# Minke whales (*Balaenoptera acutorostrata*) respond to navy training

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Minke whales (*Balaenoptera acutorostrata*) were acoustically detected and localized via their boing calls using 766 h of recorded data from 24 hydrophones at the U.S. Navy's Pacific Missile Range Facility located off Kauai, Hawaii. Data were collected before, during, and after naval undersea warfare training events, which occurred in February over three consecutive years (2011–2013). Data collection in the during periods were further categorized as phase A and phase B with the latter being the only period with naval surface ship activities (e.g., frigate and destroyer maneuvers including the use of mid-frequency active sonar). Minimum minke whale densities were estimated for all data periods based upon the numbers of whales acoustically localized within the 3780 km$^2$ study area. The 2011 minimum densities in the study area were: 3.64 whales [confidence interval (CI) 3.31–4.01] before the training activity, 2.81 whales (CI 2.31–3.42) for phase A, 0.69 whales (CI 0.27–1.8) for phase B and 4.44 whales (CI 4.04–4.88) after. The minimum densities for the phase B periods were highly statistically significantly lower ($p < 0.001$) from all other periods within each year, suggesting a clear response to the phase B training. The phase A period results were mixed when compared to other non-training periods. *© 2015 Acoustical Society of America.*
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## I. INTRODUCTION

There have been concerted efforts to understand the role of active sonar in the stranding of marine mammals since the multi-species stranding event in the Bahamas in 2000.[1] Much of the focus has been on beaked whale species as this stranding event resulted in seven dead animals, six of which were beaked whales. This stranding was also unusual in that two minke whales (*Balaenoptera acutorostrata*) stranded. One of the stranded minke whales spent over 24 h on the beach and was physically removed to deep water by a boat. The second stranded minke stayed in a shallow enclosed harbor for 2 days before being escorted to deep water by a boat. Neither minke whale was examined while in shallow water or on the beach, and they were not reported to re-strand.

Various reports have shown behavioral responses (e.g., cessation of foraging clicks and changes in dive ascent rates) of beaked whales to mid-frequency active sonar (MFAS) activity at the U.S. Navy's three test ranges: the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas, the Southern California Offshore Range (SCORE) off California, and the Pacific Missile Range Facility (PMRF) in Hawaii.[2–4] MFAS is defined as active sonar containing frequencies from 1 to 10 kHz. The Behavioral Response Study (BRS) conducted off southern California has also reported that some of the blue whales (*Balaenoptera musculus*) studied responded to simulated naval MFAS by a cessation of deep feeding, increased swimming speeds, and directed travel away from the sound source.[5] It is noteworthy that some of the blue whales did not exhibit any observable response despite exposures at moderately high levels of simulated MFAS (up to 165 dB re 1 $\mu$Pa). Fin whales (*Balaenoptera physalus*) have also shown changes in acoustic signal parameters resulting from shipping noise and seismic air gun activity.[6]

There have been suggestions that some reported effects could partially be due to ship activity rather than solely from MFAS or air guns. Richardson *et al.*[7] documented disturbance reactions of baleen whales to multiple disturbance sources including ships and boats. Watkins[8] reported on four baleen whale species [minke, fin, right (*Eubalaena*), and humpback (*Megaptera novaeangliae*)], reactions to boats in Cape Cod waters with a general finding that avoidance was especially strong when boats directly approach whales and that whales go silent when disturbed. Richardson[9] observed that when boats (e.g., seismic vessels, drill ships, and dredging vessels) approached within 1–4 km of bowhead whales (*Balaena mysticetus*), the whale's surface/dive cycles became shorter and the whales swam away rapidly. Moore and Clarke[10] reviewed potential short-term impacts of multiple sources of human activity including commercial shipping on gray whales (*Eschrichtius robustus*) in the northeast Pacific where whales usually responded to specific levels of continuous broadband noise by altering course to avoid the

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sources. A study of minke whales on a feeding ground off Iceland found a possible decrease in foraging behavior in the presence of whale watching craft.[11] Minke whales in Hawaii are believed to be there for breeding purposes, so sensitivity to boats may be different from that on feeding grounds.

Minke whales are a difficult species to sight due to their relatively small size, low visibility blow, and short surfacing intervals, which is compounded in Hawaiian waters in the winter/spring months due to generally higher sea states. A boing sound had been seasonally acoustically detected off Hawaii[12] since the 1960s and was suspected to be produced by a whale species,[13] but was only recently determined to be a minke whale vocalization.[14] Given the seasonal and spatial overlap of minke whale boing calls with humpback whale songs, it is suspected that only sexually active males make boing calls for breeding purposes, similar to the humpback whale.[15] The minke whale boing call has been previously automatically detected[16] and localized[17] using recorded acoustic data from PMRF. Model-based localization methods have also been applied to U.S. Navy range hydrophone data for sperm whale (*Physeter macrocephalus*) clicks[18,19] and more recently for humpback whales.[20] A model-based localization method was utilized in this study to investigate minke whale boing calling behavior for all available recorded data during the month of February over three consecutive years (2011–2013).

