

Analysis of long-term acoustic datasets for baleen whales and beaked whales within the Mariana Islands Range Complex (MIRC) for 2010 to 2013¹

Erin M. Oleson¹, Simone Baumann-Pickering², Ana Širović², Karlina P. Merkens¹, Lisa M. Munger^{1,3}, Jennifer S. Trickey², and Pollyanna Fisher-Pool¹

¹NOAA Fisheries, Pacific Islands Fisheries Science Center, Protected Species Division

²Scripps Institution of Oceanography, Marine Physical Laboratory

³Oceanwide Science Institute

Introduction

Cetacean distribution and abundance in the Mariana Archipelago was relatively unstudied until recently. Although there has been increasing effort to understand the occurrence of various cetacean species in both near shore and offshore waters, there is still relatively little known about their occurrence seasonally, or their prevalence relative to other regions. To better understand the seasonal distribution of cetaceans in the Marianas, the NOAA Pacific Islands Fisheries Science Center (PIFSC) deployed a long-term acoustic recorder in the region in 2010, expanded that effort to two sites in 2011, and has been monitoring both sites since that time.

Large whales have long been known to occur in the Marianas region, though documented sightings and strandings have been infrequent and concentrated in the winter and spring months. During a Navy-sponsored ship survey in 2007, visual and acoustic survey teams documented sperm (*Physeter macrocephalus*), Bryde's (*Balaenoptera edeni*), and sei (*B. borealis*) whales, and an acoustic team detected humpback whales (*Megaptera novaeangliae*) (Fulling *et al.* 2011, DoN 2007) and minke whales (*B. acutorostrata*) (Norris *et al.* 2012). Researchers in Guam and the Commonwealth of the Northern Marianas Islands (CNMI) have documented strandings of sperm whales on Guam and a Bryde's whale on Saipan, as well as other unidentified large whales on Guam and Tinian (Eldredge *et al.* 2003, Trianni & Tenorio, 2012). Aerial surveys conducted by the Guam Department of Agriculture and Water Resources over the nearshore waters around Guam have also commonly noted "large whales", most likely humpbacks during the winter months (Tebbatts, pers. comm.) and an August 2007 aerial survey conducted by the Navy reported Bryde's whales near Guam (Mobley *et al.* 2007). A few reports on large whale occurrence from whaling records (Townsend 1935, Camba 1965, Masaki 1972) or from surveys focused on large whale distribution in the western North Pacific (Darling and Mori 1993, Shimada and Miyashita 2001, Ohizumi *et al.* 2002) also provide evidence of occasional occurrence of large whales in Marianas waters. However, visual observations of large whales in Marianas waters are rare and the occurrence of several species, including blue (*B. musculus*) and fin whales (*B. physalus*) has not been noted previously. For those species that are known to occur, the precise timing of their arrival in Marianas waters and their relative occurrence during their stay has not been studied. Many species of

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large whale produce stereotypic low-frequency sounds that can be identified to species with high certainty. With knowledge of these species-specific vocalizations, assessment of seasonal occurrence and relative abundance may be assessed from year-round acoustic recordings from the region.

Beaked whales have been reported very infrequently in Marianas waters. The group of species is often very difficult to see because of their cryptic diving behavior, likely resulting in low visual encounter rates during the surveys that have been conducted. Three groups of unidentified beaked whales were observed during the 2007 Navy survey (Fulling *et al.* 2011), a Cuvier's beaked whale (*Ziphius cavirostris*) was sighted during an August 2007 aerial survey (Mobley *et al.* 2007) and Blainville's (*Mesoplodon densirostris*) and Cuvier's beaked whales have been sighted during PIFSC surveys near Saipan and Rota in recent years (Hill *et al.* 2014). One stranding of a Cuvier's beaked whale on Saipan in 2007 and two strandings in 2011 also confirm the occurrence of this species in the region (NMFS PIRO Marine Mammal Stranding Response Network). No other information is available on the occurrence of other beaked whale species, the seasonality of any species, or their relative abundance compared to other regions that have been more intensively studied.

Beaked whales have been shown to produce species-specific frequency modulated (FM) echolocation pulses (Baumann-Pickering *et al.* 2013). Blainville's beaked whale, Cuvier's beaked whale, Longman's beaked whale (*Indopacetus pacificus*), and possibly Deraniyagala's beaked whale (*M. hotaula*) are species expected in the study region, based on their sighting or stranding records, or based on their general distribution patterns globally, and whose FM pulse types are described (reviewed by Baumann-Pickering *et al.* 2014). A signal type with beaked whale typical characteristics, first recorded at Cross Seamount (McDonald *et al.* 2009), was subsequently shown to occur at most subtropical and tropical recording sites, referred to as BWC (Baumann-Pickering *et al.* 2013). Ginkgo-toothed beaked whales (*M. ginkgodens*) may produce the BWC signal type (Baumann-Pickering *et al.* 2014).

Beginning in 2013, the U.S. Navy partnered with PIFSC to analyze the existing acoustic monitoring data for the occurrence of baleen whales and beaked whales to better understand the seasonal use of the Mariana Island Range Complex (MIRC) by these species and their seasonal relative abundance. Study objectives were driven by the specific questions outlined in the MIRC monitoring plan, including:

1. What species of beaked whales and other odontocetes occur around Guam and Saipan?
2. What is the seasonal occurrence of baleen whales around Guam, Saipan, Tinian, and Rota?

A number of analysis components were undertaken on the available datasets. Because much of the data had not yet been scanned prior to this effort, it was difficult to know in advance how long it would take to assess daily occurrence of each species of interest with the 5 total data sets (Table 1). For this reason, work proceeded in the order provided below. Although we felt it was unlikely that the time allocated would allow for all five analysis priorities to be completed as part of this project, all have been done and the results are reported here. In some cases additional datasets beyond the required scope were also analyzed and those results are also reported to allow for more complete assessment of large whale and beaked whale occurrence in the region.

Data analysis priorities:

1. Model sound propagation and detection range for detected baleen whale calls under 1kHz
2. Assess daily occurrence of baleen whales with low frequency (< 1 kHz) calls in all 5 data sets.
3. Assess daily occurrence of all beaked whales within one dataset
4. Determine species-ID for detected beaked whale sounds
5. Assess daily occurrence of minke and sperm whales within one dataset

Methods

PIFSC maintains long-term acoustic datasets collected near Saipan and Tinian in the southern Mariana Archipelago. High-frequency Acoustic Recording Packages (HARPs) were used to record underwater sounds from 10 Hz to 100 kHz with 16-bit quantization. The HARP sensor and mooring package are described in Wiggins and Hildebrand (2007). For the MIRC deployments, the HARP was configured as a mooring, anchored on the seafloor with the hydrophone suspended 30 m above. Each HARP is calibrated in the laboratory to provide a quantitative analysis of the received sound field. Representative data loggers and hydrophones have also been calibrated at the Navy’s Transducer Evaluation Center (TRANSDEC) facility to verify the laboratory calibrations. Deployment and recording details for all acoustic data collected in the region are provided in Table 1.

