Spatio-temporal patterns of beaked whale echolocation signals in the North Pacific

SIMONE BAUMANN-PICKERING [1*], ANNE E. SIMONIS [1], MARIE A. ROCH [1,2], MARK A. MCDONALD [3], ALBA SOLSONA-BERGA [1,4], ERIN M. OLESON [5], SEAN M. WIGGINS [1], ROBERT L. BROWNELL JR. [6], JOHN A. HILDEBRAND [1]

[1)] *Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0205, USA*
[2)] *Department of Computer Science, San Diego State University, 5500 Campanile Drive, San Diego, California 92182-7720, USA*
[3)] *WhaleAcoustics, 11430 Rist Canyon Road, Bellvue, Colorado 80512, USA*
[4)] *Universitat de Barcelona, 585 Gran Via de les Corts Catalanes, Barcelona 08007, Spain*
[5)] *Pacific Islands Fisheries Science Center, NOAA, 2570 Dole Street, Honolulu, Hawaii 96822, USA*
[6)] *Southwest Fisheries Science Center, NOAA, 1352 Lighthouse Avenue, Pacific Grove, California 93959, USA*

Contact e-mail address[*]: sbaumann@ucsd.edu

ABSTRACT

Passive acoustic assessment of cetacean species, populations, and their distribution has been a useful tool for a number of species. This method was applied to study highly elusive beaked whales. Ten species of beaked whales are known to inhabit the North Pacific and the species-specific frequency modulated (FM) echolocation pulses made by Baird's, Blainville's, Cuvier's, Longman's, and an unidentified beaked whale occurring at Palmyra Atoll, have been recorded with visual confirmation and described. Stejneger's beaked whale highly likely produces FM pulses recorded autonomously near the Aleutian Islands. Additionally, one described FM pulse (BWC) from Cross Seamount, Hawaii, and four undescribed beaked whale like FM pulses (BW40, BW43, BW50, BW70) have been identified within data collected autonomously at 26 sites throughout the North Pacific over the course of seven years. Wake Atoll, Cross Seamount, Pearl and Hermes Reef, and a site in the Southern California Bight near the shelf break had the highest beaked whale presence. Most sites had a dominant FM pulse type and no or a small number of acoustic encounters were registered from other types. There does not seem to be a strong seasonal influence on the occurrence of these FM pulses at all sites but longer time series may reveal smaller, consistent fluctuations. Local effects on prey abundance and preferred habitat structures likely drive their presence at a site. Only the species producing signals first described at Cross Seamount (BWC), detected broadly throughout the Pacific Islands region, consistently showed a strong diel cycle with nocturnal foraging activity. Cuvier's and Blainville's beaked whales diel variations varied regionally and were less pronounced. The most dominant pattern in their acoustic activity in some regions was higher counts from midnight to midday. In comparing stranding and sighting information for all species with the acoustic findings, we hypothesize that BWC signals are likely to be produced by Ginkgo-toothed beaked whales. High visual sighting rates for Hubb's beaked whale occurred off the coast of Washington, Oregon, and California. It might be an indicator that Hubb's beaked whale possibly produced the single BW40 signal encounter off central California. BW43 signal encounters were restricted to the Southern California Bight and offshore, and could possibly be produced by Perrin's beaked whale. The BW50 signal was distributed more broadly, also off central and southern California and at sites in the central Pacific and its identification remains unknown. The only signal detected in the Gulf of California was the BW70 type and it was found in the core habitat of Pygmy beaked whales.

KEYWORDS: Acoustics, Monitoring, Echolocation, Habitat, Distribution, Ziphiidae, Strandings, Pacific Ocean

1 INTRODUCTION

The North Pacific is known to be inhabited by ten species of beaked whales: Baird's (*Berardius bairdii,* Bb), Cuvier's (*Ziphius cavirostris.* Zc), Longman's (*Indopacetus pacificus,* Ip), Blainville's (*Mesoplodon densirostris,* Md), Stejneger's (*M. stejnegeri,* Ms), Hubb's (*M. carlhubbsi,* Mc), Perrin's (*M. perrini,* Mpe), Ginkgo-toothed (*M. ginkgodens,* Mg) and Pygmy beaked whale (*M. peruvianus,* Mpu) (Jefferson et al. 2008). The tenth species is the Indo-Pacific beaked whale, *M. hotaula* (Dalebout et al. 2007), which is likely the beaked whale that has been visually and acoustically observed at Palmyra Atoll (BWP) (Baumann-Pickering et al. 2010). Information on the abundance and distribution of these species is scarce due to their highly elusive behavior. They are pelagic, deep-diving odontocetes that undergo long foraging dives with short surface intervals (Tyack et al. 2006). In recent years, advances have been made in acoustically identifying beaked whales by their echolocation signals. These signals are mostly frequency-modulated (FM) upsweep pulses, which appear to be species specific and distinguishable by their spectral and temporal features (Figure 1). From the North Pacific, we are able to identify FM pulses made by Baird's, Blainville's, Cuvier's, Longman's beaked whale, and the unidentified beaked whale occurring at Palmyra

Atoll (Dawson et al. 1998, Johnson et al. 2004, Madsen et al. 2005, Zimmer et al. 2005, Johnson et al. 2006, Baumann-Pickering et al. 2010, Rankin et al. 2011, Baumann-Pickering et al. 2012). Baumann-Pickering et al. (2012) associated FM pulses in the Aleutian Islands on passive acoustic recorders with Stejneger's beaked whales. This association was based on two factors. Two of the three FM signal types occurring in the region correspond well to descriptions of Baird's and Cuvier's beaked whales (Dawson et al. 1998, Zimmer et al. 2005). Stejneger's is the only other beaked whale known to inhabit this area where it is the most commonly visually encountered whale.

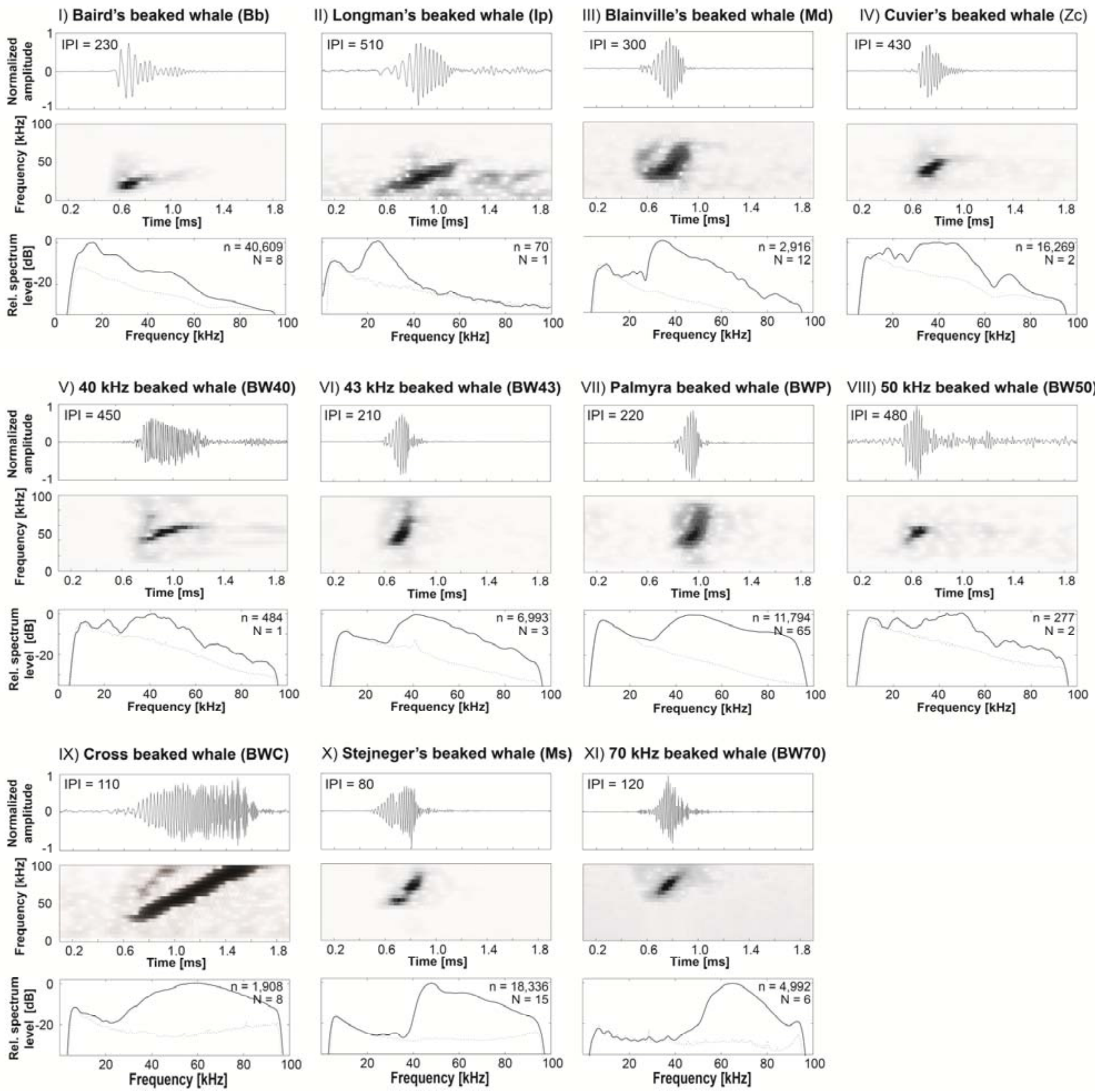

Figure 1: Overview of frequency-modulated (FM) upsweep pulses from known (I-IV, VII, X) and unknown sources (V, VI, VIII, IX, XI). Each FM pulse type is shown with an example pulse time series (top) and spectrogram (middle, Hann-windowed 2 ms, 40-point DFT, 97% overlap), as well as a mean spectra (bottom, solid line) over n FM pulses from N acoustic encounters and mean noise (dotted line) extracted before each pulse. Inter-pulse interval (IPI) is specified in ms (top, upper left).

One distinct FM pulse of unknown origin was described for the region around Cross Seamount (BWC), south of Hawaii, likely produced by a beaked whale (McDonald et al. 2009). Additionally, four FM pulse types (BW40, BW43, BW50, BW70, named by their peak frequency), reminiscent to those being produced by beaked whales, have been identified on autonomous acoustic recordings throughout the North Pacific (Baumann-Pickering et al. 2011). These signals have distinct spectral features and the temporal parameter inter-pulse interval (IPI) is relevant for classification (Figure 1).

Passive acoustics have been used to distinguish stocks as well as describe their geographic ranges for a number of marine mammal species such as killer (*Orcinus orca)*, blue (*Balaenoptera musculus)*, and fin (*Baelaenoptera physalus*) whales (Ford 1991, McDonald et al. 2006, Delarue et al. 2009). In this work, we examine the geospatial characteristics of the above mentioned species. For the unknown beaked whale like signals, there are no known recordings of these signals in the presence of visual observers. As they are strikingly similar to the general characteristics of beaked whale FM pulses, we consider their distribution along with the well described FM pulses in the conte xt of known distributions for beaked whales from stranding and sighting data. We describe the spatio-temporal distribution and relative abundance of North Pacific beaked whales based on the acoustic detections of FM pulses on long-term autonomous acoustic recorders from 26 sites over the years 2005 to 2011.