Utilizing recorded acoustic data from the PMRF underwater range hydrophones, individual minke whales were automatically detected and localized based upon their boing calls. This study included times of naval training activities involving multiple vessels (various sized surface ships and undersea vessels) and aircraft (both fixed and rotary wing) that were participating in, and supporting, the training activity. The number of individual boing calling minke whales in the study area was quantified on hourly intervals, grouped as being from times before, during and after the naval training events. The average number of boing calling minke whales in 1 h observation intervals provided minimum estimated densities of minke whales in the study area for the periods of time for which recorded data were available.

## II. METHODS

### A. Study area

The study area of 3780 km$^2$ was 54 km in the east-west direction and 70 km in the north-south direction, which represented the area where minke whales could be reliably localized. The study area was approximately centered on the area where U.S. Navy training occurs offshore the island of Kauai, HI, but had been extended to the east and west of the hydrophones by approximately 20 km. The study area was not extended significantly to the north beyond the hydrophone range due to localization accuracy concerns or to the south due primarily to different bathymetry characteristics. The majority of the study area (approximately 98%) had water depths greater than 2 km and relatively slowly varying depth contours. Approximately 45% of the study area was over 4 km depth, 41% was 3–4 km, 12% was 1–3 km depth and less than 2% of the area was less than 1 km in depth (the southeast corner of the study area). Figure 1 provides a map of the study area with approximate locations of the 24 hydrophones utilized in the analysis.

### B. Training activities

The same types of anti-submarine warfare training events, Submarine Commanders Course (SCC) operations, occurred during the month of February in 2011, 2012, and 2013. The Hawaii-Southern California Training and Testing Activities Final Environmental Impact Statement/Overseas Environmental Impact Statement[21] (EIS/OEIS) provides additional information for the SCC training events that were done to train prospective submarine commanders in rigorous and realistic scenarios. The SCC training events are advanced, integrated anti-submarine warfare (ASW), multidimensional training events conducted in coordinated at-sea operations in rigorous and realistic scenarios. The SCCs incorporated ASW tracking exercise and ASW torpedo exercise, which are further broken down by platforms involved (submarine, surface ships, helicopter, and maritime patrol aircraft). Tracking exercises became torpedo exercises when a lightweight or heavyweight exercise torpedo was launched. Training was categorized into two phases for this study, phases A and B. The phase A period represented submarine crews searching, tracking, and detecting other submarines almost exclusively without active sonar used as active sonar use would reveal the tracking submarine's presence to the target submarine. Phase B training incorporated the other platforms (surface ships, helicopters, and maritime patrol aircraft) in the ASW training. Other periods of time of available data were before and after the training with an additional weekend period only in 2013 between phases A and B (termed between). Training may have involved activities

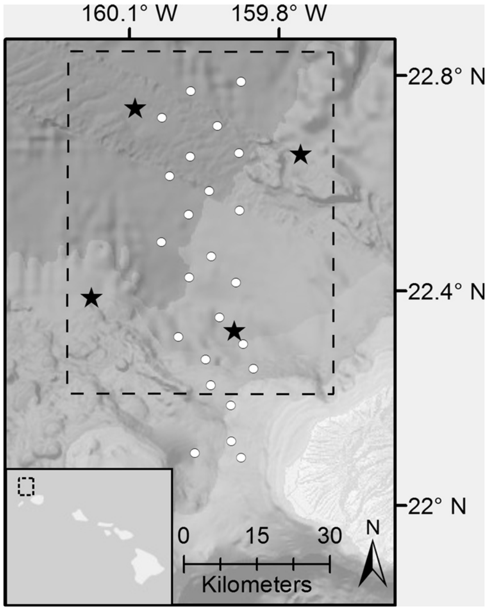

FIG. 1. Map view of the region with the 3780 km$^2$ study area located off the Na Pali coast of Kauai, HI, indicated with dashed lines. Approximate locations of the 24 range hydrophones utilized in the analysis are indicated by the white circles. Stars indicate localizations of four minke whales (each containing from 7 to 11 separate localizations) for the 1 h period ending at 12:00 GMT on 11 February 2012.

from other countries; in those cases, the ships were treated as similar to U.S. Navy ships (e.g., frigate, destroyer, cruiser, and submarine). Given the complexity of the training event, no effort was made in this study to evaluate individual ship-animal encounters; rather this study was conducted over a relatively large scale area to investigate the effect of the training as a whole on the boing calling behavior of minke whales.