Table 1: Overview of deployments at Saipan and Tinian. The duty cycle refers to 5 minutes of recordings over a recording interval varying between deployments. All times are in GMT.

Deployment	Latitude	Longitude	Depth (m)	Start Effort	End Effort	Duty Cycle
Saipan01	15-19.0 N	145-27.5 E	689	3/5/10 0:00	8/25/10 15:25	5/40
Saipan02	15-19.0 N	145-27.5 E	696	4/27/11 0:00	10/19/11 22:22	5/20
Saipan03*	15-19.1 N	145-27.4 E	700	6/20/12 0:00	7/11/12 14:13	5/6
				8/2/12 11:55	3/8/13 14:37	5/6
Tinian02	15-02.3 N	145-45.1 E	995	4/13/11 0:00	11/22/11 14:05	5/20
Tinian03*- LF	15-02.4 N	145.45.3 E	998	6/23/12 0:00	11/24/12 12:00	5/7
Tinian03*- HF				6/23/12 0:00	5/14/13 19:35	5/7

* There is a gap in recording effort at Saipan03 due to a failed hard drive.

† Overlapping effort periods are provided for Tinian03, as low-frequency (LF) data collection became unusable mid-deployment due to a hydrophone failure. Data above approximately 5 kHz were not impacted by the failure and continued until the HARP was retrieved.

Large whale detection

Detection of large whales within the HARP data was carried out by manual inspection by trained analysts. The original HARP data were decimated to lower frequencies to allow more efficient viewing at the appropriate frequency and time resolution. A low-frequency (LF) dataset was created by decimating the HARP data to 2 kHz sample rate, and these low-frequency data were scanned for blue, fin, sei, and Bryde’s whales. A mid-frequency (MF) dataset was decimated to 10 kHz sample rate, with this data

scanned for minke and humpback whales. Sperm whales were detected within the full-bandwidth data (HF), but with reduced viewing window extending only up to 40 kHz. Each data set was visually and aurally analyzed using the program Triton, a Matlab-based software package for acoustic data display and analysis (Wiggins 2003). A long-term spectral average (LTSA) was computed for each data set by averaging power spectral density (Welch 1967) in 5 s time bins and 1 Hz frequency bins for LF data, 10 Hz bins for MF data, and 100 Hz bins for HF data. The analyst visually inspected the LTSA spectrogram display to search for potential calls of each species, and calls were verified by visual examination of spectrograms and, in some cases, audio playback. In LTSA search mode, the frequency display was typically set to the band from 0-300 Hz when scanning LF data, 0-2 kHz for MF data, and 0-40 kHz for HF data.

The presence of calls was logged on a per day basis; that is, if at least one call was detected on a particular day, the analyst did not search for further calls from the same species on the same day. Because baleen whale calls may be faint or hard to detect within an LTSA if they do not occur in an extended series, for each day with calls detected in the LTSA, spectrograms from one day before and one day after were scanned until no additional calls were found. Calls were assigned to species based on resemblance to known calls published in the literature. Sounds that were consistent in frequency and spectral characters to other baleen whales sounds, but whose source was unknown, were also marked and labeled as 'unknown whale.'

Low frequency propagation modeling

To estimate distances to calling whales, information on (1) call source levels (SL), (2) received levels (RL), and (3) transmission loss (TL) in the studied environment are required. TL models were run based on the predominant frequency component for each call type, and all SL and RL assumptions and measures use the same frequency characteristics. Because our knowledge of call SLs is relatively poor in general, and almost non-existent for calls produced in this particular region, the estimates we used for this analysis were based on the best-available published records. As there are no SL estimates for tonal Western Pacific blue whale call type, we used 186 dB re: 1 μ Pa @ 1 m which was estimated for relatively similar tonal calls of Eastern Pacific blue whales (McDonald et al. 2001). For fin whale 20 Hz calls we adjusted Weirathmueller et al. (2013) levels for the average 5 Hz bandwidth of fin whale calls (Watkins 1981, Watkins et al. 1987) and used 182 dB re: 1 μ Pa @ 1 m at 20 Hz. We used average estimated SL for the humpback whale song of 155 dB re: 1 μ Pa @ 1 m (Richardson et al. 1995). No SL estimates exist for minke whale boings, but based on estimates of other minke whale calls (e.g. Gedamke et al. 2001), we used 160 dB @ 1 m as the best guess estimate for boing SL.

Received levels were measured based on 1 s of data at the appropriate frequency for each species and call type. Thus for blue and fin whales, we measured RL at 20 Hz, while for humpback and minke whales they were measured at 300 Hz and 1500 Hz, respectively. Before we could measure these RLs, data were scanned for presence of individual calls. Due to overall low number of baleen calls detected at these locations, to increase our overall sample size, deployments used for these analyses included Saipan 01 and 03 and Tinian 02 and 03 (Table 1). A subset of three calls from each calling sequence of blue whale tonals, fin whale calls, and humpback songs was used to estimate the average RL for that calling bout. In

an effort to minimize overrepresentation of calls from a single animal, we used sequences that were separated by at least 2 or more hours. The logged start times from this subset of calls were used to extract 1 s of data and estimate the RL at the appropriate frequency. For minke whale boings, which generally do not occur in long bouts, the RL of each individual call was measured.

Finally, we developed TL models out to 100km range for low frequency sounds at the two HARP deployment locations using ESME Workbench (Boston University) framework. To develop these models, we used environmental data (0.5 degree resolution bathymetry, 0.1 degree resolution sediment properties data, and historical average of monthly sound speed and wind profiles) available in ESME. We developed separate models for each species' call types of interest over four seasons. We used January data as representative of winter, April for spring, July for summer, and October for fall. By using parabolic equation modeling, we calculated TL along 16 radials centered at the HARP deployment location out to the distances of 100 km in 495 m bin increments for blue, fin, and humpback whale call frequencies. For minke whale calls we used a Bellhop model calculated out to 50 km in 10 m bin increments. In all cases, we assumed whales were calling at 30 m depth.

Based on assumed whale call SLs described above, and measured RL, we used these models to estimate ranges over which baleen whale calls can be detected at the two sites. This was done by calculating the TL of each species using the formula: $TL = SL - RL$. A set of ranges at which that calling animal could be located was extracted from the model results based on ranges at which the calculated TL occurred. The distributions of modeled ranges given our measured RLs are given for each species and site where they were recorded.

Beaked whale detection and classification

The full bandwidth HARP dataset was used for detection and classification of beaked whales. An automated multi-step beaked whale detector, described in detail in Baumann-Pickering *et al.* (2013), was run on the dataset to detect periods of beaked whale calling. All echolocation signals were initially identified with a click detector (Soldevilla *et al.* 2008, Roch *et al.* 2011). The individual click 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. The click parameters peak frequency, center frequency, and bandwidth were calculated according to definitions in Au (1993). Duration was derived based on the detector output. Sweep rate was computed with spectrograms over 1.2 ms of data centered on the signal (0.3 ms Hann windows and 98% overlap). Sweeps were traced by selecting the frequency bins with maximum spectrum level for each frame. The -8 dB level from the maximum spectrum level of the traced sweep defined the beginning and ending of a sweep. A line of best fit through the sweep was calculated, resulting in a sweep rate. All detected echolocation signals, independent of distance and orientation of the recorded animal with respect to the recorder, were included in the analysis.