2 MATERIALS AND METHODS

2.1 Data collection

Acoustic recordings were collected with autonomous High-frequency Acoustic Recording Packages (HARPs) (Wiggins & Hildebrand 2007) from 26 sites in the North Pacific including the west coast of North America and the Pacific Island region (Table 1, Figure 2). Within the eastern North Pacific, recording effort occurred at several sites along the west coast of the United States including two sites off the coast of Washington, one site in central California, several sites throughout the Southern California Bight and offshore to Hoke Seamount, and south to the tip of the Baja California Peninsula in the Gulf of California. The Southern California Bight had the highest effort with eleven sites at various bathymetric or topographic features within the Bight. Within the central North Pacific, recording effort occurred at two sites in the Aleutian Islands, and at several more tropical sites within the Main and Northwestern Hawaiian Islands (Hawaii, Kauai, Cross Seamount, and Pearl and Hermes Reef), and at Palmyra and Wake Atolls. A single site has been monitored within the western North Pacific near Saipan in the Northern Mariana Islands. HARPs at the different sites had a variety of recording durations from a few weeks to several months and recording schedules ranging from continuous to 5 minutes of recording every 40 minutes. Sites were often maintained over several deployment missions resulting in a total of 19 years of analyzed deployment time (approximately 11 years of actual recording time) over the period 2005 to 2011. Most recorders were deployed to seafloor depths between 700 and 1300 m, but ranged from as shallow as 100 m to as deep as 4000 m, with the deepest deployments using modified moorings to maintain the hydrophone near 1000 m below the sea surface. HARPs were generally bottom-mounted, either in a seafloor packaged configuration or as a mooring with the hydrophone at about 10 to 30 m above the seafloor. All HARPs were set to a sampling frequency of 200 kHz with 16-bit quantization. The recorders were equipped with an omni-directional sensor (ITC-1042, International Transducer Corporation, Santa Barbara, CA), which had an approximately flat (±2 dB) hydrophone sensitivity from 10 Hz to 100 kHz of –200 dB re V/µPa. The sensor was connected to a custom-built preamplifier board and bandpass filter. The preamplifiers were designed to flatten the frequency response of the ambient ocean noise, which provided greater gain at higher frequencies where ambient noise levels are lower and sound attenuation is higher (Wiggins & Hildebrand 2007). The calibrated system response was corrected for during analysis.

2.2 Signal detection and classification

Signal processing was performed using the MATLAB (Mathworks, Natick, MA) based custom software program *Triton* (Wiggins & Hildebrand 2007) and other MATLAB custom routines. Trained analysts (SBP, AES, ASB, MAM) manually identified beaked whale type frequency-modulated (FM) echolocation pulses in the HARP data. These signals had, in comparison to known delphinid clicks, longer durations, a stable inter-pulse interval (IPI) and an upswept frequency. Long-term spectral averages (LTSAs) were calculated for visual analysis of the long-term recordings. LTSAs are long-term spectrograms with each time segment consisting of an average of 1000 spectra, which were created using the Welch algorithm (Welch 1967). The averages were formed from the power spectral densities of unoverlapped 5 ms Hann-windowed frames. The resulting long-term spectrograms have a

Table 1: HARP deployment details with recording start and end dates spanning multiple deployments, geographic location and depth. Depth values indicate approximate depth of recorder and hydrophone near the seafloor, value in parentheses indicates seafloor depth when the hydrophone was positioned much shallower than the seafloor, multiple values indicate different depths over different deployments near the same site. Recording schedule was either continuous (cont.) or on a fractional schedule with the number of 5 minute recording periods over the number of 5 minute non-recording periods. Recording days are the sum of recorded days of all deployments, not normalized for recording schedule.

Project	Site	Recording Start	Recording End	Longitude	Latitude	Depth (m)	Recording Schedule	# Deploy	Recording Days
North East Pacific									
Aleutian Islands	Kiska	03-Jun-10	20-Jul-10	178° 31.240” E	52° 19.007” N	1092	cont.	1	48
	Buldir	27-Aug-10	26-May-11	175° 37.990” E	52° 38.000” N	783	cont.	1	272
Washington	Cape Elizabeth	17-Jun-08	06-Nov-11	124° 43.256” W	47° 21.117” N	100	1/7 or cont.	2	527
	Quinault Canyon	27-Jan-11	07-Oct-11	125° 21.203” W	47° 30.003” N	1400	cont.	1	253
Point Sur	Point Sur	03-Oct-06	16-Jan-07	122° 23.628” W	36° 17.946” N	1392	1/3	1	105
Hoke Seamount	Hoke	15-Sep-08	06-Jun-09	126° 54.580” W	32° 06.370” N	770	1/7	1	265
Gulf of California	Puerto Pescadero	27-Nov-05	05-Jun-07	109 °37.668” W	23° 49.645” N	750	1/5 or cont.	3	401
Southern California (SOCAL)									
SOCAL	A	09-May-07	10-Jul-07	118° 15.835” W	33° 14.861” N	600	cont.	1	62
	B	13-Jul-07	23-Oct-07	120° 01.443” W	34° 16.519” N	500	1/2	1	102
	C	12-Mar-09	05-May-09	120° 48.367” W	34° 18.885” N	800	cont.	1	54
	CCE1	17-May-09	15-Dec-09	122° 31.400” W	33° 28.400” N	1000 (4000)	1/4	1	6
	E	03-Sep-06	12-Jul-09	119° 28.389” W	32° 39.379” N	1300	cont.	6	322
	G	18-Jan-07	28-Apr-07	118° 36.307” W	32° 55.507” N	300	1/2	1	100
	G2	13-Jan-09	04-Mar-09	118° 52.815” W	33° 08.407” N	1150	cont.	1	51
	H	05-Jun-08	03-Jan-09	119° 10.624” W	32° 50.823” N	1000	cont.	6	278
	M	13-Jan-09	02-Oct-11	119° 14.875” W	33° 30.887” N	950	cont.	10	804
	N	14-Jan-09	23-Sep-11	118° 33.803” W	32° 22.189” N	1300	cont.	8	597
	SN	19-May-09	02-Jun-10	120° 22.544” W	32° 54.913” N	1100	1/7	1	379
Pacific Islands									
Main Hawaiian Islands	Hawaii	23-Apr-09	16-Jun-10	156° 00.930” W	19° 34.889” N	600	1/3, 1/5, 3/7 or cont.	4	294
	Kauai	08-Oct-09	20-Aug-10	159° 53.383” W	21° 57.224” N	700	1/4 or cont.	2	294
Cross Seamount	Cross	20-Nov-05	11-May-06	158° 15.221” W	18° 43.343” N		1/5	1	172
NW Hawaiian Islands	Pearl & Hermes Reef	20-Oct-09	17-Sep-10	175° 37.946” W	27° 43.620” N	750	1/4 or cont.	2	325
Palmyra Atoll	WT	19-Oct-06	02-Apr-09	162° 09.385” W	05° 51.777” N	600	1/4	4	595
	NS	02-Jun-09	25-Aug-10	162° 02.224” W	05° 53.690” N	700/1100	1/4 or cont.	3	230
Pacific Islands	Wake Atoll	31-Jan-10	04-May-10	166° 41.000” E	19° 13.000” N	800	1/2	1	94
Northern Mariana Islands	Saipan	05-Mar-10	25-Aug-10	145° 27.542” E	15° 18.998” N	700	1/8	1	174
								Total	**19 years**

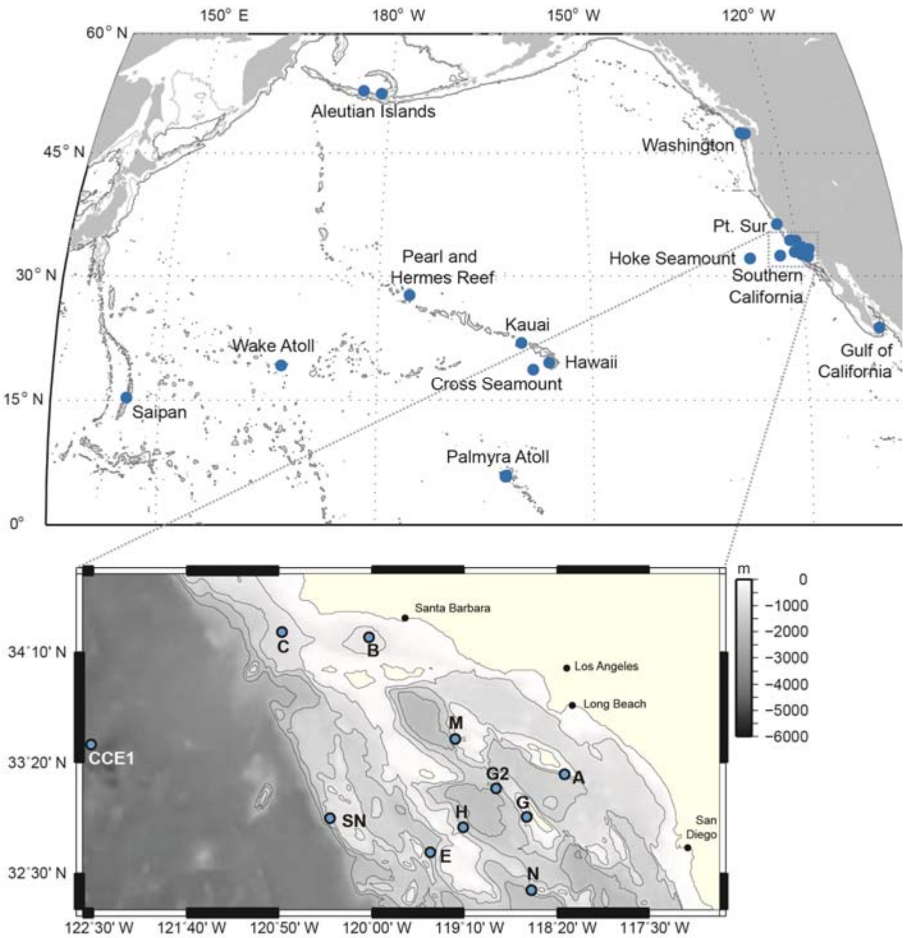

Figure 2: Locations of HARP recording sites (blue points) across the North Pacific (top) and within the Southern California Bight (bottom).

resolution of 100 Hz in frequency and 5 seconds in time. When echolocation signals were notable in the LTSA, the sequence was inspected more closely. Time series of 5 s lengths gave indications of IPI, time series of 3 ms lengths displayed the shape of the waveform, and spectrograms of Hann-windowed 3 ms segments (60 samples, 333 Hz bandwidth) overlapped by 99% revealed the presence of FM pulses. Start and end times of acoustic encounters were noted if beaked whale like FM pulses were identified. Analysts initially labeled these acoustic encounters as having been produced by one of the species whose echolocation signals are well known, one of the groups of echolocation signal categories whose origin has not yet been determined, or as unidentifiable with beaked whale echolocation signal characteristics.

All presumed beaked whale acoustic encounters were reviewed in a second analysis step. Individual echolocation signals were automatically detected using a computer algorithm during time periods when FM pulses were manually detected using a two-step approach (Soldevilla et al. 2008). The individual FM pulse detections were digitally filtered with a 10-pole Butterworth band-pass filter with a pass-band between 5 kHz and 95 kHz. Filtering was done on 800 sample points centered on the echolocation signal. Spectra of each detected signal were calculated using 2.56 ms (512 samples) of Hann-windowed data centered on the signal. Peak frequency was determined as the spectral frequency with the highest amplitude. FM pulse duration was derived from the detector output and IPIs were calculated from the start of an FM pulse to the start of the previous one. All detected echolocation signals, independent of distance and orientation of the recorded animal with respect to the recorder, were included in the analysis. A software tool displayed for each acoustic encounter histograms of peak frequency and IPI, mean spectra with mean noise preceding each click, and concatenated spectra (Figure 3). This classification tool computed and plotted median values for peak frequency, duration, IPI, and received level and overlaid the mean spectra of the acoustic detection against spectral templates of all beaked whale FM pulse types (Figure 3, top panel). The analyst optionally browsed through plots of individual time series and spectrograms (2 ms Hann-windowed data, 500 Hz bandwidth, 40-point DFT, 97% overlap) of echolocation signals detected within the acoustic encounter, sorted by peak-to-peak received level displaying high quality signals first. This lead to a final judgment about the label for each acoustic encounter and the analyst submitted a decision. In case the acoustic encounter was not classifiable to one of the eleven FM pulse types, based on low quality of the acoustic encounter, very few FM pulse detections, or based on spectral and temporal values that were not fitting, the acoustic encounter was labeled as a probable "unidentified beaked whale" (UBW), being an inhomogeneous group, likely comprised of a variety of FM pulse types.

