Assessing the coastal occurrence of endangered killer whales using autonomous passive acoustic recorders

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Using moored autonomous acoustic recorders to detect and record the vocalizations of social odonotocetes to determine their occurrence patterns is a non-invasive tool in the study of these species in remote locations. Acoustic recorders were deployed in seven locations on the continental shelf of the U.S. west coast from Cape Flattery, WA to Pt. Reyes, CA to detect and record endangered southern resident killer whales between January and June of 2006–2011. Detection rates of these whales were greater in 2009 and 2011 than in 2006–2008, were most common in the month of March, and occurred with the greatest frequency off the Columbia River and Westport, which was likely related to the presence of their most commonly consumed prey, Chinook salmon. The observed patterns of annual and monthly killer whale occurrence may be related to run strength and run timing, respectively, for spring Chinook returning to the Columbia River, the largest run in this region at this time of year. Acoustic recorders provided a unique, long-term, dataset that will be important to inform future consideration of Critical Habitat designation for this U.S. Endangered Species Act listed species. [http://dx.doi.org/10.1121/1.4821206]

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I. INTRODUCTION

Determining cetacean seasonal occurrence patterns (i.e., temporal and spatial locations) is important for a number of aspects of these species' ecology. There are several potential approaches to obtain this type of information (e.g., systematic and opportunistic surveys, satellite tagging) some of which are useful for obtaining information on these species distributions in remote regions, seasons of inclement weather, or nighttime. However, social odontocetes, and in particular fish-eating killer whales, offer a unique opportunity for non-invasive monitoring by virtue of their routine production of various sounds, some of which are within human hearing range, allowing easy detection and recording via passive acoustic monitoring. Killer whale vocalizations have been described as discrete, variable, and aberrant (Ford, 1989) and in North Pacific Ocean there are three killer whale eco-types ("residents," "transients," "offshores"), each of which produces unique stereotypic calls (Ford, 1987) that generally allow identification to eco-type, or community within the eco-type. Each resident killer whale pod has a pod-specific dialect that is made up of 7–17 discrete calls and is stable over time, (Ford, 1987, 1991) and in the case of endangered southern resident killer whales (SRKW) call signatures can be used to identify each of the three pods within this community (J, K, L) (Hoelzel and Osborne, 1986; Ford, 1987, 1991).

SRKW have been well-studied in their summer range, the protected inland waters of Washington State and southern British Columbia, over the past 35 years because of their consistent occurrence there during the months of July through September (Hauser *et al.*, 2007). As required under the U.S. Endangered Species Act (ESA), the National Marine Fisheries Service (NMFS) considered this data and designated Critical Habitat for endangered SRKW in inland waters of Washington State in 2006 (NMFS, 2008). However, on average the whales occur in inland waters less than half of the days each year, with only limited information being available on their distribution outside this area, particularly during the winter and spring (Krahn *et al.*, 2002, 2004). Although, thousands of sightings of SRKWs have been logged in inland waters since the mid-1970s, only a few dozen confirmed sightings have been obtained in outer coastal areas. Although limited in number, these sightings have documented an extensive range; from Monterey Bay, CA (Black *et al.*, 2001) to southern southeast Alaska (Hilborn *et al.*, 2012). As identified in the Recovery Plan for this ESA listed species, more information on the whale's distribution in the coastal waters of the U.S. is needed (Krahn *et al.*, 2002, 2004; NMFS, 2008). These data will inform management and recovery and are also needed to inform future consideration of the designation of Critical Habitat in other parts of the SRKW's range (NMFS, 2008). In order to

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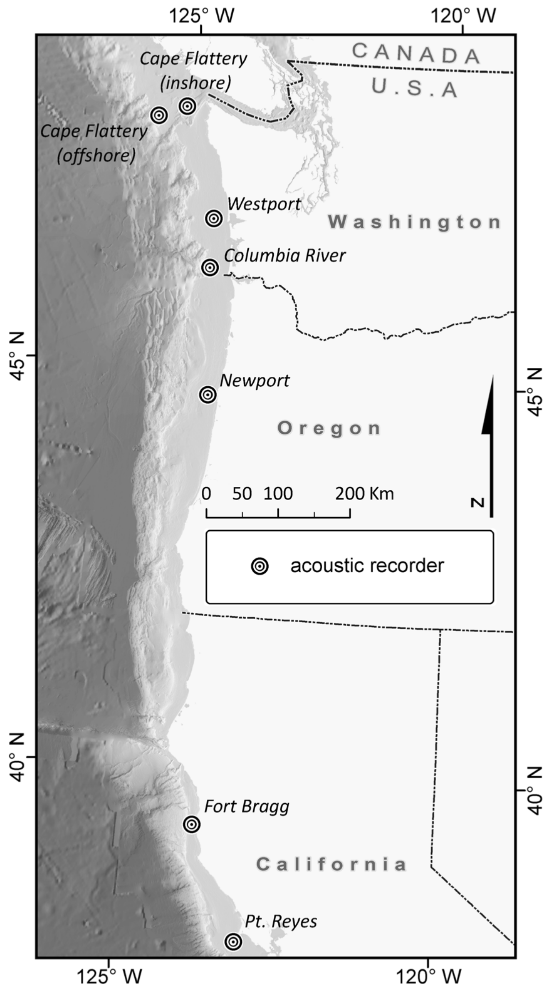

FIG. 1. Deployment locations of acoustic recorders on the U.S. west coast from 2006 to 2011.

start addressing this data gap, the winter and spring distribution (January–June) of SRKW was assessed by deploying passive acoustic recorders on the U.S. west coast at seven sites from Cape Flattery, WA to Pt. Reyes, CA during 2006–2011.