An expert system classified 75 s of data containing at least 7 detections as having beaked whale clicks given these conditions: 1) echolocation signals had a peak and center frequency above 32 and 25 kHz,

respectively, a duration of more than 355 μ s, and a sweep rate of more than 23 kHz/ms. 2) If more than 13% of all initially detected echolocation signals over 75 s remained after applying these criteria, the segment was classified to have beaked whale FM pulses. This method detects acoustic encounters with central and western Pacific FM pulse types with approximately 5% missed detection rate, with the exception Longman's beaked whales. Because this species produces only very few FM pulse type signals and considerably more delphinid-like echolocation clicks (Rankin *et al.* 2011) that are to-date not distinguishable from dolphin echolocation clicks, it is not yet possible to distinguish Longman's beaked whale within our classification scheme.

A third classification step, based on computer assisted manual decisions by trained analysts, labeled the automatically detected segments to species level and rejected false detections (method in Baumann-Pickering *et al.* 2013). In short, for each acoustic encounter, custom software for analyst-assisted signal discrimination displayed temporal and spectral characteristics of the encounter. This consisted of histograms of peak frequency and IPI, their medians, and those of peak-to-peak received level, center frequency, and duration. Mean spectra of all pulses and mean noise preceding each FM pulse was plotted against an overlay of spectral templates from all currently known FM pulse types (see Baumann-Pickering *et al.* (2013) for descriptions). The overlay of the mean spectra of the encounter with the spectral templates allowed for comparison of all spectral features, with special emphasis on smaller spectral peaks at frequencies below the main energy content and the slope at which the main energy content rose. The analyst also could optionally browse through individual time series and spectrograms of echolocation signals detected within the acoustic encounter, sorted by peak-to-peak received level displaying high quality signals first. A final judgment about the signal type was based on comparison to the templates and labeled to species or unknown signal-type level by the analyst.

Results

Large whale occurrence

Blue, fin, humpback, minke, and sperm whales were identified within the Saipan and Tinian acoustic datasets. Unidentified whale sounds were also observed and their occurrence noted given their relative prevalence. A sharp increase in instrument noise at low frequencies was evident within the Tinian03 dataset beginning in late November 2012. No low-frequency sounds were detected from large whales after that time, but it is more likely that their sounds were masked or that hydrophone sensitivity was reduced by physical damage, rather than that the whales were not present. Since low frequency sounds were not detectable, we have indicated that there was no acoustic recording effort after late-November 2012 for all low and mid-frequency species. The high-frequency data were still usable after November 2012, such that it was still possible to determine the occurrence of sperm whales.

There were marked differences in large whale detection between the Saipan and Tinian HARP sites, with far more days with large whale calls at Saipan than at Tinian. Sperm whales were the most common large whale detected at both sites, heard on 241 out of 607 days of recording effort at Saipan, and on 44 of 550 days of recording effort at Tinian. Sperm whales were heard during all months with recording

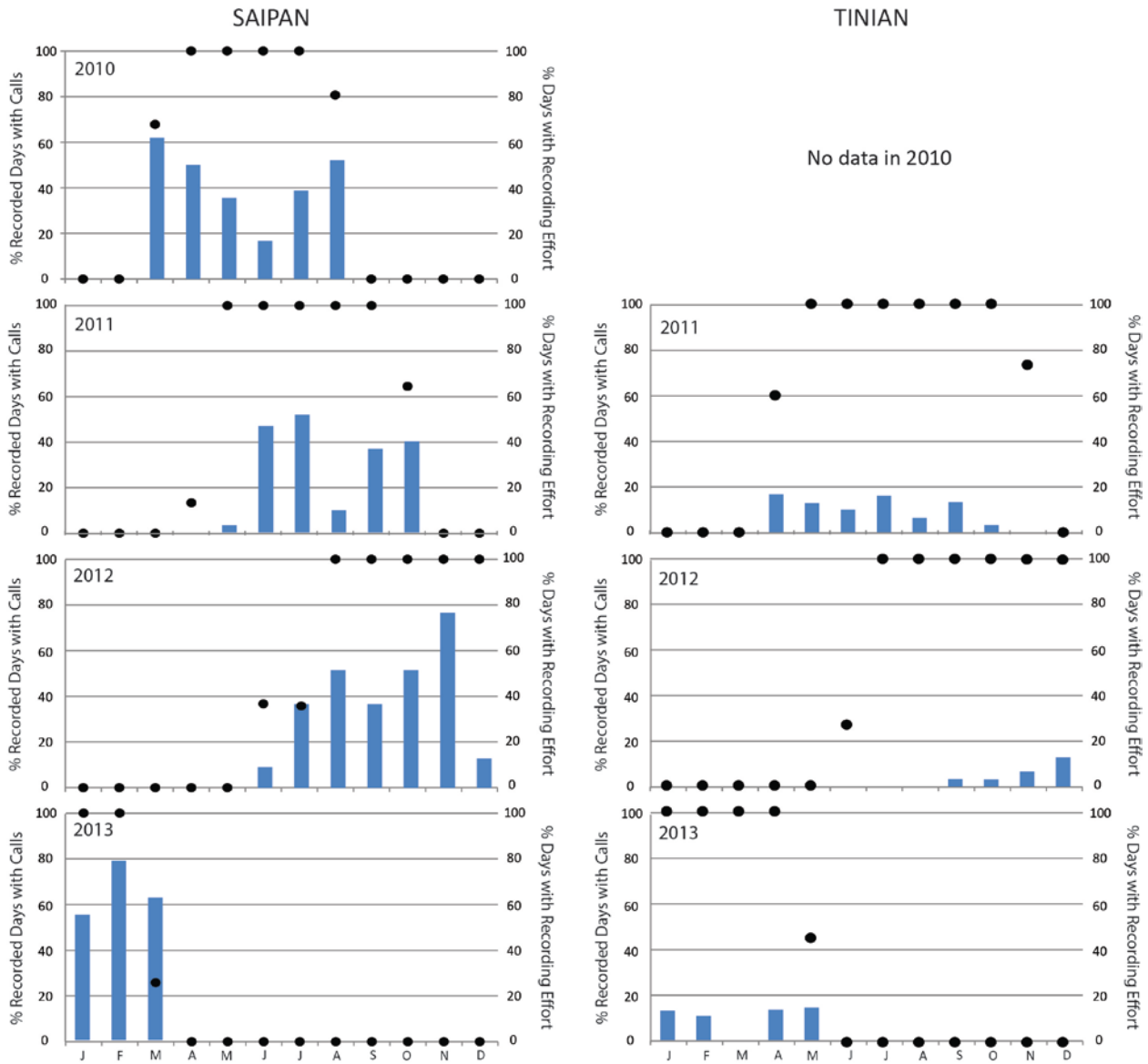


Figure 1. Percent daily occurrence of sperm whales from 2010 through 2013 within the Saipan (left panels) and Tinian (right panels) HARP datasets. Acoustic recording effort is noted as the black circles and represents the percentage of days with data available per month. Although data were duty-cycled and therefore data volume by month may vary between years, these duty-cycle differences are not noted in this figure (see Table 1). The percentage of days with acoustic data during which sperm whale sounds were detected is noted by the blue bars.