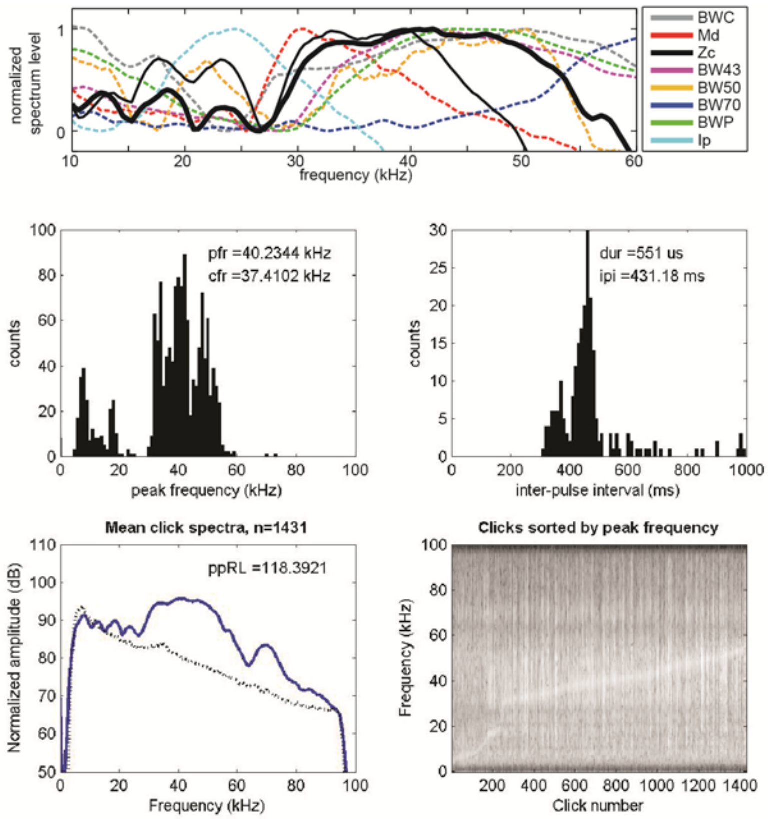

Figure 3: Example of classification tool used to label an acoustic encounter consisting of 1431 Zc FM pulses. Top panel: Mean spectra of all automatically detected FM pulses of the example encounter denoted by black bold line. Mean spectra of templates for all other FM pulse types are denoted as thin dashed lines with the exception of Zc, which is shown as a thin solid black line to highlight the similarity with the example encounter. Middle panel: Histograms of peak frequency (left, pfr) and IPI (right) with median values for pfr, center frequency (cfr), duration (dur), and IPI. Bottom panel: mean spectra of encounter (left, solid line) and mean noise before each FM pulse (left, dashed line). Concatenated spectrogram of all FM pulses sorted by peak frequency showing variability (right).

2.3 Statistical analysis

Relative occurrence of FM pulse types at each site and on a FM pulse type-basis across sites will provide insight into the geographic range of each FM pulse type and relative probability of encounters for a given area. For acoustic encounters of known beaked whale species this may refine the spatio-temporal knowledge of these species. For species whose signal types are currently unknown but whose geographic range is identified, a geographic overlap with new signal types might provide information leading to which species produces which new signal type.

For each site, the relative occurrence of FM pulse types was evaluated in two different ways. The first method determined the relative occurrence of acoustic encounter durations by FM pulse type on a per site basis, based on the total number of minutes that each signal type was heard. This analysis highlights which species are most common overall within a site, but obscures those FM pulse types which may occur regularly, but are not heard for very long during any individual encounter. Consequently, a second distribution was computed using presence/absence of each FM pulse type on a daily basis.

The remaining statistics required normalization for the quantity of acoustic effort at each site. The normalization factor took into account both the total number of recorded days, possibly over multiple deployments at the same site, and the recording schedule (Table 1). Acoustic encounter durations and counts were normalized by this factor prior to subsequent analysis. For each site, a relative detection effort was defined as the proportion of the effort [0, 1] relative to the site with the greatest effort. A relative presence was defined as the proportion of the summed acoustic encounter duration at any site relative to the site with the greatest sum of acoustic encounter durations. Similar to the daily presence/absence computation by site, a distribution of each FM pulse type across sites was computed.

For seasonal analysis, acoustic encounter durations were normalized for recording effort on a per site basis to permit pooling of data across deployments with different duty cycles. Monthly acoustic encounter durations were scaled [0, 1] to the greatest sum per site, to permit comparison of presence between sites. For diel patterns, hourly presence/absence counts were computed by FM pulse type over all sites and on a per site basis.

3 RESULTS

3.1 Relative presence

The highest acoustic encounter rate by effort normalized duration for beaked whale signals occurred at Wake Atoll (Table 2, encounter duration). Very high relative presence for FM pulses was also found at Cross Seamount, Pearl and Hermes Reef, and SOCAL E. Medium site presence was noted for Hoke Seamount, SOCAL C, CCE1, G2, H, N, and SN. Beaked whales were relatively uncommon at Aleutian Island and Washington sites, at Point Sur, at the Gulf of California site, SOCAL M, nearshore Main Hawaiian Islands and Palmyra Atoll sites, and Saipan. SOCAL A, B, and G had no acoustic encounters of beaked whales.

A site-specific analysis, looking at the presence of encounters over a 24-hour period per species and site, revealed that each site had one highly dominant FM pulse type, which occurred at a site with no or up to 4 (μ=1.6, σ=1.2) other FM pulse types. Acoustic encounter durations of the dominant signal accounted for 75±16% of all encounters across all sites (Table 2). Zc type signals dominated all of the SOCAL sites except SOCAL C, which had highest acoustic encounter rates for Bb signals. Zc signals were also dominant at Point Sur, Hoke Seamount, and Wake Atoll. Md signals were the prevailing ones at Hawaii, Kauai, Pearl and Hermes Reef, and Saipan. Ms FM pulses were most often encountered on recordings of the Aleutian Islands sites and the deep Washington site Quinault Canyon. BWP signals were dominant at both Palmyra Atoll sites, BWC signals were the only FM pulse type acoustically encountered at Cross Seamount, and BW70 signals were the only FM pulse type at the Gulf of California site (Figure 4, Table 2).

For a signal-specific analysis, the same data were reorganized showing the distribution of each FM pulse type by site, investigating the number of days of recording effort after taking into account recording schedule (Table 3). This indicates geographic range of each species, and probability of acoustic encounters disregarding encounter durations. Zc signals were encountered in all areas of the monitored North Pacific as the most common signal (62% of all encounters), particularly often at Hoke Seamount, SOCAL SN, CCE1, and Wake Atoll (13-19% of all detected encounters). Acoustic encounters of Md signals were the second most common (24%) but were restricted to the Pacific Islands region with the exception of one encounter off Washington State. BWP and BWC signals had relative encounter rates of 4% across all sites and acoustic encounters. BWP signals were only heard at Palmyra Atoll, and were more common at the north shore site NS (85%) over the southwestern site WT. BWC signals were encountered acoustically in all the Pacific Islands regions with detections during 65% of days at Cross Seamount, followed by 24% at Saipan. Ms and Bb signals made up 2% of all encounters over all sites each. Both FM pulse types were more common at the cooler, northern sites, such as the Aleutian Islands and Washington, as well as various SOCAL sites. Ms signals were more frequently encountered near the Aleutians and off Washington. The highest percentage of Ms encounters occurred at SOCAL CCE1, which likely was an artifact of the analysis with only 6 recording days at that site and two Ms signal encounters during that period. Bb signal type acoustic encounters were highest at SOCAL C (59%). All other FM pulse types made less than 1% of all acoustic encounters each. The BW70 FM pulse was only found on the Gulf of California recordings. The BW50 FM pulse occurred throughout the Pacific, specifically off central and southern California and in the central Pacific near Pearl and Hermes Reef and at Wake Atoll. The BW43 FM pulse was most often detected at Hoke Seamount, comprising 72% of its encountered days, as well as at SOCAL E, N, and SN. A single acoustic encounter of the BW40 signal occurred off central California.

Table 2: Relative distribution of daily presence of acoustic encounters for all FM pulse types by site, normalized for effort. Presence relative to the site with the highest encounter rate is reported both by duration (as in Figure 4) and by the effort normalized daily presence. Star (*) indicates a value with less than 1%. Grey shaded area shows no encounters of a type at a site.

		Relative presence %		Species										
Project	Site	Encounter duration	Daily encounters	Zc	Md	BWP	Ms	Bb	BWC	BW40	BW43	BW50	BW70	UBW
North East Pacific														
Aleutian Islands	Kiska	2	10				94	6						
	Buldir	*	2	7			93							
Washington	Cape Elizabeth	1	*					50						50
	Quinault Canyon	5	12		1		72	26						1
Point Sur	Point Sur	6	34	95						3		3		
Hoke Seamount	Hoke	13	86	97							3			
Gulf of California	Puerto Pescadero	*	2										100	
Southern California (SOCAL)														
SOCAL	A													
	B													
	C	12	15					96				4		
	CCE1	25	90	60			40							
	E	85	28	93				5			1	1		
	G													
	G2	20	24	100										
	H	19	22	99								1		
	M	2	8	91			2	6				1		
	N	15	19	93				5			1	1		*
	SN	19	81	92				4			1	3		
Pacific Islands														
Main Hawaiian Islands	Hawaii	9	16	6	90				4					
	Kauai	4	15		68				32					
Cross Seamount	Cross	96	75						100					
NW Hawaiian Islands	Pearl and Hermes Reef	80	100	35	55				3			1		6
Palmyra Atoll	NS	2	34		4	95			1					
	WT	*	7	9	6	74								11
Pacific Islands	Wake Atoll	100	64	87					7			5		
Northern Mariana Islands	Saipan	4.7	97	9	63				28					

Table 3: Percentage of number of days with detections per FM pulse type over all sites. Star indicates value with less than 1%. Grey shaded area shows no encounters of a type.