II. METHODS

A. Study area

Autonomous passive acoustic recorders were deployed along the U.S. west coast for the purpose of detecting and recording killer whale vocal sounds, including community or population-specific pulsed calls (Ford, 1987, 1989). Each recorder, mounted in a protective metal cage, was part of a subsurface mooring that also included an acoustic release connected to an anchor, and a float assembly located above it in order to position the recorder approximately mid-water column, about 30–60 m below the surface. Moorings were deployed on the continental shelf in depths of 60–175 m. The selection of moored acoustic recorder locations was predicated on various factors which included: (1) sites that southern resident killer whales had been previously sighted, (2) sites where enhanced productivity would likely be concentrated due to bathymetric features, i.e., canyons heads (Denman and Powell, 1984; Mackas *et al.*, 1997; Allen *et al.*, 2001), and (3) accessibility for mooring deployment and recovery. Optimal deployment locations were adjusted to reduce the likelihood of interactions with local fisheries. Deployment locations are shown in Fig. 1 and deployments dates are listed in Table I.

B. Data collection

Two types of autonomous passive acoustic recorders were used to collect acoustic data during this project, passive aquatic listeners (PALs), and ecological acoustic recorders (EARs). A general overview of the units and the settings used in this study is provided below. Additional details and specifications can be found in Foote and Nystuen (2008) or Miksis-Olds *et al.* (2010), for the PALs or Lammers *et al.* (2008), for the EARs.

1. Passive aquatic listeners

Passive aquatic listeners (PALs) were originally developed to monitor the underwater sound environment, particularly sound-producing physical processes including wind

TABLE I. Deployment dates and durations (days) for acoustic recorders at up to seven locations along the U.S. west coast from January to June, 2006–2011.

	Year				
Location	2006	2007	2008	2009	2011
Cape Flattery Inshore	23 Jan.–30 June (159)PAL	24 Jan.–30 June (158)PAL		1 Jan.–23 Feb. (54)EAR	1 Jan.–4 April (94)EAR
Cape Flattery Offshore	23 Jan.–30 June (159)PAL	24 Jan.–30 June (158)PAL	17 Jan.–30 June (166)PAL	1 Jan.–4 Mar. (63)EAR	1 Jan.–30 June (181)EAR
Westport	24 Jan.–30 June (158)PAL	27 Jan.–30 June (155)PAL	1 Jan.–30 June (169)PAL	1 January–23 March (23)EAR	1 Jan.–30 June (181)EAR
Columbia River			19 Mar.–30 June (104)EAR	1 January–1 May (121)EAR	1 Jan.–30 June (181)EAR
Newport, OR				7 April–30 June (84)EAR	1 Jan.–30 June (133)EAR
Fort Bragg			4 Feb.–7 May (101)EAR		1 Jan.–30 June (181)EAR
Pt. Reyes					1 Jan.–30 June (181)EAR
Total days	476	471	540	345	1132

Instrument deployed:
PAL–passive acoustic listener.
EAR–ecological acoustic recorder.

and rainfall (Ma and Nystuen, 2005). For this project, the sampling strategy was adapted to detect stereotypic calls and clicks from killer whales.

PALs are comprised of a low-noise wideband hydrophone, signal pre-amplifiers, and a recording computer powered by internal batteries. The nominal sensitivity of these instruments is −160 dB relative to 1 V/Pa. PALs are autonomous and depend on internal batteries for operation.

The PAL was designed to be an event recorder rather than a continuous acoustic sampler in order to allow the instrument to record data for up to one year with a broadband frequency response from 200 Hz to 50 kHz (Nystuen, 1998). To achieve this duration, the PAL uses a low power "sleep mode" between each data sample. The time interval between data collection sequences is variable depending on the acoustic source detected and the mission requirements. For these deployments, the default sampling interval was 5 min, changing to 2 min when a potential whale call was detected. These sampling intervals were chosen so that if a group of whales stayed in the vicinity of the PAL for an extended period, e.g., 30 min, there would be a high enough number of samples, e.g., 10–15 samples, when the whales might be vocalizing so that detection would be likely to occur (Miksis-Olds *et al.*, 2010). Multiple positive samples during an encounter increased confidence of the identity of the group of whales detected.

A data collection sequence consisted of a 4.5-s time series at a sampling rate of 100 kHz. When the PAL was used in prior studies for environmental monitoring, i.e., recording rain and wind events, the 4.5 s time series for each data collection sequence was discarded because these "sound bite" files are relatively large, about 1 Mb each. Therefore, only a limited number of sound bites (2200) could be stored on a PALs 2GB memory card during a given deployment. Although this represents only about 150 min of actual recordings, by limiting the records to sounds of interest, it has the advantage of greatly reducing the amount of data that has to be reviewed.

A daily rationing algorithm (quota) was used to insure that sound bites were recorded throughout the duration of the deployment, but this meant that on days of high activity, no sound bites were recorded in the later part of the day. Consequently, there was a bias to recording sound bites early in the day. Although spectral levels (which allowed for detection of killer whale clicks) were recorded throughout each day, regardless of the quota on sound bites, these click detections only allowed for the documentation of the presence of killer whales, not the identification to ecotype or pod and as such were not included in the analysis.