effort at Saipan (Fig. 1), with the exception of April 2011, when only 4 days of recording effort occurred during that month. Because of the pattern of recording effort over time it is difficult to discern specific seasonal patterns of occurrence in sperm whales at Saipan, though it does appear that they may move in and out of the region over the course of a few months with temporary increases or decreases in detection over time. During the one year with acoustic data available in the winter, the daily occurrence of sperm whales suggests they may be somewhat more common

from January to March than during other months. Sperm whales were less common at Tinian, detected on less than 20% of days per month with acoustic data available. There are several months with acoustic data available when sperm whales were not heard at Tinian, though no clear seasonal pattern in their occurrence is evident for this site.

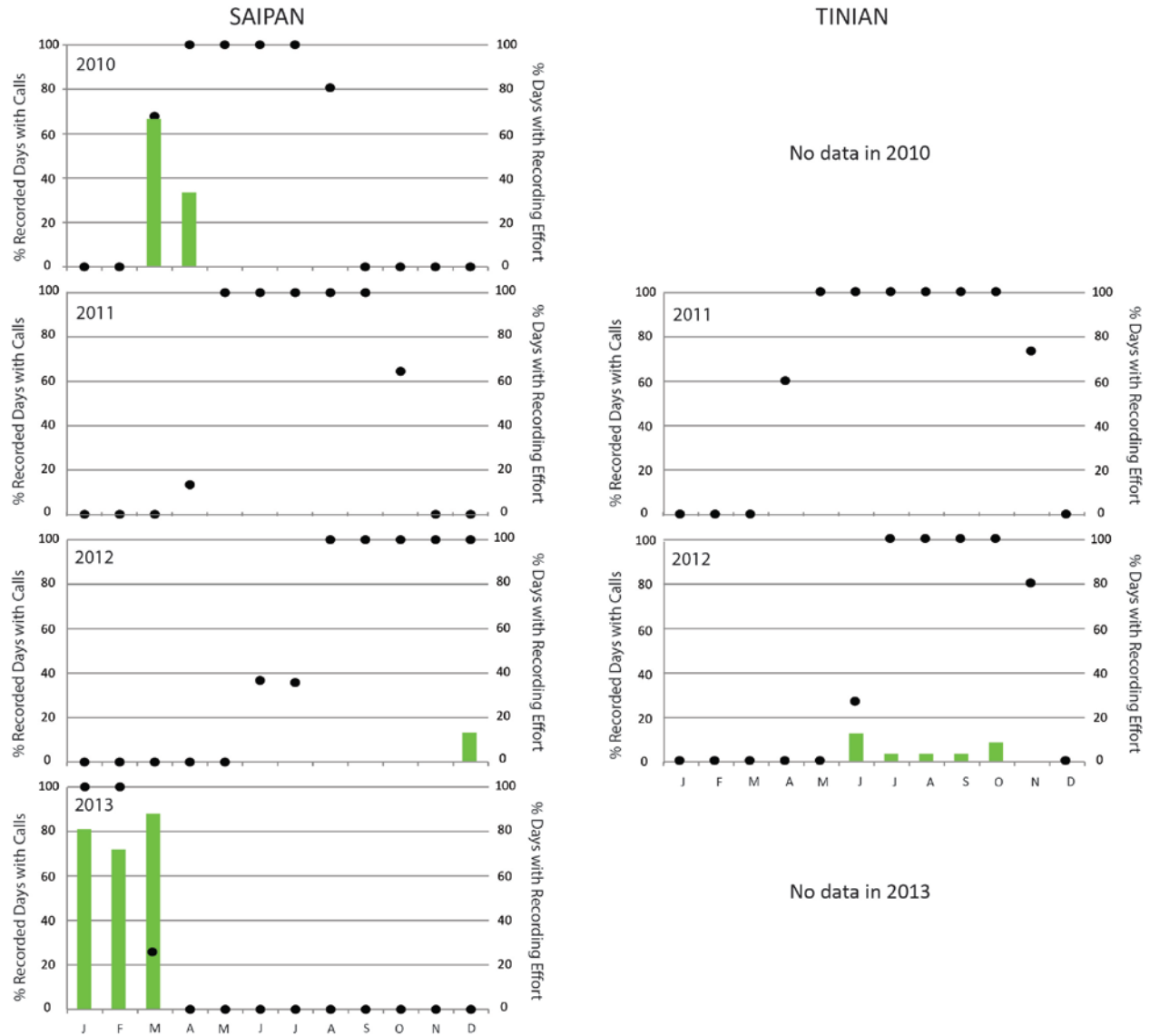


Figure 2. Percent daily occurrence of humpback whales from 2010 through 2013 within the Saipan (left panels) and Tinian (right panels) HARP datasets. Acoustic recording effort is noted as the black circles and represents the percentage of days with data available per month. Although data were duty-cycled and therefore data volume by month may vary between years, these duty-cycle differences are not noted in this figure (see Table 1). The percentage of days with acoustic data during which humpback whale sounds were detected is noted by the green bars.

Humpback whales were the second most common large whale detected at the Saipan and Tinian HARP sites. Humpback song was heard December through April at Saipan in all years with recording effort during that period (Fig. 2). No humpback song or calls were heard outside of that winter period at Saipan, such that there were no detections in 2011 when effort spanned only the period from May to October, and few detections in 2010 and 2012 when recording effort was similarly constrained. Humpback whale sounds were infrequently detected at Tinian during the summer months, from June to October, of 2012. There was no detection of humpback whales at Tinian during the period of acoustic effort in 2011.

Unidentified whale sounds with consistent spectral characteristics were also frequently detected at the Tinian HARP site. Calls described as 50Hz or 38Hz tonals were detected in most months with low-frequency acoustic data available at Tinian (Fig. 3), though were notably absent in July of both 2011 and 2012. We suspect these sounds are produced by Bryde’s whales, based on similarity to calls produced by that species in other regions (e.g Oleson *et al.* 2003), but at this time we do not have any regional recordings of Bryde’s whales with which to verify the sounds’ source.