		North East Pacific							Southern California (SOCAL)												Pacific Islands							
	Number of acoustic encounters (not normalized for effort) [%]	Aleutian Islands		Washington		Point Sur	Hoke Seamount	Gulf of California	SOCAL												Main Hawaiian Islands		Cross Seamount	NW Hawaiian Islands	Palmyra Atoll		Pacific Islands	Northern Mariana Islands
		Kiska	Buldir	Cape Elizabeth	Quinault Canyon	Point Sur	Hoke	Puerto Pescadero	A	B	C	CCE1	E	G	G2	H	M	N	SN	Hawaii	Kauai	Cross	Pearl and Hermes Reef	NS	WT	Wake Atoll	Saipan
Zc	4425 [62]		*			7	19					12	6		5	5	2	4	17	*			8		*	13	2
Md	1728 [24]				*															10	7		39	1	*		43
BWP	310 [4]																							85	15		
Ms	156 [2]	3	17		15							65					*										
Bb	131 [2]	*		1	13						59		6				2	4	15								
BWC	254 [4]																			1	4	65	3	*		4	24
BW40	1 [*]					100																					
BW43	10 [*]						72						6					6	17								
BW50	24 [*]					10					7		3			1	*	2	27				9			39	
BW70	8 [*]							100																			
UBW	44 [1]			4	2													1					83		11		

Table 4: Presence (+) or absence (-) of beaked whales based on strandings (S), visual sightings (V), and acoustic FM pulse encounter (A)

	Zc			Md			Mh		BWP	Ms			Bb			Ip			Mg		BWC	Mpe		BW43	Mc		BW40	BW50	Mpu		BW70
Project Site	S	V	A	S	V	A	S	V	A	S	V	A	S	V	A	S	V	A	S	V	A	S	V	A	S	V	A	A	S	V	A
Aleutians	+	+	+	-	-	-	-	-	-	+	+	+	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Washington	+	-	-	-	-	+	-	-	-	+	-	+	+	+	+	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
Point Sur	+	+	+	-	-	-	-	-	-	+	-	-	+	+	-	-	-	-	-	-	-	-	-	-	+	-	+	+	+	-	-
SOCAL	+	+	+	+	-	-	-	-	-	+	-	+	-	+	+	-	-	-	-	-	-	+	-	+	+	-	-	+	+	-	-
Gulf of California	+	+	-	-	-	-	-	-	-	-	-	-	+	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	+	+	+
Main HI	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	+	+	-	-	-	+	-	-	-	-	-	-	-	-	-	-
NW HI	+	+	+	+	-	+	-	-	-	-	-	-	-	-	-	-	-	+	-	-	+	-	-	-	-	-	-	+	-	-	-
Palmyra Atoll	+	+	+	-	-	+	+	+	+	-	-	-	-	-	-	-	+	+	-	-	+	-	-	-	-	-	-	-	-	-	-
Wake Atoll	+	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	+	-	-	-
Saipan	-	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-

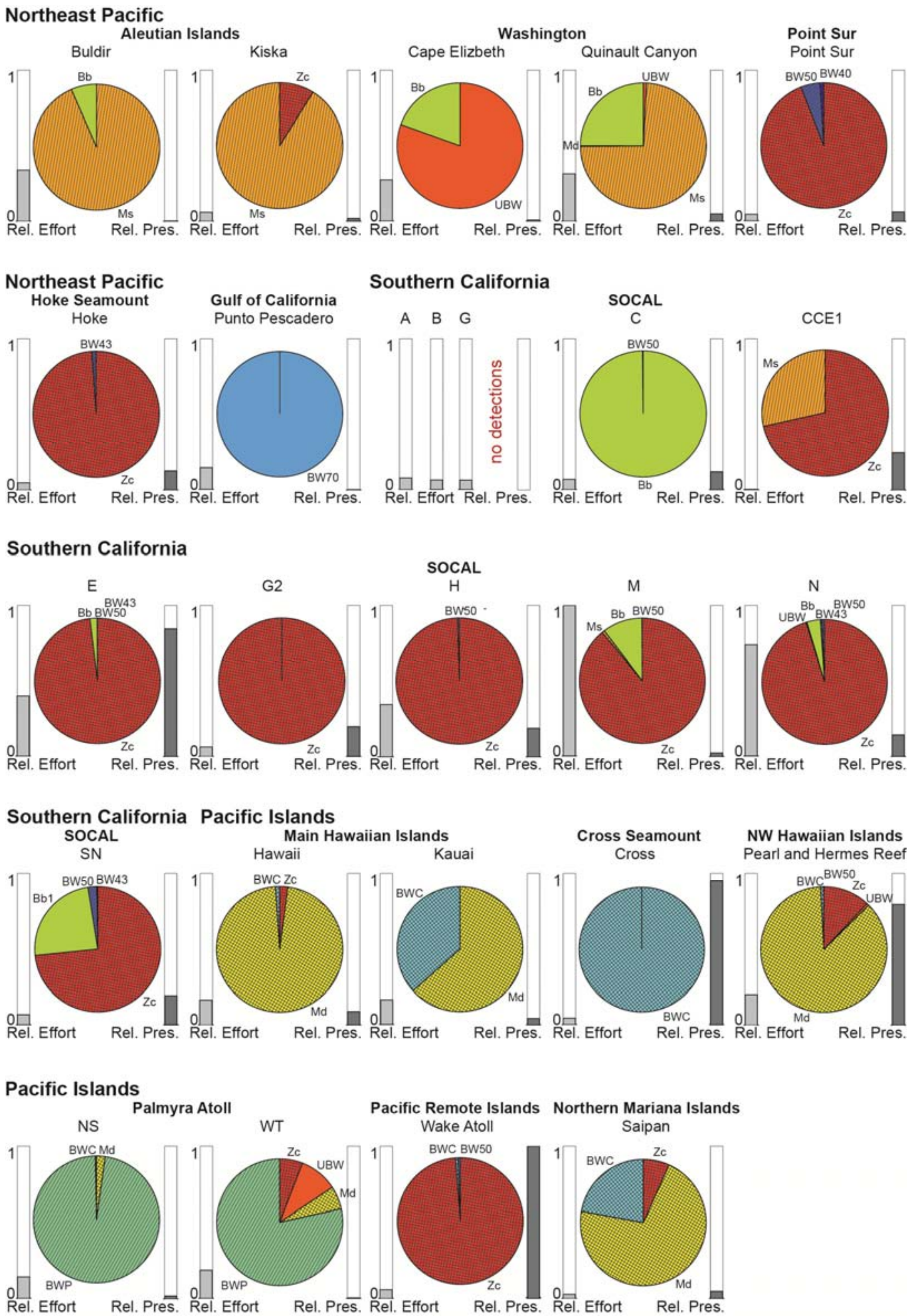

Figure 4: Relative sum of acoustic encounter durations of all FM pulse types by site (pie chart, see Table 2). For each pie chart, the relative detection effort is displayed on the left, and the relative presence on the right. Site M in the Southern California Bight had the highest effort (relative effort of 1) and Wake Atoll had the greatest sum of acoustic encounter durations (relative presence of 1). Sites A, B, and G in the Southern California Bight did not have any detection of beaked whale calls and are thus grouped in the figure.

3.2 Seasonality

Good seasonal coverage was available for SOCAL, particularly sites M and N with 3 years of nearly continuous data, Palmyra Atoll, and the Gulf of California (Table 1). Multi-year coverage was also achieved by looking at a regional rather than a site-by-site scale. Our data did not suggest strong seasonal patterns for most FM pulse types and in most regions or sites, also lacking a larger number of acoustic encounters for many signal types. Bb and BW43 signals occurred in various months and at a number of sites throughout SOCAL. No apparent seasonal pattern was visible for BW50 signals in any of the regions. BW70 and BWP signals were heard at the Gulf of California and Palmyra Atoll sites, respectively, throughout the recording period without seasonal pattern.

However, one seasonal pattern was interesting and some shorter-term variations noteworthy. Zc signals showed a higher occurrence in SOCAL M and N during the summer in three consecutive monitoring years except at site M in 2009 when winter months had highest acoustic encounter rates. In a little over one year of recording at the Hawaii site, Zc signals were relatively rare (Table 3), with higher numbers of encounters in fall of 2009 (Figure 5, top panel).

Ms signals were very rare in SOCAL but appeared over the three year monitoring period at site M in July and September of 2010. The only other acoustic encounter in SOCAL was in late spring of 2009 at site CCE1. During 2010 at the Aleutian Island site Buldir, Ms signals were detected prior to November and after December. There were a high number of Ms signal acoustic encounters off the Washington coast in the first six months of 2011, with a sudden drop in July and no further encounters throughout October of 2011 (Figure 5, middle panel).

Acoustic encounters of Md signals occurred mainly around the Pacific Islands sites. Noteworthy were the higher numbers of acoustic encounters over the late spring and early summer months at the island of Hawaii with few or no detections over late fall and winter between November and March. From one year of data from Kauai there were many acoustic encounters observed in fall of 2009 followed by lower encounter rates throughout the rest of the recording year (Figure 5, bottom panel).

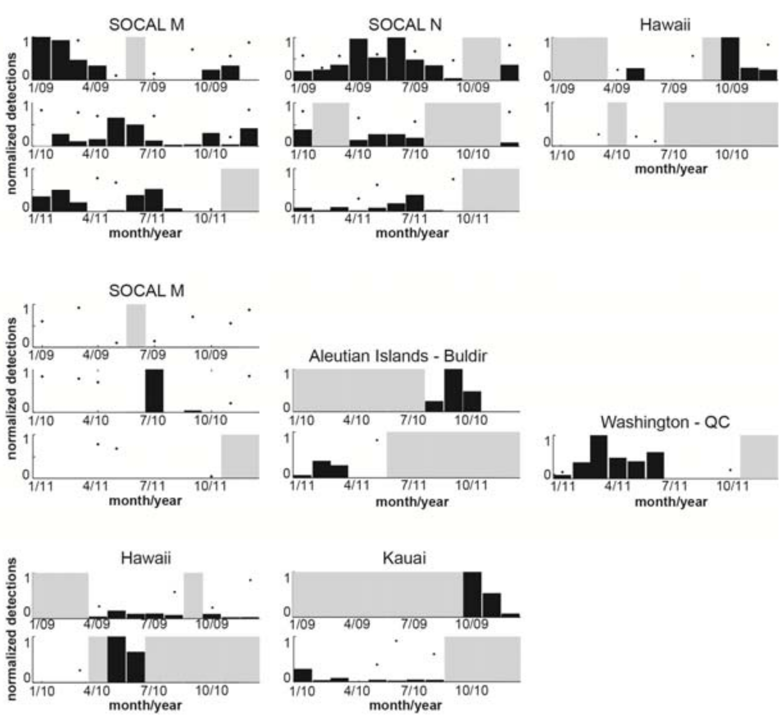

Figure 5: Seasonality of *Z. cavirostris* (Zc, top panel) at sites SOCAL M, N and Hawaii, of *M. stejnegeri* (Ms, middle panel) at sites SOCAL M, Aleutian Islands Buldir, and Washington Quinault Canyon, and of *M. densirostris* (Md, bottom panel) at sites Hawaii and Kauai. A point indicates partial monthly recording effort and data in that month was adjusted for reduced effort. Grey shaded areas show no monthly effort

3.3 Diel pattern

The BWC FM pulse type was the only signal that was heard only during one portion of the day, with most acoustic activity at night across all sites (Figure 6, top left). When sites with encounters of Zc signals were pooled, this FM pulse type displayed a trend of higher acoustic activity between midnight and midday and lower activity in the afternoon and first half of the night (Figure 6, top right). This pattern was particularly pronounced at Pearl and Hermes Reef, and SOCAL H (Figure 6, bottom middle and right), but also at SOCAL G2, and N. SOCAL M had an opposing pattern with highest activity in the afternoon. Most other sites did not have enough data points for Zc signals or did not display a diel pattern (Figure 6, top center). Md signals pooled across all sites did not show a diel pattern. However, at Hawaii (Figure 6, bottom left), and to a lesser extent at Kauai, the diel pattern for Md signals was similar to what was observed for Zc signals with highest acoustic activity in the early morning hours to midday.