For this study, a modification to the operating software was developed to store only those 4.5 s time series that included "transient" sounds that might be killer whale calls. In order to limit records to killer whale calls, a decision algorithm was designed to identify and store sound bites that met specific requirements. The objective was to collect the maximum number of calls in order to be able to later classify these calls to specific ecotypes or, in the case of SRKWs, each pod. A typical killer whale stereotypic call lasts less than 4 s (Ford, 1987). In order to determine if a 4.5 s time series contained a killer whale call, eight subsamples were taken of it, generating 1024 pt or 10.24 ms short time series. Each of these sub-samples was fast Fourier transformed (FFT) to obtain a 512-point (0–50 kHz) power spectrum which was then spectrally compressed to 64 frequency bins, with a frequency resolution of 200 Hz from 100–3000 Hz and 1 kHz from 3–50 kHz. If each of the sub-samples was within 12 dB of the mean spectrum and within the 1–12 kHz frequency band, then the sound source present was assumed to be quasi-stationary: i.e., wind, rain, drizzle, continuous ship noise, etc., and not a whale. Alternatively, if one or more of the spectra were different from one another, then a "transient" sound is assumed to be detected. Although these "transient" sounds are likely to be killer whales, there are some sounds associated with shipping, or other biological sources may also meet the "transient" sound detection criteria. Killer whale communication whistles have a dominant frequency band of 6–12 kHz (Richardson *et al.*, 1995). To eliminate false positives outside of this frequency range a recording protocol was applied such only "transient" sound bites detected in this frequency band were recorded. Human reviewers were the ultimate filter for the sound source, and were able to easily identify most of the sound bites, especially when several samples were available during a particular encounter.

2. Ecological acoustic recorder (EAR)

The EAR is comprised of four principal components: (1) the environmental interface module (hydrophone and water/pressure proof case), (2) the signal conditioning module including the analog-to-digital device, (3) the central processing and storage unit, and (4) the power supply. The frequency response of the EAR hydrophone is 1 Hz 28 kHz and its sensitivity is −193.5 dB that is flat (+/−1.5 dB) from 1 Hz to 28 kHz. Additional details on the specifications of the EAR are provided in Lammers *et al.* (2008).

An EAR can be programmed to record the full acoustic waveform on a duty cycle or as an event recorder. In this study EARs were used on a duty cycle. The sampling rate used on all deployments, 25 kHz, which provided 12.5 kHz of bandwidth, was chosen as a tradeoff for preserving hard drive space and battery life while providing enough information to identify killer whales. The recording duty cycle and duration used for a deployment was chosen based on several factors. These included the likelihood of capturing the signals of interest, the length of the deployment, the number of recordings that can be stored on the hard disk drive, and the expected power consumption. In the initial deployment of EARs in 2007, the recorders were set at a 10% duty cycle, recording 30 s of continuous sound every 300 s. Four battery packs were used in 2007 and 2008 and six packs were used thereafter. Based on the relatively long length of southern resident killer whale detection episodes documented in the first year, it was felt that the duty cycle could be decreased without decreasing the probability of detecting killer whale calls such that in 2008 the sleep mode was increased to 420 s and then to 600 s thereafter. The combination of a lower duty cycle and larger battery packs in 2011 allowed for a year-long service life.

C. Data analysis

For the PALs, all of the recorded 4.5 s sound bites were reviewed visually and aurally using Matlab and the likely sound source was identified. For the EARS, all 30 s recordings were concatenated and converted into wave files and sorted by day (the number of files per day was determined by the duty cycle), and the sounds sources present were identified. Those sound bites and wave 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 all SRKW detections (at least one stereotypic call or calls distinguishable to community or pod on a given day), each detection was classified as: specific pod (e.g., J pod) pod aggregations (e.g., J and K pods), SRKWs, probable SRKWs, and possible SRKWs. Only specific pod, pod aggregations, SRKWs, and probable SRKWs were included in this analysis.

D. Statistical analysis

We first summarized observed and expected detections by month and location. In order to account for unequal sampling between months we estimated the expected number of monthly detections by multiplying the total number of detections for a given month in the study by the proportional contribution of days monitored in a given month (total number of days for a given month divided by total number of days monitored in the study). Similarly, expected number of detections by location were calculated by multiplying the total number of detections for a given location during the study by the proportional contribution of days monitored in a given location (total number of days monitored for a given location divided by the total number of days monitored in the study). Second, we used statistical models with model selection tools to evaluate the data support for differences in detection between locations, months, and years. SRKW detection was modeled as a binary response (presence/absence), using the "glm" function in R, with a logistic link (Hosmer and Lemeshow, 2000). Only detections from the four sites that were sampled for the entire time period were included in this analysis (Cape Flattery Inshore, Cape Flattery Offshore, Westport, and Columbia River). Location ($n = 4$), year ($n = 5$) as factor variables, and month as a factor, linear, or quadratic predictor were considered for inclusion. Akaike's information criteria (AIC) was used to evaluate the data for support of different combinations of these variables, as well as their interactions, and a null model with no covariates (Burnham and Anderson, 2002). Using the estimated coefficients from the best model, Wald tests were conducted (Draper and Smith, 1998) to examine which levels of factor variables were significantly different from each other.

III. RESULTS

A. Acoustic recorder effort

1. Annual

Acoustic data were obtained from three to seven recorders deployed off the Washington, Oregon, and California coast each year (except 2010) from 2006–2011. Although data were collected throughout almost every year, the focus of this study was from January to June, resulting in a total of 2964 days monitored (Table I). Over a third of the data were collected in one year, 2011 ($n = 1132$ days) when data from all seven of recorders that had been deployed were recovered. All previous years had fewer days of monitoring (range 345–540) due to fewer instruments being deployed, delays in deployment schedules, mooring failures, instrument service life limitations, or fishing gear interactions (Fig. 2).