The EIS/OEIS lists various acoustic sources with potential impact concerns including mid-frequency sonars and countermeasures, high frequency sonars, torpedo sonars, and vessel and aircraft noises. MFAS has been identified as the Navy's primary tool for detecting and identifying submarines in the EIS/OEIS. Mid-frequency sonars involved in the training included: hull mounted sonars (e.g., surface ships' AN/SQS-53C and AN/SQS-56 and submarines' AN/BQQ-10), helicopter dipping sonars, and sonobuoys. Mid-frequency acoustic countermeasures listed for SCC training includes mid-frequency towed active acoustic countermeasures (e.g., AN/SLQ-25) and mid-frequency expendable active acoustic countermeasures (e.g., MK 3). A high-frequency potential source listed includes hull-mounted submarine sonars (e.g., AN/BQQ-10). Torpedo sonars listed in the EIS/OEIS include lightweight torpedoes (e.g., MK 46, MK54) and heavyweight torpedoes (e.g., MK 48).[21]

Range support activity (smaller surface craft and rotary-wing aircraft for recovery of exercise torpedoes) occurred in both phases of the training. The phase B training period had more potential contribution to impacts on minke whale behavior compared to the phase A training due to more platforms being involved (multiple surface ships, ASW rotary-wing and fixed-wing aircraft) as well as being the only phase with MFAS from surface ships. The majority of activity from fixed-wing aircraft was during phase B, although some activity also occurred during phase A. The hours of surface ship MFAS operations in phase B were logged and represented as relative overall levels (highest, nominal, and lowest), and a comparison was made of the amount of phase B time that consisted of two surface ship MFAS sources operating at the same time. The MFAS sources typically operate with duty cycles well under 10%.

### C. Automated acoustic detection, classification, and localization

The minke whale boing consists of an initial transient component followed by a long call (mean duration of 2.6 s) with both frequency and amplitude modulation.[14] The call is complex, with multiple spectral components from around 100 Hz to over 10 kHz (Fig. 2 in Ref. 17). For bottom mounted hydrophones located in deep (>1 km) water such as at PMRF, the last detectable component of the minke boing at distances over 30 km is typically detected in the 1350–1440 Hz band.[16,17] The peak frequency in this band, termed the dominant spectral component (DSC), has been shown to be a feature to help isolate individuals in some situations.[17] Boing sounds had previously been documented to typically have intervals of 5–6 min[13] as well as a much faster average rate of 28 s between calls.[14]

Thirty-one bottom-mounted range hydrophones were recorded; of those, 24 had suitable bandwidth for detection of minke boing calls. Eighteen of the 24 hydrophones had a frequency response range of approximately 50 Hz to 48 kHz and were located in relatively flat bathymetry in water depths from 2400 to 4800 m. The remaining six hydrophones (the six most southern shown in Fig. 1) had different response characteristics (approximately 100 Hz to 48 kHz) and were located in shallower water (650–1750 m) in areas of steeper bathymetry. The study area was focused in the deeper waters, and the southernmost four hydrophones were outside the study area. In late August of 2012 an additional 31 hydrophones were added; 23 of these had response frequencies from approximately 50 Hz to 48 kHz and were located within the study area, bringing the total number of hydrophones recorded suitable for minke whale boing analysis to 47. For compatibility with the earlier years, this study utilized the same 24 hydrophones for the February 2013 data. However, an additional analysis was conducted for February 2013 to compare the localizations from the 47 hydrophones with the subset of 24 hydrophones which were recorded in the prior years.

An improvement to the boing detector previously utlized[16,17] was made to better detect the onset of the call; this improved the accuracy of the automatic detection start time and in turn improved the localization accuracy. Automatic minke boing detections were required to exceed the background noise level estimate in the detection band for at least 0.8 s. Previous localizations of boing-vocalizing minke whales were performed using two-dimensional hyperbolic methods and times of arrival with four hydrophones were required in the solution.[17] While the previous localization method worked well for animals located within the hydrophone array, model-based localization was added to improve localization farther from the hydrophone array.

The model-based localization utilized is similar to other methods previously reported.[18–20] Model-based methods compare measured time differences of arrival (TDOA) across multiple hydrophones with arrival times based upon modeled TDOAs from potential source locations. Measured TDOAs have typically been based upon cross correlation of signals received from spatially separated hydrophones. Here the measured arrival times were based upon the automatic detection start times. The time difference of arrival between two hydrophones, $i$ and $j$ ($TDOA_{ij}$ or $\Delta T_{ij}$) is defined as $T_i - T_j$ where $T_i$ is the measured presumed first detected arrival of a single call and $T_j$ is the measured arrival of the call at the $j$th hydrophone. The weighted least squares ($LS$) between measured ($\Delta T_{ij,measured}$) and modeled ($\Delta T_{ij,modeled}$) TDOAs as defined by Eq. (1) were minimized utilizing a spatial grid search method where $i$ represents the hydrophone with the first detected arrival of a single call and $j$ represents hydrophones with subsequent arrivals of the call to the maximum of $N$ hydrophones

$$LS = \sqrt{\sum_{j=2}^{N} W_{Tj,modeled} \frac{\left(\Delta T_{ij,measured} - \Delta T_{ij,modeled}\right)^2}{N}}. \quad (1)$$

The weighting function $W_{Tj,modeled}$ weighs the contributions to the *LS* according to their order in the time of arrival with the later arrivals weighted less than earlier arrivals and normalized such that $\sum_{j=2}^{N} W_{Tj,modeled} = N$. Using these results, a new search grid was established with reduced spacing centered at the cell location possessing the lowest *LS* value. This process was repeated for a maximum of 16 iterations with subsequent iterations resulting in finer grid resolutions provided that the *LS* thresholds were achieved. If the final candidate location met threshold criteria, the localization was kept; otherwise, the localization was discarded, and a new set of detection times was loaded into the algorithm. Animal depth was assumed to be at or near the surface, and the actual hydrophone depths were utilized with an assumption of iso-velocity water, computed as the average over the historical sound velocity profile for the area and time.