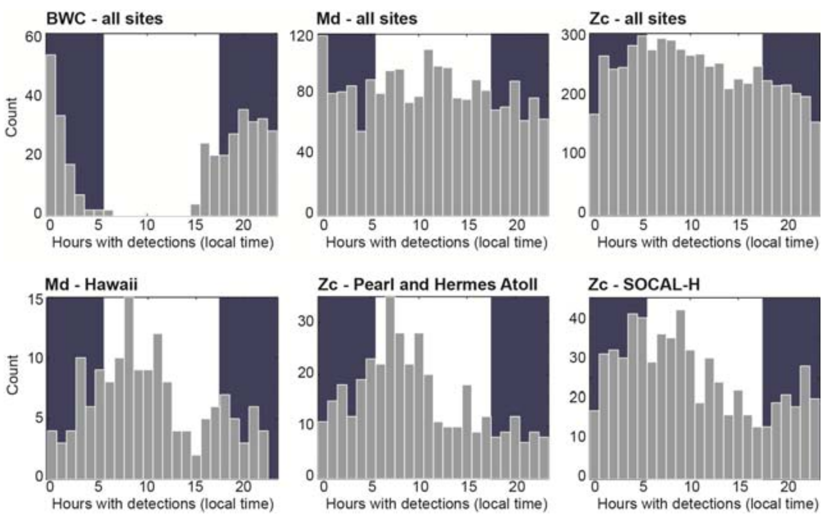

Figure 6: Diel cycle of Cross beaked whale (BWC), *M. densirostris* (Md), and *Z. cavirostris* (Zc) pooled over all sites and geographic regions (top panel), as well as for Md an Zc at select sites. Dark blue areas indicate nighttime. BWC displayed a clear nocturnal activity over all sites, Zc had a slight diel pattern with higher activity in the early morning hours to mid day over all sites, particularly pronounced at Pearl and Hermes Reef and SOCAL H. Md did not have a diel pattern, except at Hawaii, where the pattern was similar to Zc. Dark blue areas indicate night time.

4 DISCUSSION

4.1 Acoustic analysis

Manual detection of FM pulse type acoustic encounters typically provides a low number of missed or false detections. The method of screening long-term data with LTSAs offers a fast overview for long periods of time (usually 1 h) and allows for efficient data analysis. Despite the compressed view, the analyst is capable of detecting periods with very few (~3-5) echolocation signals. However, we have found that results can vary even between experienced analysts, particularly in data sets with many different species emitting echolocation signals simultaneously. Therefore, while the number of missed detections is relatively low, a precise characterization remains unknown. A multi-step labeling process minimized the number of false classifications and we are confident that these labels and categories are valid.

Beaked whale FM pulses have been proven to be species-specific with one FM pulse type per species (Zimmer et al. 2005, Johnson et al. 2006, Gillespie et al. 2009, Baumann-Pickering et al. 2010, Rankin et al. 2011). Besides FM pulses, some beaked whales also produce dolphin-like echolocation clicks and dolphin-like buzz clicks (Dawson et al. 1998, Johnson et al. 2006, Rankin et al. 2011). It cannot be ruled out that a beaked whale species may produce multiple FM pulse types, possibly with geographic variation; however, we have not yet observed such behavior in our recordings. Also, while there may be geographic variation, which has yet to be quantified, FM pulse characteristics seem to be stable enough across ocean basins to reliably categorize FM pulse types to known species (SBP unpublished data).

Echolocation signals of odontocetes are known to vary largely in their frequency content based on the orientation of the animal in relation to the recording hydrophone due to its highly directional echolocation beam (Au et al. 2012). Additionally, higher frequencies attenuate more over distance than lower frequencies such that distance of the animal to the hydrophone will impact the frequency content of the received signal. However, Soldevilla et al. (2008) have shown consistent spectral peaks on long-term acoustic recorders for two dolphin species, where a similar situation is expected. While there is considerable variability within each species (see Zc example in Figure 3, concatenated spectrogram bottom right), particularly the frequencies below and at the onset of the broadband energy, and the overall shape of the mean spectra up to the peak frequency appears to be consistent. Frequencies beyond the peak are highly variable, likely depending on the distance between the animal and the hydrophone.

Besides the FM pulse types of known species, this manuscript discusses the spatio-temporal distribution of four undescribed (BW40, BW43, BW50, and BW70) and one described FM pulse type (BWC) (McDonald et al. 2009), for which visual identification of the species producing these signals do not yet exist.

The four FM signal types BW40, BW43, BW50, and BW70 have preliminary descriptions (Baumann-Pickering et al. 2011). The categories were manually identified based on spectral and temporal grouping. It has yet to be shown if these signals are indeed species-specific and produced by beaked whales. BW40 has been encountered only once on HARP recordings from Point Sur. This signal type is highly similar to Zc signals but occurred with two other dolphin-like echolocation click types in a continuous sequence likely produced by one animal. Zc is not known to make dolphin-like echolocation clicks aside from buzz sequences. It is possible that, based on the similarity to Zc signals and the high relative presence of Zc signals in the region, this signal type was more frequent and misclassified as Zc, or that Zc produces other signal types under certain behavioral circumstances of which we are currently not aware. However, while the main frequency content of the BW40 FM pulse is highly similar to the Zc signal, the two spectral peaks at 17 and 23 kHz common in Zc signals were not present in the BW40 encounter. Additionally, while not all BW40 pulses show a long duration, the signal duration of most BW40 FM pulses were distinctly longer than what is usually found for Zc signals.

Manual detection of the Ip pulse type has proven difficult and conclusive long-term and spatial results have been yet to be obtained for this signal type. While we did have two Ip signal acoustic encounters, one at Palmyra Atoll and another at Pearl and Hermes Reef, we are likely to have missed a number of acoustic encounters. Ip has three types of echolocation signals, an FM pulse with 25 kHz peak frequency, and two dolphin-like echolocation clicks with 15 and 25 kHz peak frequency (Rankin et al. 2011). Current knowledge suggests that only about one third of Ip signals are FM pulses and the time spent during manual analysis browsing signals in each sequence for FM pulses may not be sufficient to classify these encounters as Ip, with an analyst instead labeling these signals as belonging to other odontocetes. It is also a possible that Ip signals recorded at the surface with one system appear different to those received at the seafloor with a different recording system as has been found for other delphinids (SBP, unpublished data). However, the two Ip signal encounters on the HARPs matched well what has been described from surface recordings.

4.2 Relative presence

Relative site presence might be seasonally dependent, such that our results may be biased for those sites where there was only a partial year of data. An extreme example is site SOCAL CCE1, which was included in the analysis as it is the only deep-water offshore pelagic site and had detections of Ms signals. However, the recording lasted only six days. Within that time there were five FM pulse acoustic encounters, two of which were Ms signals, the other three Zc signals. This high percentage of Ms signals at this mooring influenced the distribution for Ms (Figure 4, Tables 2, 3), but the brief deployment makes it likely that seasonal presence or chance encounters have skewed the statistics. Relative site presence should also not be directly related to abundance. The detection range, detectability and echolocation activity may vary with species.

Figure 4 and Table 2 present similar, but not identical information. Figure 4 shows the relative amount of time during which specific FM pulse types were produced whereas Table 2 reports relative presence over 24 h periods. In many cases, the two statistics are similar, but when a large number of encounters occur on a daily basis, this can influence the results. This can be seen in the relative presence columns of Table 2. The encounter duration column repeats the relative presence of Figure 4 whereas the daily encounter relative presence column is derived from the effort normalized days of presence at each site. There can be large differences between these two statistics. A good example of this can be seen at Hoke Seamount. By effort-normalized duration, Hoke has 13% of the detections seen at Wake Atoll. However, many of the acoustic encounters at Hoke were on different days. When one considers the daily encounter rate, it can be seen that animals are observed quite frequently, with 86% of the detections seen at Pearl and Hermes Reef, the site with the highest daily encounter rate. The difference between these two statistics could be attributable to a number of causes. As the recording duty cycle for Hoke was 5 min of recording every 35 min, the duration of many acoustic encounters is likely to be truncated and many possible encounters may have been entirely missed. Normalization for effort will address the truncation, but not missed encounters. In addition, differences in the statistics can be driven by species-specific behavior (e.g. dive durations) or habitat usage.

Another source of variation in the relative occurrence of FM signals among sites can be seen from results at the two very closely located Palmyra Atoll sites and over the larger SOCAL region. While both sites at Palmyra Atoll were in similar water depths and there was no apparent reason why one site should be favorable to the other, there was a higher site presence on the northern shore over the southern. Prey aggregation based on oceanographic factors favoring the north shore of the atoll may have caused such a site difference. Assessment of relative occurrence in a particular region may be strongly impacted by the choice of monitoring location, such that inferences on the presence or absence of a species based on a single site recording should discuss the potential for local oceanographic or other habitat variables, which may influence the ability to detect a species. Comparison of FM signal encounters across the entirety of the Southern California Bight, based on several recording sites, likely does provide a good assessment of overall beaked whale occurrence and how habitat preferences influence relative distribution. The lack of acoustic encounters of FM pulse types on SOCAL sites A, B, and G is likely related to their shallow deployment depths between 300 and 600 m (Table 1), shallower than is expected for beaked whale habitat (Waring et al. 2001). SOCAL C was dominated by Bb FM pulse encounters with only one acoustic encounter of BW50 signals otherwise. SOCAL C has a water depth of 800 m (Table 1), is located on a slowly down sloping area on the shelf at the entrance to the Santa Barbara Basin. This does not seem to be preferred Zc habitat but it would be interesting to investigate whether Bb preferred this type of bathymetric and topographic feature over the steep slopes that Zc favor (Waring et al. 2001).

4.3 Seasonal and diel pattern

Ms signals were detected prior to November and after December at the Aleutian Island site Buldir. While there were fewer winter acoustic encounters, this indicates that the species producing this signal, likely *M. stejnegeri* (Baumann-Pickering et al. 2012), may not completely leave the area for the entire winter season. At the Washington Quinault Canyon site on the other hand, Ms signals occurred from January to June with a peak in March and a sudden disappearance of acoustic encounters from July to October of 2011, the end of the recording time. The lack of acoustic encounters over the summer months might suggest migratory behavior and that the species left the area during that period or could suggest localized movements of prey, inshore-offshore, to another site along the coast, which the animals might follow.

It is tempting to infer seasonal movement of Md between Hawaii and Kauai based on the pattern of occurrence within those datasets; however, large gaps in each dataset and analysis of only a single year from each site suggest additional data is needed before such as assertion can be supported. Short-term residency, followed by widespread movements is common for many insular Hawaiian odontocetes (e.g. Baird et al. 2010, Schorr et al. 2010), with such movements likely driven by similar short-term patterns in prey distribution.

A strong diel pattern was only observed for BWC FM pulses. Since beaked whales emit FM pulses predominantly during foraging dives (Johnson et al. 2004, Madsen et al. 2005), the diel pattern of echolocating indicates a foraging strategy different to that of other beaked whale species and is possibly related to the behavior of the preferred prey species. Blainville's and Cuvier's beaked whales are known to echolocate at depths between 200 and 1900 m but most echolocation activity occurs below 450 m for both species (Tyack et al. 2006). The recording site at Cross Seamount was located at less than 400 m water depth on the top of the seamount. Assuming a similar dive and echolocation behavior of this species as Blainville's and Cuvier's beaked whales, as well as a highly directional beam pattern common to all currently known echolocating odontocetes, Johnston et al. (2008) hypothesized that the BWC diel pattern occurred not due to primarily nocturnal foraging but due to vertical prey movement in the water column, which allowed foraging at depth during the day, not audible to the recorder, and in more shallow water during the night. This theory does not seem to hold up as the HARPs at Kauai, Pearl and Hermes Reef, and Wake Atoll, all below 700 m water depth, recorded the same diel pattern for BWC FM pulses.

The variability of diel patterns, or the lack thereof, depending on location, for Zc and Md signals shows a very different foraging strategy as the species producing BWC signals. The regional differences likely represent a variety of food sources particular to the site, or particular to the population inhabiting the region. A comparison of stomach content analysis on a regional scale might shed light on these differences.