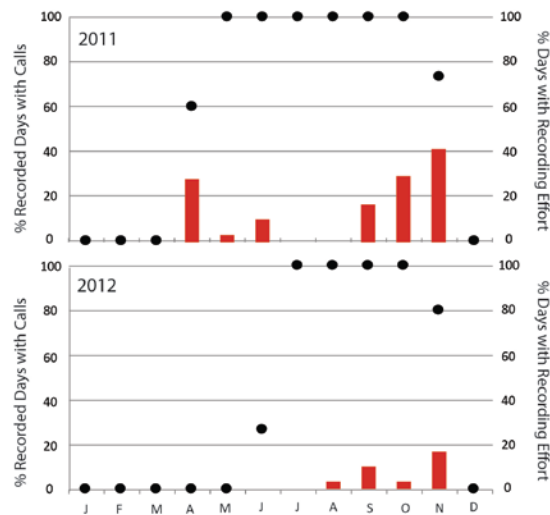


Figure 3. Percent daily occurrence of all unidentified whale calls in the 2011 and 2012 Tinian dataset. Acoustic recording effort is noted as the black circles and represents the percentage of days with data available per month. Although data were duty-cycled and therefore data volume by month may vary between years, these duty-cycle differences are not noted in this figure (see Table 1). The percentage of days with acoustic data during which UW sounds were detected is noted by the red bars.

Blue and fin whale calls were rarely detected in the Saipan and Tinian datasets, and minke whales boings were detected on a few occasions at Saipan only. Blue whale 20Hz tonal calls were detected on 7 of 607 days of monitoring effort at Saipan (in September, 2010- 1 day, and 2011- 2 days; November- 1 day, and December, 2012- 2 days; January, 2013- 1 day) and downswept D calls were detected on 4 of 379 monitoring days at Tinian (May, 2011- 1 day; June, 2012- 2 days; August, 2012- 1 day). The 20Hz tonal

calls were consistent with those previously identified as belonging to the central Pacific blue whales. Downswept D calls are generally not identifiable to population. Fin whale 20-Hz calls were detected on 4 days off Saipan (April, 2010- 2 days; May, 2011- 2 days) and two days in April 2011 off Tinian. Minke whale boings were detected during 6 days in March and April 2010 at Saipan.

Low-frequency propagation modeling

A total of one blue whale tonal, 10 fin whale downsweeps, and 28 humpback whale calling sequences in addition to eight minke whale boings, were sampled and RL was measured at the Saipan site (Figure 4) within deployments Saipan01 and Saipan03 (Table 1). In general, fin whale received levels were the highest, however that can be expected given their high source levels and better propagation characteristics at lower frequencies. From the Tinian site, six blue whale, two fin whale, and one humpback whale sequences were measured (Figure 5). Measured RLs at this site were generally lower, and there were fewer of them than at Saipan.

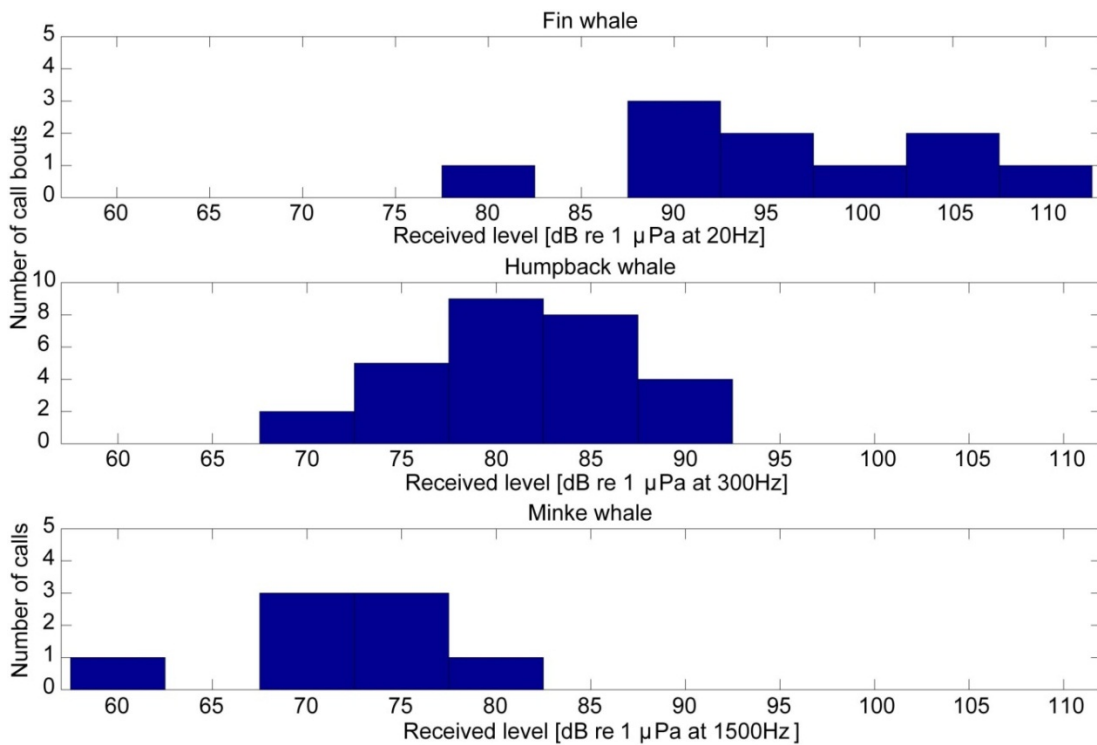


Figure 4. Frequency distribution of measured received levels at appropriate frequency for a sample of fin (top), humpback (middle) and minke whale calls (bottom) recorded at Saipan.

Based on the measured received levels and our propagation models there appears to be a spatial separation between different species of baleen whales that occur in the vicinity of Saipan (Figure 6). Based on the models from Saipan, minke whales appeared to be closest to the deployment location, mostly at ranges 10-30 km. Calling fin whales may have occurred over a range of distances, from as close to 10 or 20 km to potentially even beyond our modeled detection range (100 km). The one blue whale call sequence we measured was likely from a relatively distant whale (farther than 60 km). Calling

humpback whales were most likely found within a range of 20-60 km, although farther detection was also possible.

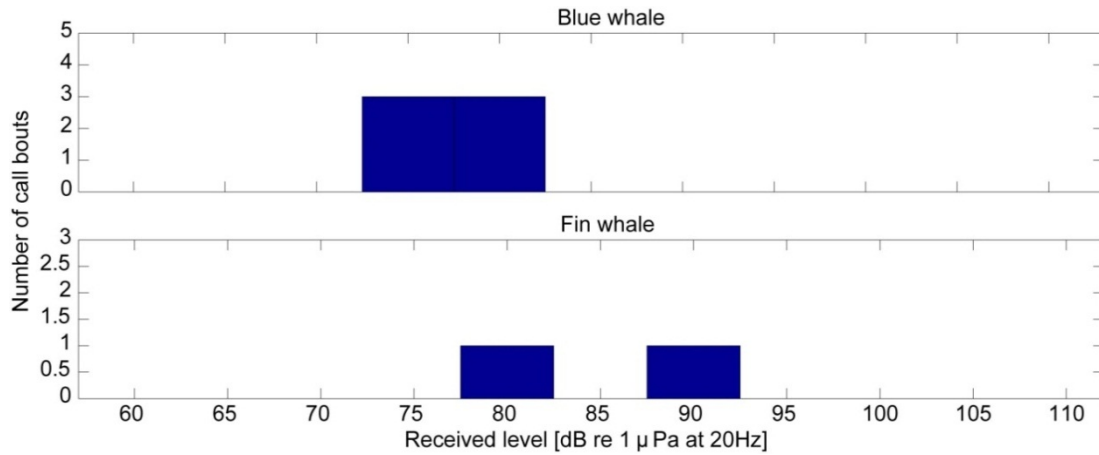


Figure 5. Frequency distribution of measured received levels at 20 Hz for a sample of blue (top) and fin whale calls (bottom) recorded at Tinian.