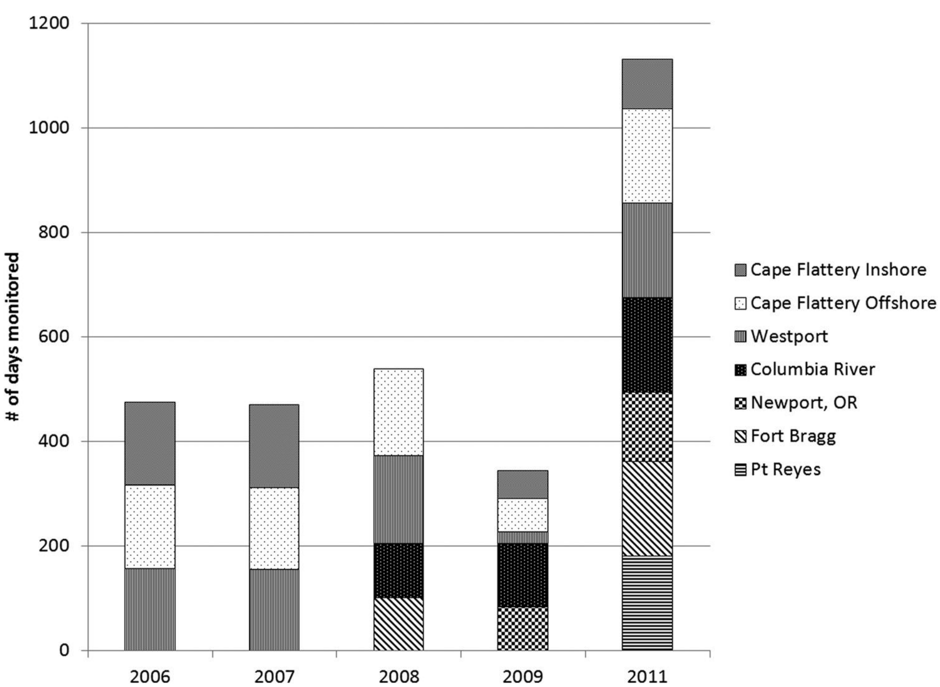

FIG. 2. Annual acoustic recorder sampling effort by U.S. west coast deployment location.

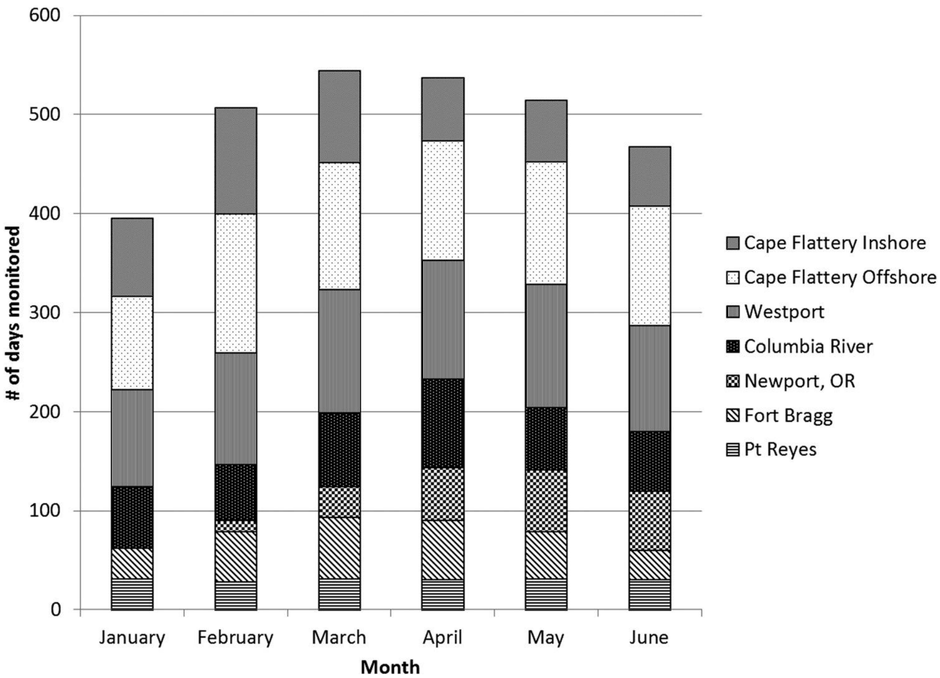

FIG. 3. Monthly acoustic recorder sampling effort by U.S. west coast deployment location.

2. Monthly

Of the 181 days between 1 January and 30 June in most years (182 in 2008 for leap year), January generally had the fewest days monitored of all the months during this six month period (0.57 of total days compared with 0.71–0.83 for other months (Fig. 3). The variability in monitoring effort was due to the reasons noted previously.

3. Location

Most of the recorder data were collected off the coast of Washington because three of the moorings were located there and an attempt had been made to monitor all these sites since the beginning of the study (Fig. 2). Data were collected during five different years at Cape Flattery Offshore (CFO), four years at Cape Flattery Inshore (CFI) and Westport, three years near the Columbia River, two years off Newport and Ft. Bragg, and one year near Pt. Reyes. The most days monitored were at CFO ($n = 727$) followed by Westport ($n = 686$), CFI ($n = 465$), Columbia River ($n = 406$), Ft. Bragg ($n = 282$), Newport ($n = 217$), and Pt. Reyes ($n = 181$).