4.4 Geographic distribution of beaked whale species and FM pulse type

4.4.1 Z. cavirostris – produces Zc FM pulse

Cuvier's beaked whales have the most extensive distribution of all the beaked whales, occurring in deep waters worldwide and nearshore around oceanic islands with deep waters and ranging from equatorial tropical to cold-temperate waters. However, they are not known to occur in the high latitude polar waters (Dalebout et al. 2005, Heyning & Mead 2009). They are perhaps the most common of all beaked whales, with more reports of sightings and strandings than any other ziphiid species (Heyning & Mead 2009).

They can often be found in waters where the steep continental slope occurs close to shore, such as around the Hawaiian Islands and San Clemente Island, off southern California, allowing for photo-identification and tagging studies in these regions (e.g. McSweeney et al. 2007, Falcone et al. 2009). These, like other island populations, appear to be at least seasonal residents. Around Hawaii, the resightings of known Cuvier's beaked whales span over 15 years and suggest they are resident with long-term site fidelity (McSweeney et al. 2007).

Cuvier's beaked whales are the most common beaked whales to strand throughout the rim of the North Pacific and also from many of the islands. Starting in Alaska and moving clockwise, Zc strandings are known from the Aleutian Islands (Samalga Island), USA (Scheffer 1949); Bella Bella, British Columbia, Canada (Cowan & Guuignet 1952, Mitchell 1968); North Ocean Lake, Washington (Scheffer & Slip 1948, Mitchell 1968); Del Mar, California (Hubbs 1946, Mitchell 1968, Danil et al. 2009); San Ramon, Baja California Norte, Mexico (Hubbs 1951, Mitchell 1968). In the western North Pacific counterclockwise from Alaska, Zc strandings are known from Bering Island, Commander Islands, Russia (Stejneger 1883); off Korean Peninsula [bycatch] (Baker et al. 2006); Miura City, Japan (RO-079, ICR); Lukang, Taiwan (Yang 1976); China (Wang 1999); Philippines [a sighting] (Dolar et al. 1997). On the offshore/oceanic islands, Zc strandings are known from Guam [RLB unpublished record], Wake Island (Mead *et al*. 1989); Sydney Island, Phoenix Islands, Kiribati (USNM 395775); Pohnpei, Caroline Islands (USNM 306284); Midway Atoll (Galbreath 1963); Kalae, Hawaii (Richards 1952); Johnston Island (Eldredge 1991); and Palmyra Atoll (USNM specimen).

Comparing sighting and stranding data to the acoustic encounters, the results confirm that Zc signals are the most commonly heard FM pulse type and with the broadest geographic spreading (Table 4). The only larger regions where no Zc signals were encountered were off the coast of Washington, and the Gulf of California, but (Barlow et al. 2006) reported that the highest density of Zc in the Pacific is in the southwest Gulf of California.

4.4.2 Berardius bairdii – produces Bb FM pulse

This species is endemic to the cold-temperate waters of the North Pacific, like *M. stejnegeri* and *M. carlhubbsi*, but based on strandings and sightings it has a larger range than either of the other two species and is more abundant (Barlow et al. 2006). In the eastern part of their range, standings are not common anywhere but they are known from various locations in Alaska and south to British Columbia, Washington, and California (Mead 1989b). From the southernmost part of Baja California, Mexico and into the Gulf of California Baird's beaked whales are know from two mass strandings near La Paz in July 1986 (Aurioles-Gamboa 1992) and from Isla San Jose in July 2006 (Urbán R. et al. 2007), respectively. In the eastern North Pacific, Baird's beaked whales stranding are known from Commander Islands, Russia; Kamchatka, Russia; and Japan (Mead et al. 1989). The southernmost record in the western Pacific is from China in the East China Sea approximately 30˚N, no records from Taiwan (Wang 1999). This species is not known nor expected from the regions around any of our tropical recording sites (Palmyra Atoll, Hawaii, Kauai, Pearl and Hermes Reef, Wake Atoll, and Saipan).

Acoustic recordings confirmed the distribution of Baird's beaked whales in cold-temperate waters with acoustic encounters around the Aleutian Islands, Washington, and Southern California (Table 4). Baird's beaked whale was the second most frequently acoustically encountered species in these regions after Ms and Zc, respectively.

4.4.3 Indopacetus pacificus – produces Ip FM pulse

This is another poorly known monotypic beaked whale occurring in the southern part of the North Pacific and south into the tropical and warm-temperate waters of the Southern Hemisphere, as well as west into the northern and central Indian Ocean. The first stranding was collected in northern Australia (Mackay, Queensland (21˚10'S, 149˚10'E) in 1882 (Longman 1926). The next specimen was collected near Danane, Somalia (01˚52'N, 45˚02'E) in 1956 (Azzaroli 1968). Dalebout et al. (2003) reported on four new specimens of this from the western and central Indian Ocean. Over the past ten years only eight more specimens have been discovered and these were found in the Maldives, Myanmar, Philippines, Taiwan and Japan (Yamada et al. 2012).

The only known stranding from the Central and Eastern North Pacific is a recent specimen from Hawaii (West *et al*. in press). As the Longman's beaked whale is only known from tropical waters on the Indo-Pacific they are not known as strandings or sightings from the regions around any of our cold water recording sites (Aleutian Islands, Washington, Pt. Sur, and Southern California).

Acoustic encounters of Ip FM pulse types were lower than expected so that these were not included in the quantitative analysis. However, the two positively identified acoustic encounters were from Palmyra Atoll and Pearl and Hermes Reef, both of which fall into the expected distribution for this species (Table 4).

4.4.4 M. densirostris – produces Md FM pulse

This species has the most extensive distribution of any *Mesoplodon* species and is found in all the world's oceans, in tropical and warm-temperate waters, including offshore, deep waters, tropical oceanic archipelagos, and on continental or insular coasts in these areas. *M. densirostris* are seen infrequently at sea, and positive identifications in the field can be difficult unless key diagnostic characters of the head and teeth in adult males are observed. As a result, our knowledge of the distribution of this species has been inferred mainly from stranding records.

In the eastern North Pacific, sighting records of this species range from rare off California (Carretta et al. 2012) to the offshore waters of the Pacific EEZ of Costa Rica (May-Collado et al. 2005) and southward. Sightings and strandings in the central North Pacific are known from the Hawaiian Islands, including Oahu, Hawaii, Molokai, Kauai, and Laysan Islands, as well as the Society Islands, the Line Islands, and Midway Atoll. Strandings have been reported from the western North Pacific in the Philippines, Taiwan, the Ryukyu Islands, Kuroshima, and Honshu, Japan (Kasuya & Nishiwaki 1971, Miyazaki 1986).

Strandings or sightings of *M. densirostris* at or near our recording sites include the following: Point Sur (Pescadero Beach, CA, Mead 1989); San Clemente Island (none); Gulf of California (none); Palmyra Atoll (USNM 593441); Hawaii (sightings, McSweeney et al. 2007); Kauai (none); Pearl and Hermes Reef (from Laysan, Nitta 1991); Wake Atoll (none); and Saipan (none). There are no strandings or sightings of this species from the Aleutian Island chain, Alaska or British Columbia, Canada; Washington, or from the cold-temperate region of the western North Pacific (Mead *et al*. 1989).

Md FM pulse type encounters were the second most detected signal type over all sites. The acoustic data finds higher encounter rates in subtropical to tropical regions, with Saipan and Pearl and Hermes Reef having the greatest percentage of days with detections, confirming what is known about *M. densirostris* preferred range (Table 4). All Pacific Islands sites except Cross Seamount and Wake Atoll had Md FM pulse type encounters. The only other site with a single Md signal encounter, outside the Pacific Islands region, was off the coast of Washington.

4.4.5 M. hotaula – produces BWP FM pulse

At this time, this species is known from only seven confirmed specimens (Dalebout *et al*. 2012). There are: (1) the holotype, from Ratmalana, Sri Lanka, (2) Tabiteuea Atoll, Kiribati, (3-5) Palmyra Atoll, Line Islands; (6) Hulhudhuffaaru, Raa Atoll, Maldives; and (7) Desroches Island, Seychelles (Dalebout *et al*. 2012). The Indo-Pacific beaked whale is best known from Palmyra Atoll, Line Islands (05˚50'N, 162˚06'W) where three specimens have stranded and what are believed to be live animals have been observed around the atoll (Baumann-Pickering et al. 2010).

The only known confirmed records for this species in the Central Pacific are from Tabiteuea Atoll, Kiribati (Dalebout et al. 2007); Onotoa Atoll, Kiribati (Dalebout *et al*. 2012); and Palmyra Atoll (Baumann-Pickering et al. 2010) (Dalebout *et al*. 2012). No Indo-Pacific beaked whale type calls were recorded around any site other than Palmyra Atoll. In that this is a tropical species, it would not be expected to be found anywhere near the Aleutian Islands nor in the eastern Pacific. To date no specimen or sighting of *M. hotaula* is known east of Palmyra Atoll. There are also no specimens or possible sightings from any of the Hawaiian Islands. Within the sites that we are currently acoustically monitoring, the only sites where we might expect to find the BWP signal would be near Saipan and/or Wake Atoll.

The BWP FM pulse type was only found at Palmyra Atoll, being the most common beaked whale species there (Table 4). However, relative presence of beaked whales at this site was comparatively low, indicating that this species is likely not abundant, even though it has been regularly sighted at Palmyra Atoll. Recording effort is continuing at Saipan and Wake Atoll and future analysis might prove acoustic encounters at these sites.

4.4.6 M. stejnegeri – likely produces Ms FM pulse

Stejneger's beaked whale was first described in 1885 from a skull collected on Bering Island, Commander Islands, Russia (True 1885). Only ten specimens were known in 1960. This species has not been reported from any central Pacific islands. There were 48 records of this species from the North Pacific including 22 new records [Table 6] (Mead 1989). Four mass strandings of this species have been reported from Kuluk Bay, Adak, Alaska between 1975 and 1989 (Walker & Hanson 1999). Other Bering Sea stranding locations include: Shemya Island, Amchitka Island, Adak Island, Saint Paul Island, Tanaga Island. There are numerous stranding records for this species in the cold-temperate waters of northern Japan (Yamada et al. 2012). The southernmost stranding in the California Current is from southern Cardiff, California (LACM 054575) on 10 August 1968. The southernmost stranding of this species is near the southern front of the Japanese cold water Oyashio Current at Tsuyazaki, Fukuoka (33.48N, 130.27E) south of Tokyo (Yamada et al. 2012). Therefore, the southern limit is about the same on both sides of the Pacific. In the Sea of Japan, a single specimen was reported in market samples of cetacean products from Korean "whale meat" markets (Baker et al. 2006) and a few strandings are known from the Korean Peninsula (Park 1999).

Strandings of *M. stejnegeri* at or near our recording sites include the following: Aleutian Islands (mass stranding events of this species are known from Adak, Tanaga, Shemya and Unalaska Islands; Baumann-Pickering et al. 2012); Washington (Leadbetter Point, Waatch River, and Twin Harbors State Park; Mead 1989). Stejneger's beaked whales are known as cold-temperate species. They are not known from the regions around any of our subtropical or tropical recording sites (Gulf of California, Palmyra Atoll, Hawaii, Kauai, Pearl and Hermes Reef, Wake Atoll and Saipan).

Acoustic encounter of the Ms FM pulse type dominating both Aleutian sites and the offshore Washington site strengthens the hypothesis that this signal type is indeed produced by *M. stejnegeri*. Also, this signal type was on rare occasions found on some of the SOCAL recordings confirming the species' range known from sightings and strandings (Table 4).