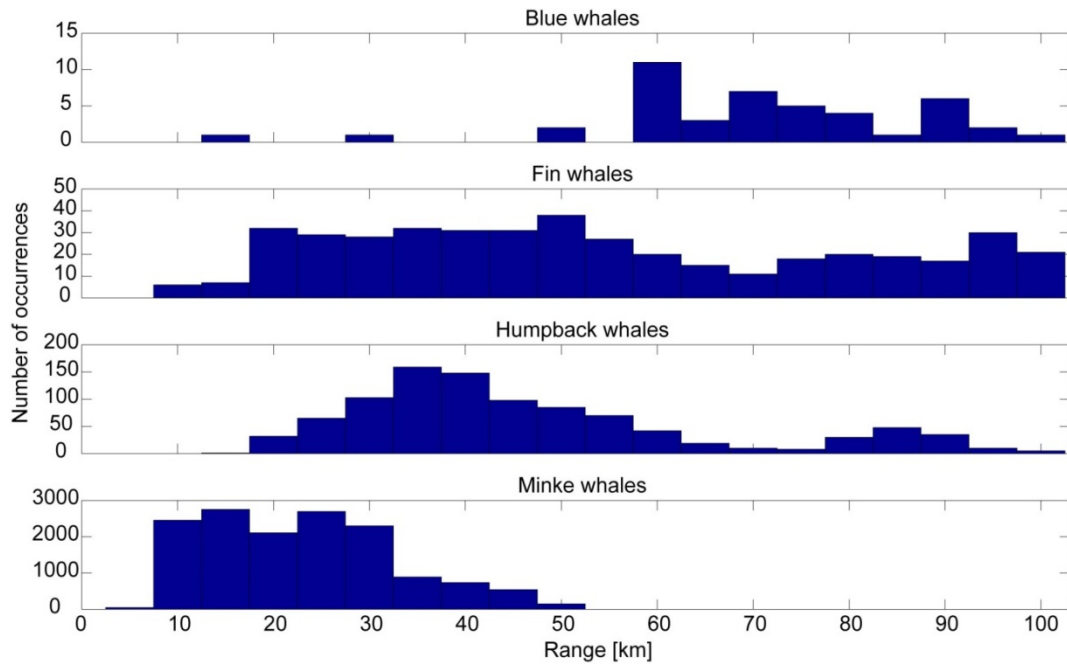


Figure 6. Distribution of possible range estimates based on measured RL and modeled TL for calling blue (top), fin (middle-top), humpback (middle-bottom), and minke whales (bottom) recorded at Saipan.

At Tinian, there was a lot less variation in range distributions in the measured examples of blue, fin and humpback whales, with all three species likely calling at a distance of more than 20 km, but most closer than 100 km (Figure 7). This contrast could be attributed to the more complex bathymetry near the Saipan site which would produce greater differences in propagation distance for a single call.

All results presented here only show propagation models for April since spring was the period when most calls occurred. Differences at other times on average were between 1 and 3 dB, with generally less TL (indicating a somewhat larger detection range) occurring in January than April, and with most TL and shorter detection ranges in July.

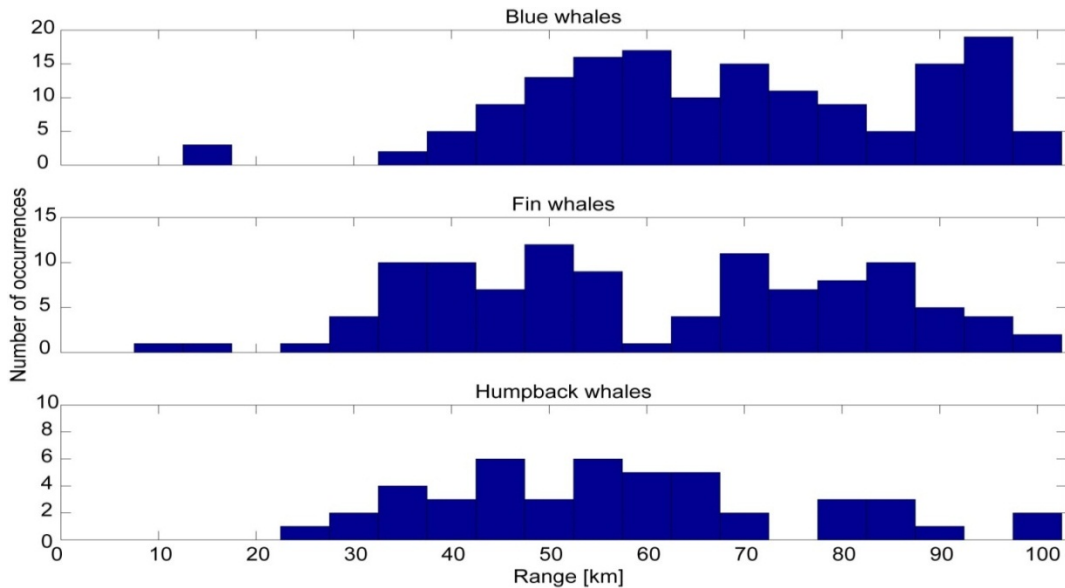


Figure 7. Distribution of possible range estimates based on measured RL and modeled TL for calling blue (top), fin (middle), and humpback whales (bottom) recorded at Tinian.

Beaked whale detection and classification

Although the scope of work called for daily assessment of beaked whales within only a single 2012-2013 dataset, a beaked whale echolocation click detector was available for use and as such all Saipan and Tinian datasets (Table 1) have been evaluated for beaked whales. The occurrence of all beaked whale clicks was quantified on a monthly basis (Figure 8). These quantifications do not account for differences in duty-cycling between datasets, such that overall differences in the number of days detected between years (2010 vs. 2011 vs. 2012-13) may not necessarily indicate differences in occurrence in the region. Increased recording effort in 2012-13 may have increased recording opportunity for a species with relatively short click bouts. The detections do indicate that, as group, beaked whales appear to occur year-round at both sites, with no clear seasonal pattern in their detection. Beaked whales were detected on 291 of 607 monitoring days at Saipan and 173 of 550 monitoring days at Tinian.