The threshold criteria for an accepted localization involved multiple requirements. The first stage of the localization process computed a tentative solution that required the DSC frequencies of the first four detections to be within 5 Hz of one another to reduce the search space down from all possible detections. This was justified, as a single call would ideally be detected with the same frequency as received on different hydrophones; however, for various reasons (e.g., propagation effects and complexities of the amplitude modulated constant frequency portion of the boing call), the precise frequency can vary a small amount. Measured TDOAs from other hydrophones were later included into the localization solution using a smaller initial start grid centered at the four TDOA locations. *LS* grid iterations continued, and the threshold criteria were again applied. Known singularities exist when the *LS* minimization process encounters local minima; however, these can be reduced by further requiring a minimum threshold requirement on the number of hydrophones used in the final localization. When processing the 24 recorded hydrophones, it was not unusual to have over a dozen hydrophones included in the localization solution for a single boing call.

Potential localization solutions also required that the weighted *LS* could not exceed 0.25 s, and individual TDOA differences from measured to modeled did not exceed 0.25 s. These parameters are configured by the user and affect localization performance with these settings providing localization solutions with maximum accuracy errors on the order of ±375 m. These settings resulted in providing more call localizations from an individual for improved call interval analysis. By tightening both of these two timing parameters to 0.075 s, the localization precision increased to a maximum on the order of 150 m; however, fewer calls are localized.

While no data existed to ground-truth the minke whale localization coordinates, the localization process had also been applied to MFAS pulses from surface ships that compared favorably with global positioning system data for the ships (typical differences under 50 m). In addition, the minke whale boing localizations described here had also been compared with other model based acoustic localization techniques for the minke whale boing call[20] with differences typically under 200 m.

Four spatially collocated and frequency coherent call localizations were utilized as a threshold for declaring the presence of an individual minke whale. The four calls must have occurred within the span of an hour and be within a few hundred meters of one another. The DSC frequency deviation of the four calls also had to be within 5 Hz of one another. Spurious localizations were often characterized as isolated in space from true localizations. Spatial/temporal review of automatic localizations helped visualize individual animal movements over time. A temporal window of 1 h was utilized to review the minke boing localizations and estimate the number of individual minke whales present in the study area. At the end of a 1 h period, the number of localized individuals in the preceding hour was logged.

The analyst would determine the number of localizations in the previous hour using features such as the time and distance between localizations, DSC frequency of calls, number of hydrophones in each solution, and the least squares of the localization solution. Figure 1 shows the result of this processing for the period 1100 to 1200 GMT on 11 February 2012 where four individual minke whales were represented by the four star symbols. Each star symbol represents multiple separate localization solutions over this 1 h period (the north-west and south-east animals had 10 localizations each while the south-west individual had 7 localizations and the north-east animal had 11). The repeated localization times for each animal represented by the star symbol fit the 5–6 min typical boing call interval[13] for minke whales.

### D. Density estimation

Ward *et al.*[22] estimated densities of localized sperm whales using two major assumptions: (a) that all periods of whale presence were identified and (b) all individuals vocalizing within the study area were included. Sub-sampling of the data was done to count whales with $k$ sample periods over the available data period with the estimated average density of sperm whales given as shown in Eq. (2), where $n$ is the number of individuals counted over the $k$ 10 min sample periods, $A$ is the study area (in km$^2$), $p_p$ is the proportion of the total time monitored (in min) and $\hat{p}_v$. is the estimated proportion of time an individual whale vocalizes at least once in the 10 min sample intervals[22]

$$\hat{D} = \frac{n\,p_p}{A\,k\,\hat{p}_v}. \tag{2}$$

The mean number of whales detected over the $k$ sample periods is represented by $n/k$. Here our mean number of whales localized in all available data was equivalent to $n/k$. Given that all available data were utilized for the measured numbers of whales in each 1 h of data, $p_p$ was equal to 1.0.

An estimation of minke whale density not only requires $\hat{p}_\mathrm{v}$ in the denominator of Eq. (2) to reflect the proportion of time an individual vocalizes but also the ratio of calling animals to all animals in cases such as minke whale boing calls (i.e., the proportion of males to females and juveniles in this area). Given there were no current estimates for these two parameters, they were both set to their maximum value of

1.0 to represent a minimum average density of minke whales based on the mean of the observed numbers of boing calling minke whales present for the duration of the period of interest. For this study, we also assumed that all vocalizing individuals in the study area were counted (probability of correctly localizing calling individuals = 1.0) and that the probability of a false positive was zero (declaring an individual present when actually not = 0). With these assumptions, the estimated minimum average density of minke whales for our study area ($A$) and time periods reduces to

$$\hat{D}_{min} = \frac{\hat{n}}{A}, \tag{3}$$

where $\hat{n}$ is the mean number of localized whales counted in the study area A. Here we use 1 h intervals for measurement of animal counts.