4.4.7 M. ginkgodens – possibly produces BWC FM pulse

Ginkgo-toothed whales are found in warm-temperate and tropical waters of the Pacific and westward into the Indian Ocean to at least western Sri Lanka (Deraniyagala 1963) and the Maldives (Anderson et al. 1999). This species was first described from Japan, based on a specimen from Oiso Beach, Sagami Bay, Japan (Nishiwaki & Kamiya 1958). Based on strandings or capture records, this species is most common around Japan and also reported from Taiwan (Nishiwaki et al. 1972). Specimens are also known from Liaoning Province, China (Shi and Wang 1984); Del Mar, California (Moore & Gilmore 1965); a specimen previously identified as *M. ginkgodens* from Baja California, Mexico (Urbán-Ramírez & Aurioles-Gamboa 1992) (Leatherwood et al. 1988, Vidal *et al*. 1993) has recently been identified as *M. peruvianus* (Pitman and Brownell 2012); Galapagos Islands (Palacios 1996); Strait of Malacca, Indonesia (Mead 1989). In the Southern Hemisphere, individuals have stranded in southeastern New South Wales, Australia (Tidemann 1980) [reported as *M. bowdoini*], Bannister et al. 1996) and Bay of Plenty, New Zealand (Baker & van Helden 1999). The specimen of *M. ginkgodens* from Chatham Islands (Baker 1983) has been reidentified as *M. grayi* (Baker & van Helden 1999). However, the identification of some of these specimens is in question (Dalebout *et al*. 2012). Strandings of *M. ginkgodens* are not common anywhere but the largest number of records are from Japan, but there are no confirmed strandings of this species at or near any of our recording sites. A specimen taken near Pohnpei (06˚50'N, 158˚15'E) is the closest confirmed *M. ginkgodens* record to Palmyra Atoll. The range of *M. ginkgodens* in the central Pacific is poorly known and may or may not overlap with *M. hotaula*.

The properties of echolocation signals produced by *M. ginkgodens* are unknown. However, its distribution overlaps very well with the occurrence of the BWC FM pulse type (Table 4). The BWC signal was encountered on all Pacific Islands sites, dominating Cross Seamount detections and contributing to a large part of Saipan detections. They were not heard in any of the other regions.

4.4.8 M. perrini – possibly produces BW43 FM pulse

The species is known only from five strandings along the coast of southern California (Pitman 2009). There are no estimates of abundance. The species is apparently rare, as there have been no confirmed sightings in several cetacean abundance surveys conducted by NOAA in Californian waters. This species appears to have the most restricted range of any species of *Mesoplodon* in the warm-temperate waters off southern California and likely occurs at least off northern Baja California, Mexico (Brownell and Pitman 2012).

Echolocation signal properties for *M. perrini* are unknown. Given its restricted range, the BW43 FM pulse seems to fit this distribution very well (Table 4). BW43 signals were detected at deep sites (1100-1300 m, Table 1) at the southwestern edge of the Southern California Bight (sites E and N), at the shelf break (site SN), and offshore at Hoke Seamount.

4.4.9 M. carlhubbsi – possibly produces BW40 FM pulse

Hubb's beaked whale is one of two *Mesoplodon* species, the other being *M. stejnegeri*, endemic in the cold-temperate waters of the North Pacific. However, Hubb's beaked whales found in the cold water of the Oyashio Current off northern Japan were believed to be disjunct from those living in the cold-water California Current (Mead et al. 1982, Mead et al. 1989). The southernmost stranding in Japan is from Numazu, Suruga Bay (Nakajima 1990) and the northernmost record is from Ayukawa (Nishiwaki & Kamiya 1959). There are no strandings of this species from the Aleutian Chain, Alaska, or the Hawaiian Islands (Mead et al. 1982, Mead et al. 1989). In the eastern North Pacific, the northernmost stranding (54º17'N, 130º22'W) is from Prince Rupert, British Columbia (Pike 1969, Willis & Baird 1998) and the southernmost stranding is from San Diego, California (Mead et al. 1982, Danil et al. 2010). There are no records from Korea as strandings or bycatch from the Sea of Japan (Kim & et 2000, Baker et al. 2006). MacLeod et al. (2006) speculated that the two North Pacific populations might be continuous across the North Pacific around 30˚N and 45˚N. This idea is supported by a specimen of Mc collected by an observer from the middle of the North Pacific (Yamada et al. 2012) while on board a fishing vessel operating in the High Seas Driftnet fisheries run by Japan, Korea and Taiwan in the central portion of the North Pacific (Yatsu et al. 1994, Watanabe 1994).

Carretta et al. (2012) reported that the minimum population estimate (defined as the log-normal 20th percentile of the abundance estimate) for mesoplodont beaked whales in California, Oregon, and Washington is 576 animals. Rarely are these mesoplodont whales identified to species, but a large number of them were observed offshore of Oregon/Washington (Yamada et al. 2012).

Strandings of *M. carlhubbsi* at or near our recording sites include the following: Washington (Oyhut, USNM 274591); Pt. Sur (Cypress Point and San Simeon Bay, Mead et al. 1982); Southern California (Santa Monica, LACM 84043) and San Clemente Island (USNM 504883); Hubb's beaked whales are a well-known cold-temperate species and they are not known from the regions around any of our tropical recording sites (Gulf of California, Palmyra Atoll, Hawaii, Kauai, Pearl and Hermes Reef, Wake Atoll, and Saipan). Based on the known distribution of this species it is not expected to occur around the Aleutian Islands.

Hubb's beaked whale echolocation signals have been recorded and described on two occasions. Both descriptions were made from stranded, captive animals, one of which was a very young specimen (Marten 2000). The described signals in one manuscript were recorded with a sampling rate lower than necessary to likely describe the full bandwidth of the echolocation signal of beaked whales (Lynn & Reiss 1992), and presented in a way that the typical beaked whale FM pulse properties – sweep and inter-pulse interval – were not clearly identifiable and comparable.

Hubb's beaked whale may have produced the single BW40 FM pulse type encounter at Point Sur and the low number of detections of this signal does not disagree with the very low number of strandings (Table 4).

4.4.10 M. peruvianus – possibly produces BW70 FM pulse

Pitman and Brownell (2012) reviewed the records (strandings and sightings) for *M. peruvianus* and reported the northernmost record of this species was a specimen that stranded alive in Moss Landing, California (36°47'N 121°47′W), in January 2001. Another, specimen stranded at Newport Beach, California (33° 22'N 117° 34'W), in February 1998. The northernmost live sighting of this species was from 26° 10'N 110° 48'W on 11 August 2006, in the central Gulf of California, Mexico (NOAA Southwest Fisheries Science Center unpublished data). The southernmost record in the eastern Pacific was a stranded specimen from northern Chile at 29°17'S, 71°24'W, collected in May 1995 (Sanino et al. 2007). The only record of this species away from the eastern Pacific was a stranding of a 327 cm male from Oaro, Kaikoura, South Island, New Zealand in 1991 (Baker & van Helden 1999). Whether this specimen is indicative of a wider distribution for this species, or just an errant individual is unknown, but it seems unlikely this species would normally occur in the cooler waters around New Zealand. In addition, New Zealand has one of the oldest stranding programs, if not the oldest, and only the 1991 specimen has been identified as *M. peruvianus*.

Pitman and Brownell (2012) also noted that based on 24 at-sea sightings (of *Mesoplodon* sp. A) presented by Pitman et al. (1987) and 85 different sightings by Hamilton et al. 2009, *M. peruvianus* appears to be endemic to the eastern tropical Pacific Ocean, with most at-sea sightings concentrated in the warmest waters of the ETP, the "Eastern Pacific Warm Pool", an area with sea surface temperatures > 27.5°C (Fiedler & Talley 2006). Comparing the plots in Fig. 27 (*M. peruvianus*) with Fig. 28 (*Mesoplodon* sp.) in Hamilton et al. (2009), it seems likely that this species may be particularly abundant in the southern Gulf of California (see also Ferguson et al. 2006).

Based on the available stranding and sighting data, this species may be most abundant in the southern region of the Gulf of California as the warm surface waters extend northward into the Gulf. Also based on all records, it seems unlikely that this species would have been recorded from any of our other recording sites, even in the Central and Western Pacific if they are truly endemic to the warmest waters of the ETP.

While no acoustic recordings have been collected in the presence of Pygmy beaked whales, the most likely FM pulse type to fit the distribution of this species would be the BW70 signal, recorded only in the Gulf of California (Table 4) at the core of the species' habitat, and with *Z. cavirostris* expected to be the only other beaked whale species in the Gulf.

5 CONCLUSIONS

Passive acoustic monitoring of elusive beaked whales has proven a feasible technique to study the distribution and relative presence of these species throughout the North Pacific. Comparison with sighting and stranding data has given a good indication for possible species producing new undescribed beaked whale like signals. Relatively low numbers of acoustic encounters with rare signal types, the lack of multi-year data for many sites, variability within a region, and low density of recording instruments reduced the value for interpreting seasonal movement and diel foraging patterns. However, with continuing data collection this caveat can be reduced. Furthermore, knowledge gained about behavioral and distributional patterns of rare species may help with planning fieldwork for concurrent acoustic and visual species identification. Future research should investigate how habitat preference and local oceanographic features rather than large-scale seasonal aspects may control prey abundance and in return beaked whale presence, particularly at temperate and tropical sites.

Acknowledgements

ONR, Mike Weise, CNO-N45, Frank Stone, Pacific Life Foundation, Bob Haskell, Ocean Foundation, Mark Spaulding, NPS, Curt Collins and John Joseph, and the PIFSC provided funding. The authors thank R. Baird, H. Bassett, J. Burtenshaw, G. Campbell, T. Christianson, C. Garsha, R. Gottlieb, E. Henderson, B. Hurley, J. Hurwitz, J. Larese, T. Margolina, M. McKenna, D. McSweeney, M. Melcón, C. Miller, S. Rankin, E. Roth, G. Schorr, M. Stone, B. Thayre, D. Webster, L. Williams, T. Yack, and C. Yoshinaga for fieldwork, gear and analysis support.

REFERENCES

Anderson RC, Shaan A, Waheed Z (1999) Records of cetacean 'strandings' from the Maldives. J South Asian Nat Hist 4:187-202

Au WWL, Branstetter B, Moore PW, Finneran JJ (2012) The biosonar field around an Atlantic bottlenose dolphin (Tursiops truncatus). The Journal of the Acoustical Society of America 131:569-576

Aurioles-Gamboa D (1992) Notes on a mass stranding of Baird's beaked whales in the Gulf of California, Mexico. Calif Fish Game 78:116-123

Azzaroli ML (1968) Second specimen of Mesoplodon pacificus the rarest living beaked whale. Monitore Zoologico Italiano (n.s.) 2(suppl):67-79

Baird RW, Schorr GS, Webster DL, McSweeney DJ, Hanson MB, Andrews RD (2010) Movements and habitat use of satellite-tagged false killer whales around the main Hawaiian Islands. Endangered Species Research 10:107-121

Baker AN (1983) Whales and dolphins of New Zealand and Australia. An identification guide, Vol. Victoria University Press, Wellington

Baker AN, van Helden AL (1999) New records of beaked whales, Genus Mesoplodon, from New Zealand (Cetacea: Ziphiidae). J R Soc N Z 29:235-244

Baker CS, Lukoschek V, Lavery S, Dalebout ML, Yong-un M, Endo T, Funahashi N (2006) Incomplete reporting of whale, dolphin and porpoise 'bycatch' revealed by molecular monitoring of Korean markets. Anim Conserv 9:474-482

Barlow J, Ferguson M, Perrin WF, Ballance Land others (2006) Abundance and density of beaked and bottlenose whales (family Ziphiidae). J Cetacean Res Manage 7:263-270

Baumann-Pickering S, Simonis AE, McDonald MA, Oleson EM, Rankin S, Wiggins SM, Hildebrand JA (2011) Comparison of beaked whale echolocation signals 3rd Symposium on Acoustic Communication by Animals, Ithaca, NY, p 7-8