B. Southern resident killer whale detections

SRKWs were detected on 131 days between January and June of 2006–2011, and were detected at least once on each recorder in all years except at Ft. Bragg in 2008 (Table II). In the logistic regression model to examine effects of year, month and location on detection, all three of these predictor variables were statistically significant (p-values for year = 0.00013, month = 0.00002, location = 0.01) for the four locations in Washington included in the analyses (Table III). A lack of interactions between the three predictor variables were supported in the best model (lowest AIC score), though all three variables were supported as being included (month as a quadratic predictor). The lack of interactions between month and year, or location and year or month suggests that with the existing dataset, there is currently no support for seasonal shifts in presence/absence across years, or differential use in habitat over the years sampled. In other

TABLE II. Total southern resident killer whale detections by location and month.

	SRKW detections						
Location	January	February	March	April	May	June	Total no. of detections
Cape Flattery inshore	6 (6)	10 (9)	6 (5)	1	0	1	24 (20)
Cape Flattery Offshore	5 (1)	2(1)	2	5(2)	4	7 (1)	25 (5)
Westport	5	3	13	6	7	3	37
Columbia River	6	6	8	11	7	0	38
Newport, OR		1	0	0	2	0	3
Fort Bragg	0	1	0	0	0	0	1
Pt Reyes	0	3	0	0	0	0	3
Total no. detections	22 (7)	26 (10)	29 (5)	23 (2)	20	11 (1)	**131**

(No. of detections assignable to J pod)

TABLE III. Estimated logistic regression coefficients of factor variables (location, year, month) from the best GLM model for comparing detections (presence/absence) of SRKW calls on acoustic recorders.

	Estimate	SE	Z score
Cape Flattery Inshore	−6.31	0.67	<0.0001***
Cape Flattery Offshore	−5.57	0.63	<0.0001***
Columbia	−5.02	0.68	<0.0001***
Westport	−5.12	0.61	<0.0001***
2007	−0.35	0.50	0.49
2008	0.33	0.42	0.44
2009	1.43	0.46	0.001***
2011	1.17	0.37	0.001***
Month	1.15	0.28	<0.0001***
Month^2	−0.16	0.036	<0.0001***

*** Significant at $p < 0.05$.

words, there is no support for seasonal or spatial shifts over the four years in our study.

1. Annual

The annual number of days with SRKW detections ranged from a high of 57 in 2011 to a low of eight detections in 2007, with 2009, 2006, and 2008 yielding 33, 17, and 16, detections, respectively. In 2011, the year with the greatest monitoring effort (181 days at each station except CFI), we detected SRKW on 57 days, which represents approximately one third of the days of this period. Repeated detections within a day at the same recorder did not occur during the study although episodes of calls ranged widely in duration. After weighting for the variation in effort among years, detection rates per month of recorder effort were higher in 2009 (2.9) and 2011 (1.5) than in 2006–2008 (1.1, 0.5, 0.9, respectively) (Fig. 4). The model indicated that detections (presence/absence) were significantly higher in 2009 and 2011 than 2006–2008, which were not statistically different from each other. It is important to note that this difference may have been due to a difference in detections by the different recorder types because the highest detection rates were made in 2009 and 2011 (all units were EARS), while 2008 was a mix of EARs and PALs, and 2006 and 2007 were all PALs.

2. Monthly

Of the six months that were monitored (January–June), detections ranged from a high of 29 days in March to a low of 11 days in June with monthly effort corrected detection rates of 1.7, 1.4, 1.7, 1.3, 1.2, 0.7 detections/month for January through June, respectively. A comparison with expected values, based on differential effort between months, showed that January–March had higher than expected numbers of detections whereas from April to June there was a declining trend in the expected number of detections (Fig. 5). In the statistical detection (presence/absence) model, there was support for intra-annual trends, with a concave effect of month predicting the highest detection rate in mid-March. For example, the predicted 2006 detection rates

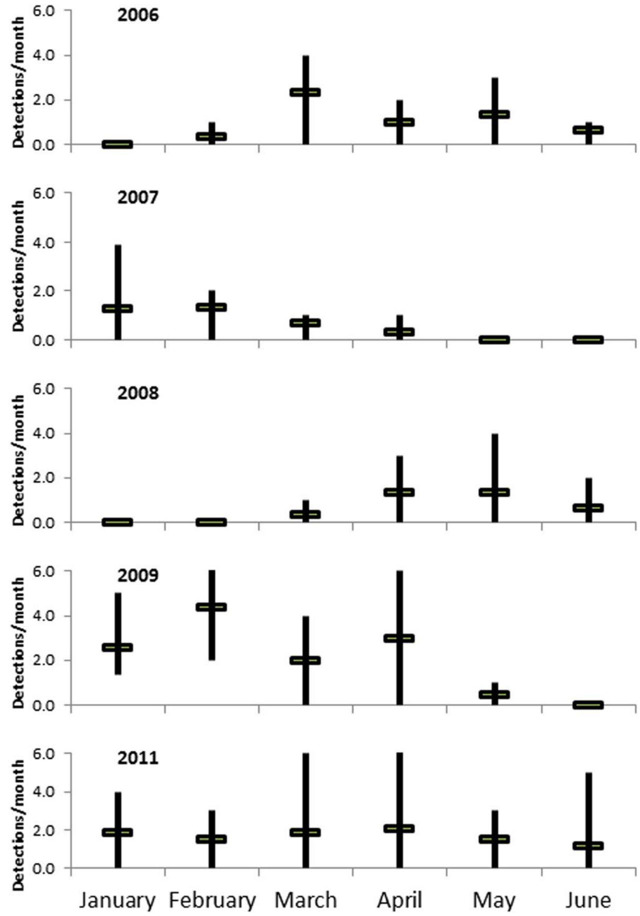

FIG. 4. (Color online) Mean number of SRKW detections/month (horizontal bar) and range in number of detections (vertical bar) by year at all recorder locations.

at the Cape Flattery Offshore recorder were approximately 2.5 times as high in March as in June.