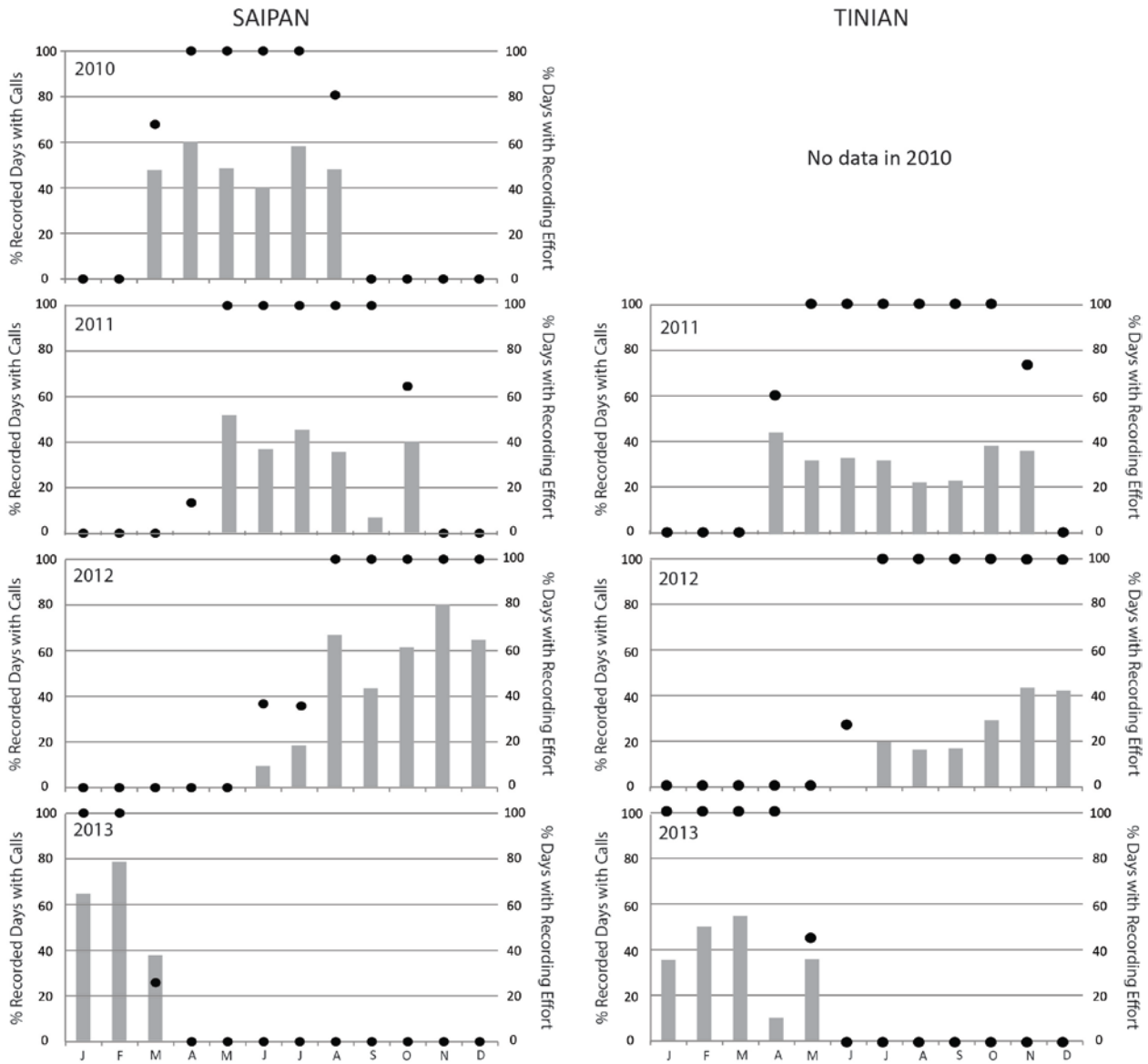


Figure 8. Percent daily occurrence of all beaked whale detections from 2010 through 2013 within the Saipan (left panels) and Tinian (right panels) HARP datasets. Acoustic recording effort is noted as the black circles and represents the percentage of days with data available per month. Although data were duty-cycled and therefore data volume by month may vary between years, these duty-cycle differences are not noted in this figure (see Table 1). The percentage of days with acoustic data during which beaked whale sounds were detected is noted by the gray bars.

Classification of detected beaked whale signals is carried out by an analyst. Only the most complete year of acoustic data (2012-13; Saipan03 and Tinian03) was processed to species-level for beaked whales. At both Saipan and Tinian three different beaked whale FM pulse signal types were acoustically encountered, produced by Blainville’s beaked whales, Cuvier’s beaked whales, and the BWC type possibly from Ginkgo-toothed beaked whales. Encounters with each species were quantified on a

monthly basis as well as the cumulative duration of each species' echolocation click bouts within a weekly period. The detections fluctuated over time likely due to changing local oceanographic conditions with no seasonal pattern (Figure 9). Detections of signals produced by Blainville's beaked whales were strongly dominating both sites (Table 2, Figure 10). Cuvier's beaked whales were encountered on more days (Figure 9) and for longer cumulative duration (Figure 10, Table 2) at Saipan than at Tinian, and were in fact, quite rare at Tinian, occurring on only 4 days of the monitoring year. The BWC type was regularly detected at both sites, however with short cumulative encounter duration (Table 2).

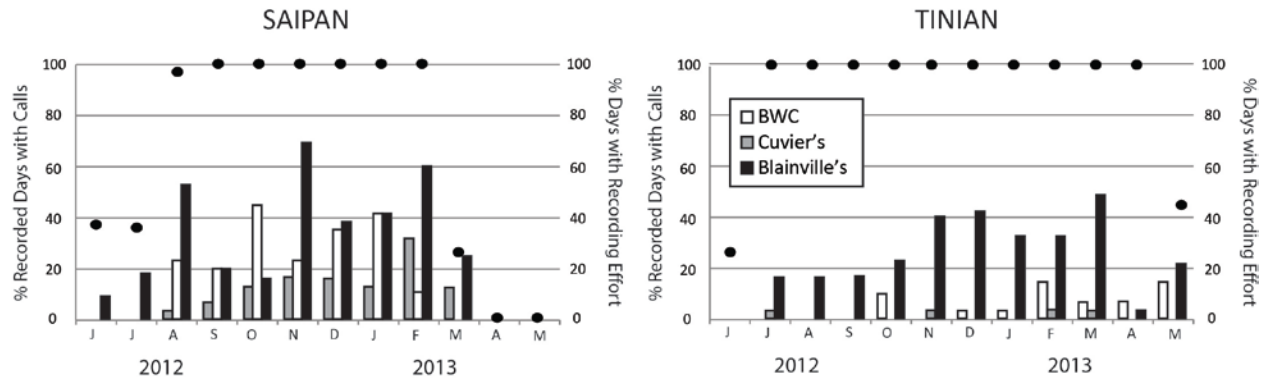


Figure 9. Percent daily occurrence of Blainville's (black), Cuvier's (gray), and BWC (white) beaked whales in the 2012-13 HARP data from Saipan (left panel) and Tinian (right panel). Acoustic recording effort is noted as the black circles and represents the percentage of days with data available per month.

