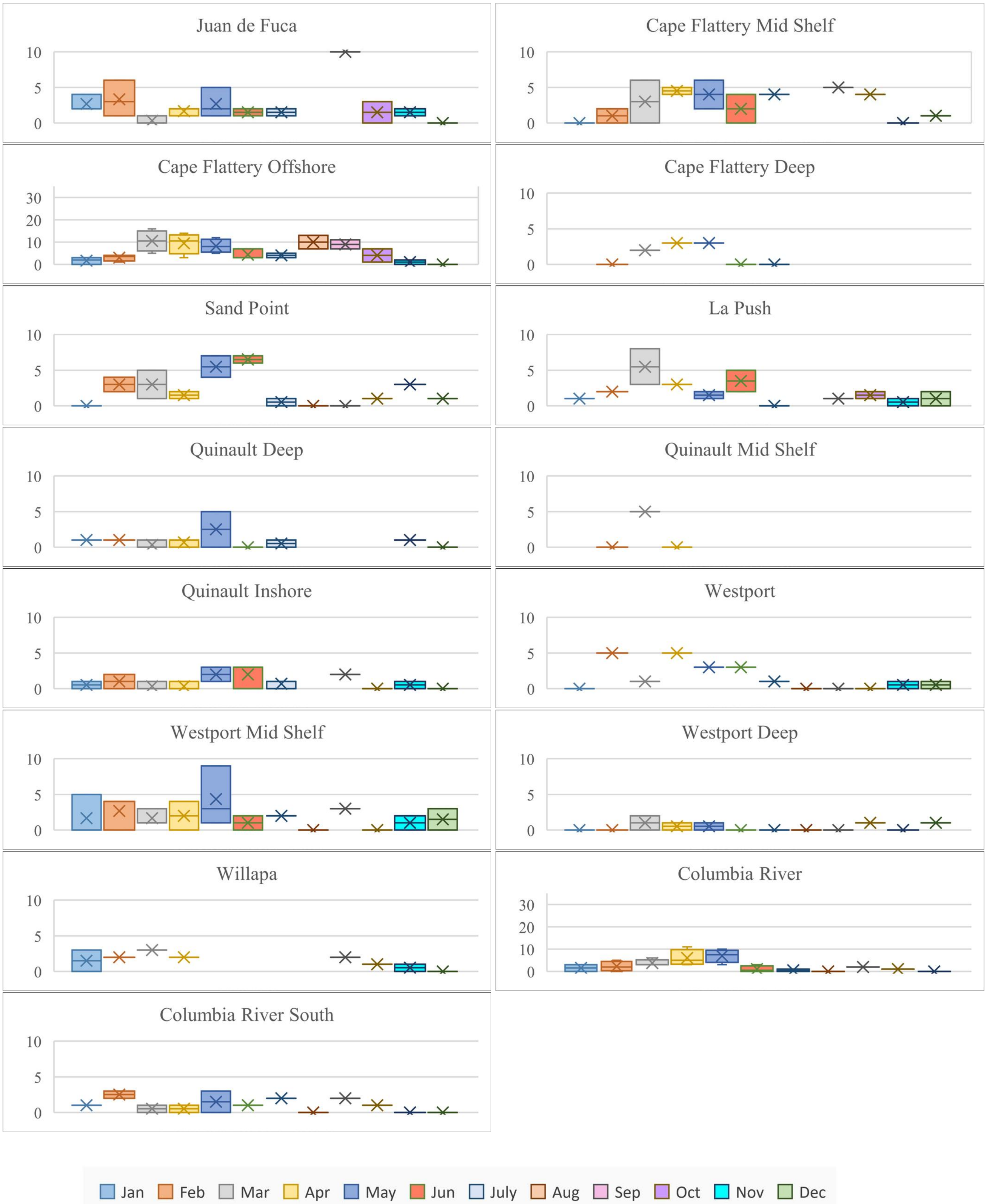