The assumption of correctly counting all calling individuals with no false positives was not unrealistic given the methods utilized and the 1 h observation intervals. The typical minke whale boing rate is a call produced every 5–6 min; however, when two calling animals are in close proximity, the call rate increases to calls produced approximately every 0.5 min.[13,14] One minke whale producing boing calls at the typical rate would result in the production of 10–12 boings in a 1 h observation interval if continuously calling. This increases the probability of localizing whales as it provides multiple opportunities for the localization of a whale given that only four localizations in the same area are required for confirmation. Also the probability of four incorrect localizations occurring in the 1 h observation interval that met all of the stated criteria (i.e., all within a few hundred meters of one another, DSC frequencies being within 5 Hz of each other, and call intervals matching known minke boing call rates) was extremely low. Observation intervals shorter than 1 h resulted in less than perfect localizations with potential false localizations, and intervals over a couple of hours resulted in duplicate counting of individual animals that stopped and resume calling within the sampling period. The accuracies of the whale localizations have not been verified with techniques such as visual sightings or global positioning system capable tags on the animals and were assumed to decrease with increasing distances from the hydrophones. Overall localization accuracy was believed to vary from a few dozen meters within the hydrophone array to a few hundred meters towards the outer boundaries of the study area.

Given the preceding assumptions, the variance of the density estimate is equal to a function of $\hat{n}$ and the coefficient of variation determined as the standard error (i.e., standard deviation of $n$ divided by the square root of the number of samples) divided by the estimate ($\hat{n}$).[23] The 95% confidence intervals of the density were estimated assuming a lognormal distribution for the density estimate and a normal approximation to the distribution of log(density).

The average noise levels in the detection band utilized for automated minke boing detection (approximately 1350–1440 Hz) is also of interest to ensure that the reduction of detections are not due to an increased noise level from training activity (e.g., surface ship noises and MFAS transmissions masking the calls). Data indicated that any increased noise level in this band was small compared to the signal to noise ratios for boing calls detected on the PMRF range.

## III. RESULTS

Throughout the month of February over the 3-yr study period (2011–2013), 766 h of recorded acoustic data from 24 bottom-mounted hydrophones were collected. All available data were utilized in the analysis with the breakdown of hours by year as 255 h in 2011, 298 h in 2012, and 213 h in 2013. Some of these data were not collected immediately adjacent in time to the training activities (e.g., one before period in 2012 and the only available after period data for 2013).

Table I summarizes the number of hours of available data for each period of time (i.e., before, phase A, between, phase B, and after) along with the mean minke whale minimum density estimates ($\hat{D}_{min}$) for the periods in the study area size of 3780 km$^2$ and the 95% CI of the minimum density estimates. In all three years, the densities during the phase A and B periods were depressed relative to the before periods. Although the estimated densities were different from year to year, the trends of densities within years being depressed during periods of training compared to the before periods holds. The 2013 phase B CIs are large due to the mean estimate being small (0.06 whales in the 3780 km$^2$ study area). The 2011 after period has the highest estimated density for all periods.

While the precise number of participants is sensitive information, in general, the numbers of training participants (e.g., vessels and aircraft) in the phase As were fairly

TABLE I. Estimated minimum densities of minke whales in the 3780 km$^2$ study area offshore of Kauai, HI, $\hat{D}_{min}$ with 95% confidence intervals in parentheses and number of hours of effort, N, for each period of time by year for the month of February.

| | | Before | Phase A | Between | Phase B | After |
|---|---|---|---|---|---|---|
| Feb 2011 | $N$ (h) | 65 | 42 | – | 70 | 78 |
| | $\hat{D}_{min}$ | 3.64 | 2.81 | – | 0.69 | 4.44 |
| | (CI) | (3.31–4.01) | (2.31–3.42) | | (0.27–1.8) | (4.04–4.88) |
| Feb 2012 | N (h) | 94 | 51 | – | 64 | 89 |
| | $\hat{D}_{min}$ | 2.77 | 2.04 | – | 0.70 | 2.08 |
| | (CI) | (2.41–3.18) | (1.65–2.52) | | (0.28–1.76) | (1.73–2.5) |
| Feb 2013 | N (h) | 5 | 52 | 67 | 67 | 22 |
| | $\hat{D}_{min}$ | – | 1.21 | 1.58 | 0.06 | 1.409 |
| | (CI) | | (0.84–1.75) | (1.14–2.19) | (0.001–4.63) | (0.93–2.12) |

consistent, while the numbers of phase B participants was highest in 2011 and lowest in 2012. The phase B participants' contributions of MFAS activity was the least for 2012 and the most for 2013. The percentage of time when hull-mounted sonar (e.g., AN/SQS-53C) was operational in phase B was approximately 20% in 2011, 20% in 2012, and 29% in 2013. The percentage of time when hull-mounted (e.g., AN/SQS-56) was operational in phase B was approximately 32% in 2011, 4% in 2012, and 33% in 2013. The percentage of time when two sonars were active concurrently in phase B was approximately 13% in 2011, 0.4% in 2012, and 25% in 2013.