3. Location

The number of detections per location ranged from 38 days on the recorder located near the Columbia River to only one day on Ft. Bragg (Table II). Surprisingly, despite some of the recorders being within the daily travel range of killer whales (approximately 120 km, Erickson, 1978), i.e., CFI and CFO were separated by 41 km, and Westport and Columbia River by 73 km, there was only one day when the whales were detected on these pairs of hydrophones. The Columbia River recorder consistently had the highest average number of detections per month of effort (Fig. 6), and although the whales were not detected there in June, this site still had the highest number of observed versus expected detections (Fig. 7). In a *post hoc* analysis (Wald test) to assess the differences between the four northern most locations, a significantly higher number of detections were found for both the Columbia and Westport locations (Table IV), but no statistically significant difference between the two Cape Flattery locations (using K and L pod detections only). Newport only had detections in February and May while all detections at Ft. Bragg and Pt. Reyes were only in February, all of which were in 2011. The timing of the presence of K

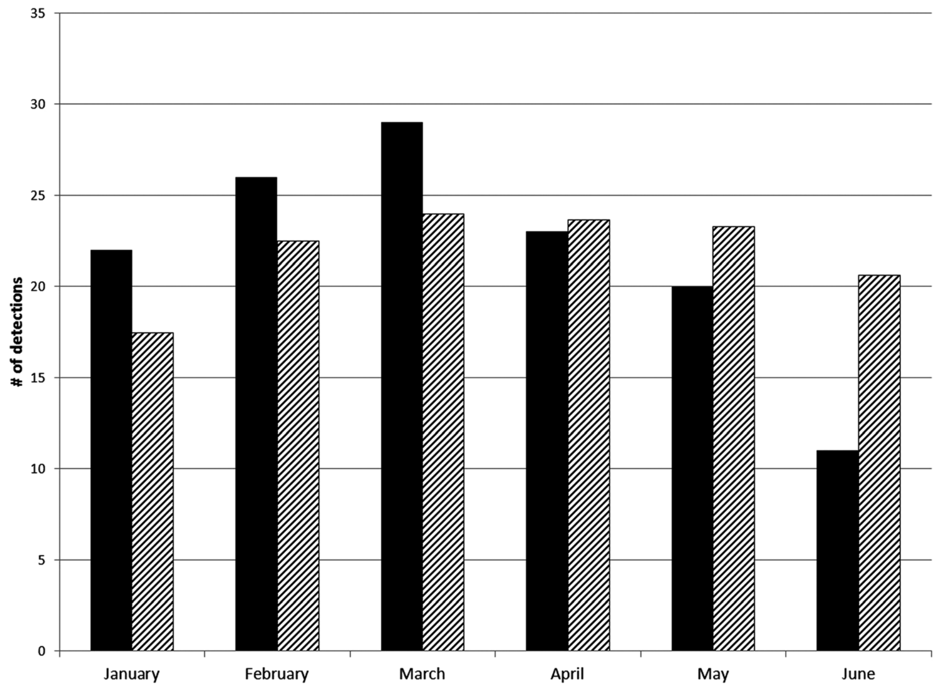

FIG. 5. Monthly observed number of SRKW detections (black bar) versus expected number of SRKW detections (diagonal bar).

and L pods on northern recorders just prior to their occurrence in California (i.e., L pod detected on the Columbia River recorder five days prior to Pt. Reyes) and again shortly after their detection in California (i.e., L pod was detected on Ft. Bragg seven days after Pt. Reyes, on Newport six days after Ft. Bragg, and at the Columbia River two days later) indicate they were south of Pt. Reyes for only about 10 days.

4. SRKW pod specific occurrence

Detections could be reliably assigned to SRKW pod level (J versus K and L) for 79 of the 131 detections. Of those detections, J pod was detected 25 times (Table II). J pod was only detected on the Cape Flattery recorders and most frequently on the CFI recorder ($n = 20$).

IV. DISCUSSION

In recent years, the use of passive acoustic recorders to monitor cetaceans has increased substantially (Mellinger *et al.*, 2007), including several studies in the North Pacific Ocean. For example, Oleson *et al.* (2009), Ŝirović *et al.* (2011) monitored for all cetaceans off the Washington coast, Riera *et al.* (2011) monitored for killer whales at a site off the west coast of Vancouver Island, as did Newman and