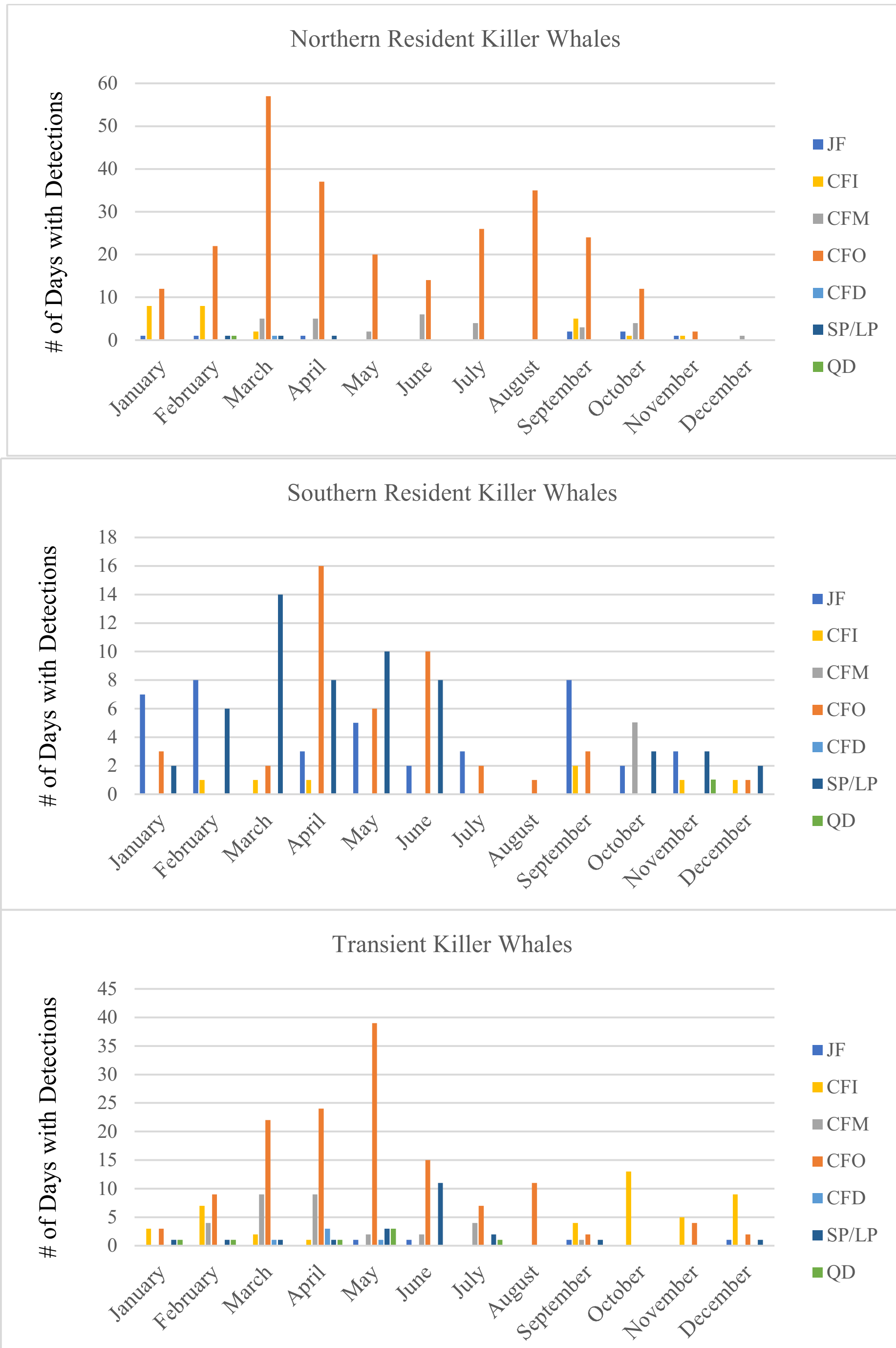