Figure 2 provides time sequence plots of the number of localized boing calling minke whales in 1 h observation intervals (*n*) in the study area for all available recorded data with the different periods of time indicated for each year. Figure 2 shows the high variability for the numbers of animals localized in the 1 h periods. The number of localized minke whales present decreased over the years for the data analyzed with a maximum of nine individuals localized in one observation period in the 2011 after data. The number of localized minke whales during phase B periods decreased relative to all other periods within the same year with the unique situation of no minke whales localized for 63 h following the start of phase B in 2013 (although in general the number of localized whales in 2013 were lower compared to the prior years).

To gain insight into the distributions of the number of acoustically localized minke whales present in 1 h observation intervals, histograms were generated for all periods of time (Fig. 3). These histograms show the numbers of acoustically localized minke whales (*n*) (minimum of 0 and maximum of 9) that were present in the 1 h observation intervals with the number of total hours available (*N*) shown in the upper right of each histogram. The 2013 phase B data had low numbers of detected minke whales; 62 of the available 67 h (93%) had no localizations. In 2013, phase A, between, and after had only one minke whale localized in the study area for the majority of the available hours. In 2011, there was a peak of four minke whales present for 28 of the available 65 h (43%) for the before period compared to the before period for 2012 with a peak of two whales for 34 of the available 94 h (36%). A comparison of the before period data with the phase A and B periods within years shows trends of reduced numbers of whales in phase A, with the phase B numbers reduced even further.

The number of localized minke whales in 1 h observation intervals was tested for normality using the Shipiro–Wilks normality test. The before periods for 2011 and 2012 data tested highly significant as non-normal ($p < 0.001$). The Mann–Whitney/Wilcoxon rank-sum test was therefore selected, given its ability to deal with non-normal distributions as well as the significant number of ties in the ranking process, to test if the means of any two distributions are the same.

The Mann–Whitney tests indicated that for the comparisons within periods *across* years (e.g., before to before, phase A to phase A, etc.), only the comparison of 2011 phase B and 2012 phase B had the same means ($p = 0.77$); all other comparisons across years were significantly different (*p* values ranged from 0.044 to less than 0.001). The before periods represent the best estimate at baseline data; however, the before periods had different means ($p < 0.05$) across all paired year comparisons (i.e., 2011 to 2012, 2011 to 2013, and 2012 to 2013). The small sample size of the before data for 2013 (5 h) should be considered when interpreting the data. The fact that before periods over different years had different means suggests that the densities of calling animals

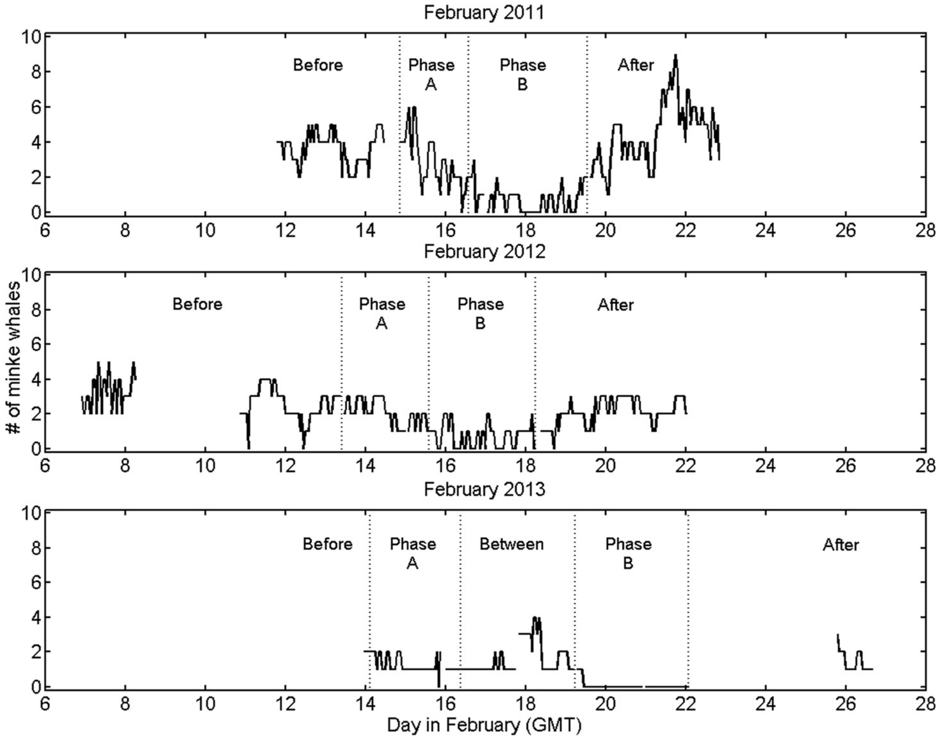

FIG. 2. Number of minke whales acoustically localized in the study area in 1 h periods for February 2011 (top), 2012 (middle), and 2013 (lower). Labels on each figure represent the periods of time associated with navy training activity (before, phase A, between, phase B, and after). Blank periods indicate periods that recorded data was not available.