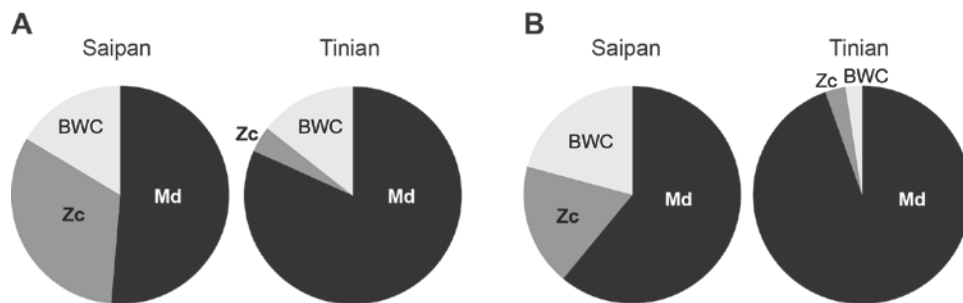


Figure 10: Relative presence of acoustic encounters at Saipan and Tinian of Blainville's beaked whale, Md, Cuvier's beaked whale, Zc, and possibly Ginkgo-toothed beaked whale, BWC. A) Relative species presence based on number of days with detections. B) Relative species presence based on cumulative duration of acoustic encounters.

Discussion

Large whale occurrence

Manual scanning of the Saipan and Tinian HARP data reveals that large whales were heard relatively infrequently in this region relative to elsewhere in the central Pacific. Blue, fin, minke, humpback, and sperm whales were detected, though blue, fin, and minke whale detection were rare across all three years of monitoring effort. An unidentified whale sound was also frequently heard at the Tinian site. Based on comparison to recordings from other locations, we suspect this sound may be produced by Bryde's whales, though visually verified recordings will be needed to be certain about the species identity. Although sei whales were known to occur in the region in the late 1800s, and were seen during the MISTCS survey (Fulling *et al.* 2011), we did not hear whale calls we could positively attribute to sei whale within our datasets. Unusual sei whale calls have been reported from the Mariana Archipelago (Norris *et al.* 2012), though the dominant frequency components of each of these call types was above 1000 Hz, and therefore beyond the scope of our scanning effort. Further, several of the described calls were heard on only one or two occasions, such that additional verification may be necessary before they can absolutely attributed to sei whales. Although the acoustic monitoring data span a three year period, only one year of data collection spanned the winter months, or part thereof, at both monitoring sites. This limitation in the available dataset limits conclusions that may be drawn from these analyses, as interannual variability may be significant in this region.

Low frequency propagation modeling

Propagation modeling on sounds detected from blue, fin, minke, and humpback whales suggests the detection range of these signals around the HARP may be quite large. Because it is not possible to determine the location of calling whales with a single instrument, we present the range of detection distances possible given the bathymetric, sound speed, and sediment properties of the region, together with known and assumed information on whale calling source level and calling depth. The range of potential detection distances can vary significantly given the differences in the local bathymetry around each HARP site; however the results do provide bounds of likely detectability in this region. Two different propagation modeling frameworks were used given the significant differences in calling frequency for minke whales versus blue, fin, and humpback whales. The Bellhop models used for minke whales employ much finer resolution around the HARP site than the parabolic equation models used for lower frequency species. The result is many more measurements of detection range for a single call than is feasible from the parabolic equation models used for blue, fin, and humpback whales. Despite the use of different models, the overall range values and general distributions can be compared across species and are good indicators of likely distances to calling animals.

Propagation was modelled only out to 100km radial distance for blue, fin, and humpback whales, and 50km for minke whales, from each HARP site. Although some of the results suggest calls may have been propagating from even greater distances, the model framework was not expanded because the assumptions that were required around call SLs and whale call depth would make the model output particularly weak beyond that distance. However, our results do suggest that both blue and fin whales,

the species with the farthest potential detection distances, were both very likely within the 100km modeled distance given the absence of a large number of outcomes at the 100km distance bin. However, very few calls were available for modeling for each of these species, as well as for minke whales, such that a more robust assessment of potential whale distribution around the HARP locations may be possible with the addition of more data as recording in these locations continues.

Beaked whale detection and classification

An automatic detector was used on all HARP datasets from Saipan and Tinian and a single dataset from each site (Saipan03 and Tinian03) was used for manual classification of those detections to the species level. The detection range of beaked whale calls around each HARP site was not modeled as part of this project; however, is likely to be quite small given the high-frequencies of beaked whale sounds. In this way, absence of beaked whale calls within the HARP data cannot be broadly interpreted as absence from the overall area, but can provide an indication of how frequently beaked whales are moving through the area and provide insights into broad seasonal fluctuations in occurrence. The detector results indicate beaked whales are regularly present in the region, though the encounter rate varies markedly over periods of days to weeks. Beaked whales were more commonly detected at the Saipan HARP site than at Tinian, with just over half of monitoring days at Saipan containing beaked whale calls and less than one-third of monitoring days at Tinian containing beaked whale calls.

Table 2: Comparison of beaked whale acoustic detections at Saipan at Tinian for three different FM pulse types.

Saipan (240 days with effort)

	Blainville's beaked whales	Cuvier's beaked whales	BWC	Total
number of days with acoustic detections	97	61	31	144
percentage of effort days with detections	40	25	13	60
cumulative acoustic encounter duration (min)	700	209	239	1148

Tinian (326 days with effort)

	Blainville's beaked whales	Cuvier's beaked whales	BWC	Total
number of days with acoustic detections	85	4	15	100
percentage of effort days with detections	26	1	5	31
cumulative acoustic encounter duration (min)	970	31	25	1026

Manual classification of the detected sounds within the single year-round dataset indicates that Blainville's, Cuvier's, and an unidentified beaked whale, potentially Ginkgo-toothed, occur regularly in this region. Blainville's beaked whales are the most commonly detected at both sites, occurring on 40% and 26% of total monitoring days at Saipan and Tinian, respectively. The relative occurrence of Cuvier's and unidentified beaked whale sounds varied between the two monitoring sites, with higher occurrence of Cuvier's beaked whales at Saipan, and higher occurrence of unidentified beaked whales at Tinian. No other beaked whale sound types have been detected at these sites. It is not yet possible to distinguish the occurrence of Longman's beaked whale from more standard echolocation clicks produced by delphinids, so their occurrence in this region has not been assessed within these data.

The differences in the occurrence rate for Blainville's, Cuvier's and BWC beaked whale signal types (Fig. 10, Table 2) is likely related to differences in detection range and local habitat characteristics at each site. Near Hawaii Blainville's beaked whales are most commonly seen in water depths of 1000-2000m, while Cuvier's beaked whales are more commonly seen in greater water depths, with a peak at 2500-3500m (Baird et al 2013). If similar habitat preferences persist in the Marianas, we would expect higher detection rates of Blainville's beaked whales at the HARP sites because of their relatively shallower depth. In addition to potential differences in habitat selection, the relative rarity of the BWC call type relative to Blainville's beaked whales may be due to a relatively smaller detection range for this species. The BWC call type has a lower source level (assumed based on a very broad bandwidth, lower received levels, and short encounters at all sites across the North Pacific; Baumann-Pickering et al. 2014), which would result in a substantially smaller detection range and therefore less opportunity to record this species even if common in the study area. Differences in detection distance at beaked whale frequencies could be modeled for the HARP sites to examine over what distance each species may be heard and better characterize space use between the two HARP sites.

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