Baumann-Pickering S, Simonis AE, Wiggins SM, Brownell RL, Hildebrand JA (2012) Aleutian Islands beaked whale echolocation signals. Mar Mamm Sci

Baumann-Pickering S, Wiggins SM, Roth EH, Roch MA, Schnitzler HU, Hildebrand JA (2010) Echolocation signals of a beaked whale at Palmyra Atoll. J Acoust Soc Am 127:3790-3799

Carretta JV, Forney KA, Oleson EM, Martien Kand others (2012) U.S. Pacific Marine Mammal Stock Assessments: 2011

Dalebout ML, Baker CS, Steel D, Robertson KMand others (2007) A divergent mtDNA lineage among Mesoplodon beaked whales: molecular evidence for a new species in the tropical pacific? Mar Mamm Sci 23:954–966

Dalebout ML, Robertson KM, Frantzis A, Engelhaupt D, Mignucci-Giannoni AA, Rosario-Delestre RJ, Baker CS (2005) Worldwide structure of mtDNA diversity among Cuvier's beaked whales (Ziphius cavirostris); implications for threatened populations. Mol Ecol 14:3353-3371

Dalebout ML, Ross GJB, Baker CS, Anderson RCand others (2003) Appearance, distribution, and genetic distinctiveness of Longman's beaked whale, Indopacetus pacificus. Mar Mamm Sci 19:421-461
Dawson S, Barlow J, Ljungblad D (1998) Sounds recorded from Baird's beaked whale, Berardius bairdii. Mar Mamm Sci 14:335-344
Delarue J, Todd SK, Van Parijs SM, Iorio L (2009) Geographic variation in Northwest Atlantic fin whale (Balaenoptera physalus) song: Implications for stock structure assessment. J Acous Soc Am 125:1774-1782
Eldredge LG (1991) Annotated checklist of the marine mammals of Micronesia. Micronesica 24:217–230
Falcone EA, Schorr GS, Douglas AB, Calambokidis Jand others (2009) Sighting characteristics and photo-identification of Cuvier's beaked whales (Ziphius cavirostris) near San Clemente Island, California: a key area for beaked whales and the military? Mar Biol 156:2631-2640
Ferguson MC, Barlow J, Reilly SB, Gerrodette T (2006) Predicting Cuvier's (Ziphius cavirostris) and Mesoplodon beaked whale population density from habitat characteristics in the eastern tropical Pacific Ocean. J Cetacean Res Manage 7:287-299
Fiedler PC, Talley LD (2006) Hydrography of the eastern tropical Pacific: A review. Prog Oceanogr 69:143-180
Ford JKB (1991) Vocal traditions among resident killer whales (*Orcinus-orca*) in coastal waters of British-Columbia. Canadian Journal of Zoology-Revue Canadienne De Zoologie 69:1454-1483
Galbreath EC (1963) Three beaked whales stranded at Midway Islands, central Pacific Ocean. J Mammal 44:422-423
Gillespie D, Dunn C, Gordon J, Claridge D, Embling C, Boyd I (2009) Field recordings of Gervais' beaked whales Mesoplodon europaeus from the Bahamas J Acoust Soc Am 125:3428-3433
Heyning JE, Mead JG (2009) Cuvier's beaked whale - Ziphius cavirostris. In: Perrin WF, Würsig B, Thewissen JGM (eds) Encyclopedia of marine mammals. Academic Press, San Diego, p 294-296
Hubbs CL (1946) First records of two beaked whales, Mesoplodon bowdoini and Ziphius cavirostris, from the Pacific Coast of the United States. Jour Mammal 27:242-255
Hubbs CL (1951) Probable record of the beaked whale Ziphius cavirostris in Baja California. Jour Mammal 32:365-366
Jefferson TA, Webber MA, Pitman RL (2008) Marine Mammals of the World – A Comprehensive Guide to their Identification., Vol. Elsevier, London
Johnson M, Madsen PT, Zimmer WMX, Aguilar de Soto N, Tyack P (2006) Foraging Blainville's beaked whales (Mesoplodon densirostris) produce distinct click types matched to different phases of echolocation. The Journal of Experimental Biology 209:5038-5050
Johnson M, Madsen PT, Zimmer WMX, de Soto NA, Tyack PL (2004) Beaked whales echolocate on prey. Proceedings of the Royal Society Biological Sciences Series B 271:S383-S386
Johnston DW, McDonald M, Polovina J, Domokos R, Wiggins S, Hildebrand J (2008) Temporal patterns in the acoustic signals of beaked whales at Cross Seamount. Biol Lett 4:208-211
Kasuya T, Nishiwaki M (1971) First record of Mesoplodon densirostris from Formosa. Scientific Reports of the Whales Research Institute 23:129-137
Kim ZG, et al (2000) Whales and dolphins off Korean Peninsula, Vol, Pusan, Korea
Longman HA (1926) New records of cetacea, with a list of Queensland species. Mem Queensland Museum 8:266-278
Lynn SK, Reiss DL (1992) Pulse sequence and whistle production by two captive beaked whales, Mesoplodon species. Mar Mamm Sci 8:299-305
MacLeod CD, Perrin WF, Pitman R, Barlow Jand others (2006) Known and inferred distributions of beaked whale species (Cetacea: Ziphiidae). Journal of Cetacean Research Management 7:271-286
Madsen PT, Johnson M, de Soto NA, Zimmer WMX, Tyack P (2005) Biosonar performance of foraging beaked whales (Mesoplodon densirostris). J Exp Biol 208:181-194
Marten K (2000) Ultrasonic analysis of pygmy sperm whale (Kogia breviceps) and Hubbs' beaked whale (Mesoplodon carlhubbsi) clicks. Aquat Mamm 26:45-48
May-Collado L, Gerrodette T, Calambokidis J, Rasmussen K, Sereg I (2005) Patterns of cetacean sighting distribution in the Pacific Exclusive Economic Zone of Costa Rica based on data collected from 1979-2001. Rev Biol Trop 53:249-263
McDonald MA, Hildebrand JA, Wiggins SM, Johnston DW, Polovina JJ (2009) An acoustic survey of beaked whales at Cross Seamount near Hawaii J Acoust Soc Am 125:624-627
McDonald MA, Mesnick SL, Hildebrand JA (2006) Biogeographic characterisation of blue whale song worldwide: using song to identify populations. J Cetacean Res Manage 8:55-65
McSweeney DJ, Baird RW, Mahaffy SD (2007) Site fidelity, associations and movements of Cuvier's (Ziphius cavirostris) and Blainville's (Mesoplodon densirostris) beaked whales off the island of Hawai'i. Mar Mamm Sci 23:666-687
Mead JG (1989) Beaked whales of the genus Mesoplodon. In: Ridgway SH, Harrison R (eds) Handbook of Marine Mammals, Vol 4: River Dolphins and the Larger Toothed Whales. Academic Press, p 349-430
Mead JG, Walker WA, Houck WJ (1982) Biological observations on Mesoplodon carlhubbsi (Cetacea: Ziphiidae). Smithson Contrib Zool 34:1-25
Mitchell ED (1968) Northeast Pacific stranding distribution and seasonality of Cuvier's beaked whale, Ziphius cavirostris. Canadian Journal of Zoology 46:265-279
Miyazaki N (1986) Catalogue of marine mammal specimens, Vol. National Science Museum of Tokyo, Tokyo, Japan
Moore JC, Gilmore RM (1965) A Beaked Whale New to the Western Hemisphere. Nature (London) 205:1239-1240
Nishiwaki M, Kamiya T (1958) A beaked whale Mesoplodon stranded at Oiso beach, Japan. Scientific Reports of the Whales Research Institute 13:53-83 + 17 plates
Nishiwaki M, Kamiya T (1959) Mesoplodon stejnegeri from the coast of Japan. Scientific Reports of the Whales Research Institute 14:35-48
Nishiwaki M, Kasuya T, Kureha K, Oguro N (1972) Further comments on Mesoplodon ginkgodens. Scientific Reports of the Whales Research Institute 24:43-56
Nitta E (1991) The marine mammal stranding network for Hawaii: an overview. In: III JER, Odell DK (eds) Marine Mammal Strandings in the United States, Vol 98. NOAA Tech. Rep. NMFS, p 56-62
Palacios DM (1996) On the specimen of the Ginkgo-toothed beaked whale, Mesoplodon ginkgodens, from the Galapagos Islands. Mar Mamm Sci 12:444-446
Pike GCaM, I. B. (1969) Marine mammals of British Columbia. Fisheries Research Board of Canada Bulletin 171:1-54
Pitman RL, Aguayo-L. A, Urban-R. J (1987) Observations of an unidentified beaked whale (Mesoplodon sp.) in the eastern tropical Pacific. Mar Mamm Sci 3: 345-352

Rankin S, Baumann-Pickering S, Yack T, Barlow J (2011) Description of sounds recorded from Longman's beaked whale, Indopacetus pacificus. The Journal of the Acoustical Society of America 130:EL339-EL344

Richards LP (1952) Cuvier's beaked whale from Hawaii. J Mammal 33:255

Schorr GS, Baird RW, Hanson MB, Webster DL, McSweeney DJ, Andrews RD (2010) Movements of satellite-tagged Blainville's beaked whales off the island of Hawai'i. Endangered Species Research 10:203-213

Soldevilla MS, Henderson EE, Campbell GS, Wiggins SM, Hildebrand JA, Roch MA (2008) Classification of Risso's and Pacific white-sided dolphins using spectral properties of echolocation clicks. The Journal of the Acoustical Society of America 124:609-624

Stejneger L (1883) Contributions to the history of the Commander Islands. No. 1- Notes on the natural history, including descriptions of new cetaceans. Proceedings of the US National Museum 6:58-89

Tidemann CR (1980) Mesoplodon bowdoini Andrews (Ziphiidae): a new whale record from New South Wales. Vict Naturalist 97:64-65

Tyack PL, Johnson M, Soto NA, Sturlese A, Madsen PT (2006) Extreme diving of beaked whales. J Exp Biol 209:4238-4253

Urbán R. J, Cárdenas-Hinojosa G, Gómez-Gallardo U. A, González-Peral U, Del Toro-Orozco W, Brownell J, R. L. (2007) Mass stranding of Baird's beaked whales at San Jose Island, Gulf of California, Mexico. Latin Am J Aquat Mammals 6:83-88

Urbán-Ramírez J, Aurioles-Gamboa D (1992) First record of the pygmy beaked whale Mesoplodon peruvianus in the North Pacific. Mar Mamm Sci 8:420-425

Walker WA, Hanson MB (1999) Biological observations on Stejneger's beaked whale, Mesoplodon stejnegeri, from strandings on Adak Island, Alaska. Mar Mamm Sci 15:1314-1329

Waring GT, Hamazaki T, Sheehan D, Wood G, Baker S (2001) Characterization of beaked whale (Ziphiidae) and sperm whale (Physeter macrocephalus) summer habitat in shelf-edge and deeper waters off the northeast U.S. Mar Mamm Sci 17:703-717

Welch PD (1967) The use of fast Fourier transform for the estimation of power spectra: A method based on a time averaging over short, modified periodograms. IEEE Trans Audio Electroacoustics AU-15:70-73

Wiggins SM, Hildebrand JA (2007) High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring UT07+SSC07, Tokyo, Japan

Willis PM, Baird RW (1998) Sightings and strandings of beaked whales on the west coast of Canada. Aquat Mamm 24:21-25

Zimmer WMX, Johnson MP, Madsen PT, Tyack PL (2005) Echolocation clicks of free-ranging Cuvier's beaked whales (Ziphius cavirostris). J Acoust Soc Am 117:3919-3927