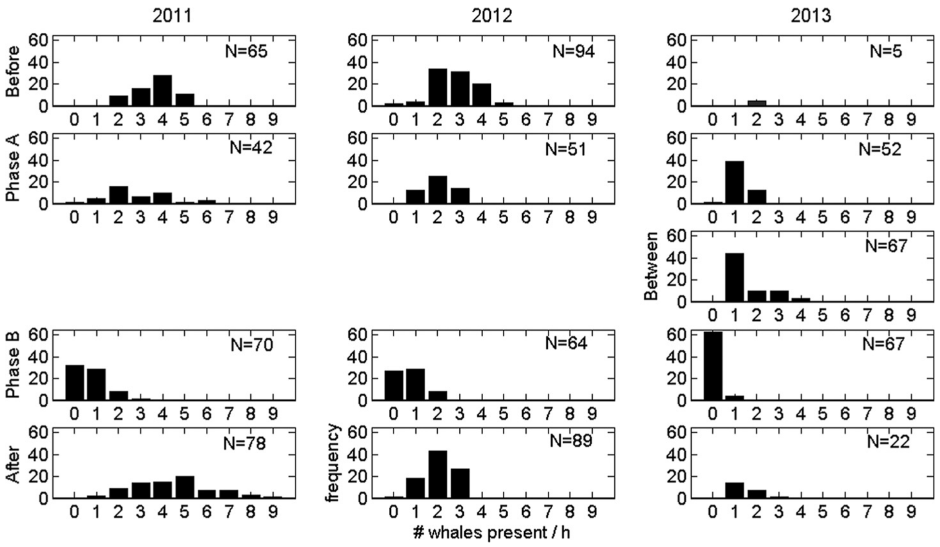

FIG. 3. Histograms of the numbers of individual minke whales localized (horz axis min 0 to max 9) in 1 h observation intervals by year (columns) and periods of time relative to training (before, phase A, between, phase B, after). Plots have the same scale for ease of comparing the distributions of localizations with the number of hours (*N*) inset in upper right of each histogram. Before periods represent a nominal baseline for 2011 (65 h) and 2012 (94 h). The 2013 before period had limited data available. Phase B distributions show clear shifts to the left indicating fewer numbers of minke whales localized in 1 h observation intervals.

in our baseline was different from year to year, and therefore interannual differences may factor into the differences observed across all sampling periods.

The Mann–Whitney tests of the 10 paired combinations involving phase B data *within* years (i.e., three paired tests in 2011, three paired tests in 2012, and four paired tests in 2013 due to the additional between period) indicate that the means of the phase B data are all highly significantly lower ($p < 0.001$). Phase B was the only period of time with activity from naval surface ships participating in the training (i.e., maneuvering and periods of MFAS transmissions as opposed to range support craft present in both the A and B periods). Phase B was also the only period when the mean number of animals in the study area was less than one per hour. This suggests that the phase B training activity impacted the number of localized minke whales, resulting in fewer calls as compared to the other time periods.

The Mann–Whitney paired tests involving phase A *within* years had mixed results compared with other periods of time (e.g., phase A to before, phase A to after). Phase A to before periods *within* each year had statistically significant different means ($p < 0.05$) as did the 2011 phase A to after period ($p < 0.001$). However, the 2012 and 2013 phase A to after periods both tested as not different ($p = 0.709$ and $p = 0.18$, respectively). Thus impacts of phase A training on minke calling behavior was not as clear as the phase B impacts and requires further study of more baseline data. Finally, the 2013 between period tested as different when compared to the after period ($p = 0.766$) but not different when compared to the before period ($p = 0.05$ but recall only 5 h of before data for this year).

The results from the localizations in 2013 that utilized the 47 available hydrophones were similar to results using only the subset of 24 hydrophones for compatibility with 2011 and 2012 comparisons. As expected there were a few more localized animals at longer distances from the hydrophones in a few of the hour periods. The Mann–Whitney test comparing the 47 to 24 hydrophone localizations across periods had means that were not significantly different across all but one of the periods (the after period $p = 0.0106$), when the larger number of hydrophones resulted in a higher mean number of animals per 1 h periods (1.95 compared to 1.41).

## IV. DISCUSSION

The use of estimated densities for calling minke whales based upon localizations of individuals to investigate density and potential responses to navy training activities is a new application of the science of acoustic detection, classification, and localization. This method is favored as much of the analyses, including localizations, were automated, and it is not unreasonable to perform the analysis for all available data rather than sub-sampling the available data. The numbers of acoustically localized minke whales producing boing calls were shown to have highly statistically significantly reduced means for the phase B training activities, which included surface ship training with MFAS, when compared with all other available periods of data (before, phase A, between, and after) within years.