Figure 17. Number of days killer whales were detected at each location are on the Y axis. Horizontal lines within the boxes indicate the median, box boundaries indicate the 25th (lower boundary) and 75th (upper boundary) percentiles, and vertical lines indicate minimum and maximum values.



Since both explosive sounds and MFA were more frequent at the northern sites (CFD, CFO, CFM, CFI, JF, QD, and SP/LP), killer whale occurrence by ecotype (resident and transient) and community (northern and southern residents) was further described (Figure 18).

Figure 18. Counts of detections at each northern recorder site by month from 2014-2017 of Northern residents, Southern residents and transients.



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Northern resident killer whales (NRKW) were the most frequently detected killer whale community at the northern sites. They were detected 329 times between 2014 and 2017, followed by transient killer whales (n=251) and southern resident killer whales (SRKW) (n=154). NRKW were most frequently detected at the CFO site with peaks in occurrence in spring and late summer/early fall. SRKW were most frequently detected at the SP/ LP sites followed closely by JF and CFO. There is a peak in occurrence of SRKW at the northern sites in April. Most detections of SRKW are at nearshore sites except for increased detections at CFO during late spring to early summer (April to June). Transient killer whales were detected at all the northern sites, but most commonly at the CFO site with a peak in occurrence in May.

Discussion

Between 2014 and 2017, recorder deployments varied in success with days monitored by location ranging from 69 days at QM to 1149 days at CR. Recorders were lost most frequently at the mid shelf and deep sites which was likely due to fishery interactions. This loss of recorders illustrates the difficulty in maintaining monitoring in these areas. Despite the limited amount of monitoring at sites like CFD and QM, both MFA and explosive sounds were heard at both sites.

MFA events were rare and most commonly detected at the offshore and deep sites. The highest number of MFA events was at the Cape Flattery offshore site. This may be in part due to the high number of days monitored at this site. When the occurrence of MFA events was corrected for effort, the sites with the highest occurrence were QM, CFM and CFD. But some caution should be used when interpreting these results given the difficulty in maintaining monitoring at these sites. For example, QM was only monitored for 69 days over the study period.

Both NRKW and transient killer whales were most frequently detected at CFO and their peak occurrence overlaps with the peak in MFA detections. The other sites which had higher MFA detections (CFM, CFD, and QM) all had low occurrence of all killer whale types.

The highest occurrence of MFA was during February and March followed by May, and this overlaps with the occurrence of the three killer whale communities monitored. Previous monitoring has shown that during March occurrence of SRKW was highest at the CR and WP (Hanson et al 2013) with movements north along the Washington coast from January to April (Hanson et al 2017).

Explosive sounds were most commonly heard at the Cape Flattery mid shelf and offshore sites. Occurrence of these sounds was low at the other sites. Most days only a few of these sounds were heard and only CFO and NP had days with more than 50 in a day. CFO had the highest occurrence of explosive sounds and the most explosive sounds per day. This location also has the highest year round occurrence of both killer whales and humpback whales.

Explosive sounds peaked in the summer months when both NRKW and SRKW are well studied in their summer core habitats in the inland waters of Washington State and British Columbia (Hauser et al 2007; Olson et at 2018). Despite this high occurrence in inland waters, all three killer whale communities were detected on the outer coast in each summer month. However, in recent years, the occurrence of SRKW in inland waters has been more variable and lower than in the past (Olson et al 2018; Shields et al 2018).

For the species monitored the monthly occurrence varied between years. Previous studies have shown that the number of acoustic detections of SRKW varies substantially between years (Hanson et al 2013; Hanson et al 2017). Some of the variability between years may be explained by warm water anomaly off Washington coast that formed in 2013 and persisted through the end of 2015 (Peterson et al 2015; Cavole et al 2016). Despite this variability some clear patterns of occurrence resulted from multiple years of acoustic monitoring from a network of recorders. For example, gray whales and humpback whales differ in their occurrence along the Washington coast. Gray whales occur year round at most nearshore sites, while humpback whale occurrence shows a strong migration signal at most sites except Cape Flattery offshore.

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