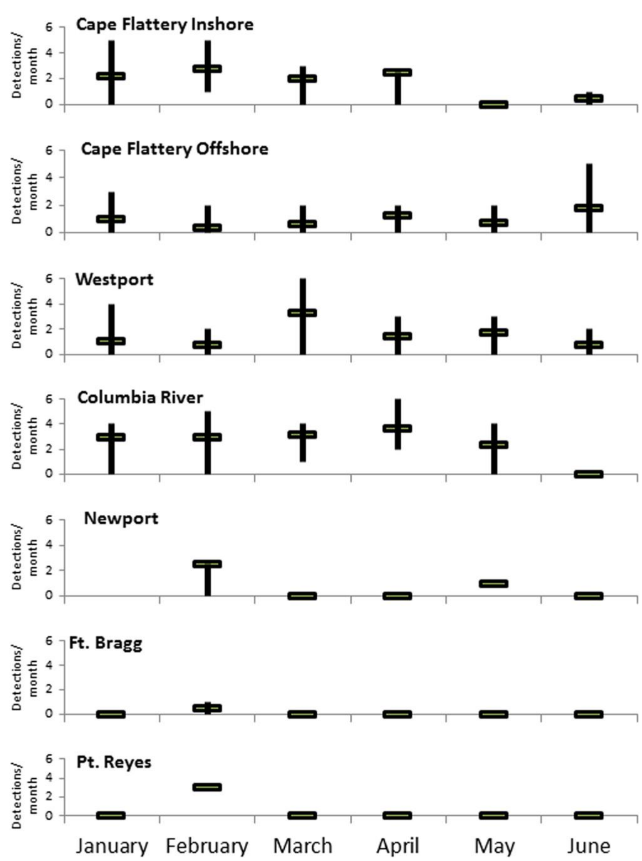

FIG. 6. (Color online) Mean number of SRKW detections/month (horizontal bar) and range in number of detections (vertical bar) by location for all years.

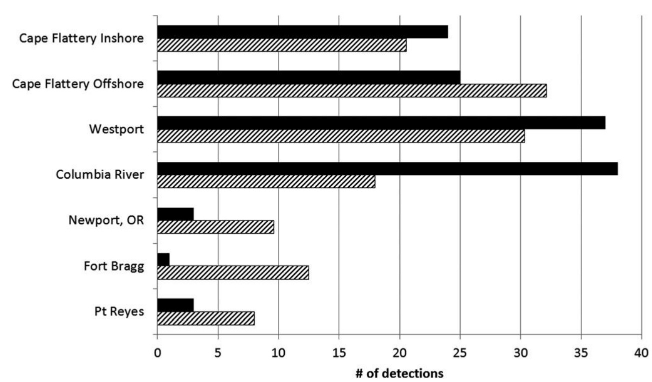

FIG. 7. Observed number of SRKW detections (black bar) versus expected number of SRKW detections (diagonal bar) for each U.S. west coast acoustic recorder location.

TABLE IV. Wald test p values from comparison of SRKW detections (presences/absence) at the four northern-most acoustic recorder locations. Cells with NA values indicate comparisons where p-value estimates failed to converge.

	Cape Flattery—Inshore	Cape Flattery—Offshore	Columbia	Westport
Cape Flattery —Inshore	–	–	–	–
Cape Flattery —Offshore	0.09	–	–	–
Columbia	<0.0001***	NA	–	–
Westport	<0.0001***	0.0007***	NA	–

***Significant at $p < 0.05$.

Springer (2008, 2011), and Love and Ŝirović (2011) for killer whales in Alaska. In all cases, however, these studies focused on relatively localized geographic areas. Our study is the first to use acoustic recorders to monitor killer whale occurrence along much of the U.S. west coast which allowed us to document not only monthly and annual patterns of occurrence but also regional patterns, all of which have important implications for this population's foraging ecology.

A. Spatial variability

Only one year (2011) had sufficiently consistent recorder effort to allow a coast-wide comparison of occurrence. Of particular note was that SRKW (only K and L pods) were only present on the California recorders in February, representing an excursion, albeit relatively brief (based on the temporal sequence of detections), to this area. The location-specific detection rates observed in this study suggest that all three SRKW pods spend a relatively large amount of time off the Washington coast although J pod occurred almost exclusively in the northeastern part and Ks and L pods tended to be in the southern part, suggesting possible habitat segregation in the winter and spring when prey resources are likely more dispersed than in summer.

B. Monthly variability

The occurrence of SRKW in early winter (January–March), particularly off the Columbia River and Westport in March, is consistent with other recent observations. Zamon *et al.* (2007) sighted members of L pod off the mouth of the Columbia River in March 2005 and this pod was also observed in this same general area or near Westport in March of 2004, 2006, and 2009 (Hanson *et al.*, 2008, 2010a). Zamon *et al.* (2007) had suggested that the timing of their sighting coincided with the return of spring Chinook to the Columbia River. Chinook salmon are known to be a primary prey item of SRKW in their summer range (Hanson *et al.*, 2010b). The first direct evidence that Columbia River spring Chinook were consumed by SRKW, albeit limited, was provided by Hanson *et al.* (2010a). Recent tagging studies of spring Chinook in the Columbia River have documented an average transit time of 22 days from the estuary to Bonneville Dam (Wargo Rub *et al.*, 2012). Adjusting the Bonneville fish counts for this passage duration would indicate that the peak number of fish are in the ocean near Westport and the Columbia River mouth sometime prior to an estimated early April peak (Fig. 8), i.e., approximately late March. The current study shows that K and L pods are spending significantly more time in this area than previously thought, particularly, in March, adding credence to previous suggestions of the potential importance of Columbia River spring Chinook in the diet of at least some of the SRKW pods (Zamon *et al.*, 2007; Ayers *et al.*, 2012).