While the mean numbers of calling minke whales in phase A were consistently less compared to the before periods, the after periods did not consistently increase relative to phase A periods. In addition, the 2013 between data were higher than the phase A data but also higher than the after data. Given that only 5 h of before data were available in 2013, and the inconsistencies in phase A comparisons with other periods, it is not certain if the phase A activities reduced the minke whale calling behavior. Reduced calling could be associated with the phase A activities, or it could be a result of not having sufficient baseline data available to fully represent the variations for minke whale calling behavior. Phase A activities included range support activities that were also present in phase B (e.g., exercise torpedo recovery surface craft and rotary-wing aircraft). The presence of both aircraft and boats have been shown to negatively affect baleen whales.[9–11]

The February 2013 phase B data were distinctive in that there were no localized minke whales for the majority of phase B; however, 2013 also had the lowest number of localized minke whales present compared to the other years. Preliminary analysis of the Feb 2014 and 2015 data indicates increased numbers of animals compared to 2013; this would not support a hypothesis of a continued downward trend, which might be inferred based upon the 2011–2013 data. This underscores the need for additional data and analysis to understand the complexities of minke whale boing calling behavior.

Acoustic density estimation for an odontocete species such as Blainvilles beaked whales (*Mesoplodon densirostris*) or sperm whales are based upon foraging echolocation clicks, which all but the youngest of the species must produce to survive. Baleen whale calls are often gender specific (e.g., humpback whale song, blue whale AB calls,[24] and minke whale boing calls) and dependent upon behavioral states. While the measured numbers of localized minke whales varied from year to year, it is not certain if the densities are varying or if the variation is the result of different behavioral states with different calling behaviors. Minke boing calling behavior is also density dependent because when two animals are relatively close to one another, call rates increase by a factor of over 10.[13] This was occasionally observed in the PMRF data with one of the animals typically ceasing to call following an increased call rate encounter with another calling whale. This behavior has also been observed in humpback whales with singers joining or being joined by other males.[25,26] However, in contrast to the behavior observed in calling minke whales, the singers typically join with non-singing males rather than with another singing male. Thus the proportion of time, on average, that a boing calling minke whale actually vocalizes is complex and potentially difficult and expensive to obtain (e.g., successfully attaching medium-term acoustic tags on multiple animals with several day attachment durations). Studies of humpback whale singer-to-overall population ratios have also been shown to vary from year to year, but currently no similar data exist for minke whales wintering in Hawaiian waters. These factors were unknown at the time of this study and will likely remain unknown for not only minke whales but many baleen whale species for the near-term future. Reporting these results as a minimum density estimates was done to highlight these limitations and yet still provide some data on density estimates.

Future efforts are planned to automatically track localized individuals to reduce the amount of manual effort in performing this type of analysis in the future and to potentially perform snapshot-type acoustic density estimation. Additional efforts are also planned to quantify the encounters between minke whales and surface ships (e.g., examine separation distances, ship speeds, and angle off the bow of the whale from the ships) during training as well as estimating receive levels on whales when MFAS is present. Minke whales have been shown to respond to disturbances such as ships and aircraft activities, reduced calling behavior should not solely be attributed to sonar activity. Previous unpublished observations have identified situations where minke whales ceased calling as a surface ship approached with and without transmission of MFAS as well as situations where a whale has continued calling as an MFAS transmitting ship is moving away (S. Martin, personal observation). Quantifying these encounters in a more detailed study may help understand the effects of each type of disturbance on minke whales. This has implications for controlled exposure studies such as the southern California BRS[3,5] and the 3S study.[27]

The use of standard statistical tests to compare the number of localized boing calling minke whales violated some of the test's assumptions. While the Mann–Whitney test is nonparametric and robust to matches in rankings, it does make assumptions that the data are independent and the variances similar. The independence assumption is of concern; if a minke whale is present in the study area at hour $N$, it is often also present and counted in subsequent hours (e.g., $N+1$, $N+2,\ldots$) for several hours or more in many cases. This could be handled by only counting the onset of boing bouts from an individual or by employing methods for dealing with the dependence of the observations (such as utilizing the autocorrelation of the observations). This is an area appropriate for future research. In spite of this concern, the number of localized minke whales were measured for all available data, and the means and distributions of the phase B periods were obviously lower compared to all other periods.

## V. CONCLUSIONS

The use of widely spaced, bottom-mounted hydrophone arrays to detect, classify, and localize marine mammals and assess behavioral responses to navy training activity is a powerful tool and is being pursued for other whale species (e.g., humpback, fin, sei, Bryde's, and sperm whales) using available PMRF data. The large number of hydrophones on U.S. Navy ranges provides unique opportunities to not only detect, classify, and provide presence information but to also localize individual whales in the area. This conceptually simplifies density estimation for vocalizing whales to a census type measurement, which can be considered a lower bound of whale density as it is only counting whales which are calling during the study periods. Such analyses are not typically possible with towed hydrophones or a handful of seafloor autonomous data recorders. In addition, the cost of obtaining range hydrophone data is low given the large quantity of existing data and relatively low cost to record additional data in the future. This favors use of the U.S. Navy range hydrophones for monitoring marine mammals on (and near) the U.S. Navy range rather than conducting separate types of acoustic data collections requiring deployment of autonomous recorders or towing of hydrophones from ships.

In addition to providing minimum density estimates for minke whales, this analysis also documented a behavioral response of calling whales related to U.S. Navy training. Previous studies of tagged beaked whales provided evidence that beaked whales depart an area during MFAS activity and later return.[2,28] No similar data currently exist for minke whales at PMRF (e.g., tagged animals), therefore it is not known if minke whales leave the area or simply cease calling.

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