C. Annual variability

The differences in occurrence observed between years in this study appeared to be similarly reflected in the other two Washington coast acoustic recorder studies, i.e., the relatively low detection rate of SRKW observed in this study in 2006–2008, while possibly related to the recorder types used, was similar to Oleson *et al.* (2009) results, whereas the significantly higher detection rate observed in this study in 2009 was similar to the other coastal study in that year (Ŝirović *et al.*, 2011). As noted previously, the timing of SRKW occurrence off the Columbia appears to coincide with the return of spring Chinook to the Columbia River. The annual variability in occurrence observed in this study may be related to the strength of spring Chinook runs returning to the Columbia River. The size of spring runs of Chinook returning to the Columbia far exceed the sizes of coastal Washington and Oregon spring Chinook runs that would be expected in coastal waters near Westport and the Columbia in the spring (PFMC, 2012). The lowest sighting rate observed in this study, 2007, coincided with the lowest return of spring Chinook (approximately only 47% of the 10 year average) since the late 1990s (PFMC, 2012), suggesting the whales were spending time elsewhere when Columbia River spring Chinook were scarce. Also in 2007, a sighting of SRKW in Southeast Alaska (Hilborn *et al.*, 2012) represented an extension of this population's previously known range. Similarly, the occurrence of K and L pod in

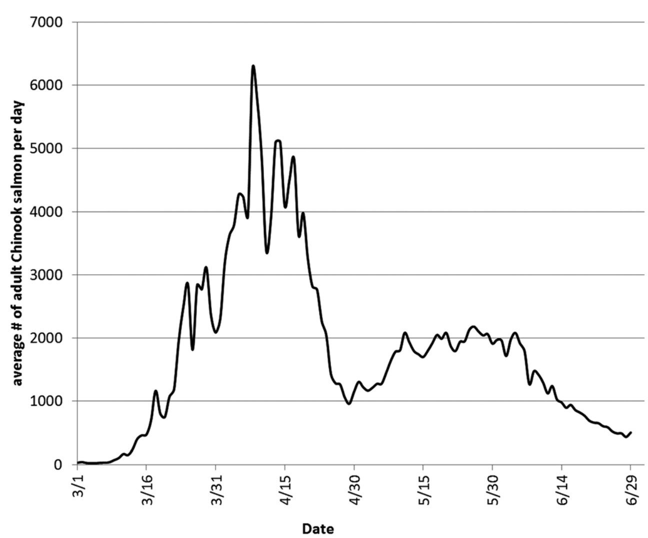

FIG. 8. Estimated timing of adult spring Chinook occurrence in the Columbia River estuary based on the average of 2006–2011 Bonneville dam counts adjusted for the average estimated 22 days travel time between the estuary and the dam.

California in 2011 was a relatively short-duration visit given the distance traveled from Washington, as the whales remained only south of Pt. Reyes for about 10 days, which coincided with an extremely poor year of Sacramento fall Chinook (PFMC, 2012). However, it is important to note that Columbia River Spring Chinook returns were similar and relatively low in 2006 and 2009 (about 0.67 of the 10 yr average from 2001–2011, PMFC, 2012) yet while SRKW occurrence was lower than expected in 2006 it was higher than expected in 2009 suggesting the existence of other factors that may influence whale occurrence.

The use of passive acoustic recorders has greatly increased our knowledge of the seasonal and annual occurrence of SRKW in the coastal waters of the U.S. During the nearly 30 years between 1976 (when it was first possible to photographically identify all SRKW individuals) and 2004 there had only been 11 documented sightings of SRKW in U.S. coastal waters (Krahn *et al.*, 2004) compared to the 131 acoustic detections collected over the recent five year span of our study. However, it is important to note that while this increase in detections demonstrates that this is a promising approach, it nonetheless suffers from a couple of important potential biases (i.e., killer whale presence is not always detected by the recorder) when attempting to use these data to determine movement or residency patterns of SRKW; (1) it is spatially biased because the detection range of the units is relatively limited by the physics of the frequency-specific sound propagation of killer whale calls (particularly given that detection range can be further impacted the highly variable ambient noise conditions known to occur in association with winter storms, i.e., wind, rain), and the deployment locations were based on the very limited information available on coastal whale distribution (Krahn *et al.*, 2004) (and the actual mooring locations were sometimes several kilometers from the preferred site in order to mitigate for potential fishery interactions) and (2) the whales do not vocalize consistently [i.e., vocalization activity may be time of day (Newman and Springer, 2008) or behavior-state specific (Hoelzel and Osborne, 1986; Ford 1989; Holt *et al.*, 2012)], and there is currently no correction factor to compensate for this un-quantified parameter such that the whales may swim by recorders undetected. Consequently, these results represent an underestimate of SRKW use of these areas. In addition, even in the best year of our study (2011) there remain gaps of several days to several weeks between detections, such that given the relatively high rates of travel (approximately 120 km/day) there are possibly areas that the whales concentrate their activities that have yet to be determined. Techniques such as satellite tagging have the potential to provide spatially unbiased data that, while temporally limited, may allow us to identify cores areas for which monitoring by acoustic recorders can provide a test of the long-term temporal value these sites. In addition, incorporation of visual sighting and detection data from other areas with our acoustic data will allow us to better assess movements through these areas and thus more accurately define regional duration of occurrence. These efforts will allow us to build a more robust database needed by managers to consider designating SRKW Critical Habitat along the west coast.

This study was also the first nearly region-wide array of acoustic recorders deployed in a Large Marine Ecosystem (California Current) and thus serves as model to illustrate the potential data such an acoustic monitoring array can provide. This loose network of recorders provided sufficient data to allow for an assessment of the implications of the whale occurrence patterns on their foraging ecology. These long-term data records will also be valuable for informing seasonal occurrence of other species of sound-producing marine mammals, as well as for measuring anthropogenic inputs in order to assess impacts of these activities, not only on SRKW, but other marine mammals.

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