

Changes in the Spatial Distribution of Acoustically Derived Minke Whale (*Balaenoptera acutorostrata*) Tracks in Response to Navy Training

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Abstract

Data from passive acoustic monitoring (PAM) of Navy training ranges can be used to test predictions of marine mammal responsiveness to naval sonar from experimental behavioral response studies. Minke whale (*Balaenoptera acutorostrata*) vocalizations were detected, classified, localized, and associated into individual tracks from data collected on bottom-mounted hydrophones on the U.S. Navy's Pacific Missile Range Facility located off Kauai, Hawaii. Data were analyzed from before, during, and after naval undersea warfare training activities in February 2014 and February 2017. The spatial distribution of acoustically derived whale tracks was modelled using "latitude," "longitude," "depth," "year," and "phase" (Before, During, and After) as covariates. It was found that, as well as inter-annual variability across all phases, the distribution of calling whales changed in both years, with fewer tracks in the vicinity of the center of ship activity in the During phase compared with the Before phase. This redistribution of calls extended for approximately five days after the end of the training activity in both years. As the data are from PAM, it is unknown whether this change in the probability of acoustic presence across the range is a result of whales moving away from the range or ceasing calling, or perhaps a combination of both. The expectation from experimental studies is that minke whales will exhibit avoidance in response to naval sonar activity. We conclude that this is a probable explanation for the results reported here, particularly given the nature of the redistribution (an increase in some areas distant from the center of ship activity coincident with a decrease near the center) and the time taken for the distribution observed in the Before phase to re-establish in the After phase of both years.

Key Words: naval sonar, passive acoustic monitoring, spatial distribution, behavioral response

Introduction

Many marine mammals rely on sound for foraging, maintaining group cohesion, navigating, finding mates, and avoiding predators (e.g., Tyack & Clark, 2000; Johnson et al., 2009; Parks et al., 2014; King & Janik, 2015). Hence, they may be affected by the introduction of anthropogenic noise, such as naval sonar, into the marine environment. There are now almost two decades of published studies that have investigated behavioral responses of marine mammals to naval sonar sounds (see Harris et al., 2018, for review). These research efforts were originally initiated to study responses of baleen whales to low-frequency sonar (Miller et al., 2000); but in the last decade, research has been motivated by atypical mass-stranding events, especially of beaked whales, some of which appear to have been caused by naval sonar activities (D'Amico et al., 2009). Harris et al. (2018) provide a synthesis of these past research efforts. In summary, studies have demonstrated clear behavioral responses to sonar in some, but not all, individuals of all species tested (Southall et al., 2016), with high inter- and intra-species and individual variability. Observed responses include changes in dive behavior often relating to foraging disruption (e.g., DeRuiter et al., 2013b; Goldbogen et al., 2013; Miller et al., 2015; Sivle et al., 2016; Southall et al., 2019), horizontal avoidance (e.g., Tyack et al., 2011; Miller et al., 2015; Kvadsheim et al., 2017), and changes in social/vocal behavior (DeRuiter et al., 2013a; Visser et al., 2016). While most of these behavioral changes are sublethal, they may lead to long-term population consequences if the health of

individuals and populations are impacted through repeated exposure (National Research Council [NRC], 2005; Pirodda et al., 2018).

Studies with a formal experimental design component have been used to establish causal relationships between sonar and behavioral responses using an approach referred to as controlled exposure experiments (CEEs) (for reviews, see Southall et al., 2016; Harris et al., 2018). In many cases, for practical reasons, scaled sonar sources have been used that transmit at a lower sound level than naval ship sonar, requiring the source to be closer to the subjects than a naval ship would have to be to achieve the same desired received sound level. Hence, there is uncertainty as to how the differences in exposure context between real Navy sonar exposure and CEEs with a scaled sonar source (e.g., sound level or source proximity) relate to the type and duration of responses observed (e.g., Ellison et al., 2012). Some CEEs with real Navy ships have been performed, but they are logistically very difficult, and sample sizes are necessarily small.

A complementary approach is to test predictions on responsiveness and expected response types from CEEs in more realistic settings and across relevant spatial and temporal scales using opportunistic exposure studies. Opportunistic exposure studies monitor responses of marine mammals to real naval training activities during which the researcher has no control over the use of sonar or the doses received by individual animals. These studies have often been associated with U.S. Navy training and testing ranges where discrete training events can be studied and passive acoustic capabilities on the range can be used to monitor the presence and distribution of vocalizing marine mammals. For example, passive acoustic monitoring (PAM) of the Atlantic Undersea Test and Evaluation Center (AUTC) range in The Bahamas before, during, and after active sonar demonstrated either a complete cessation of vocalizations or a temporary avoidance of the sonar use area on the range by Blainville's beaked whales (*Mesoplodon densirostris*) (McCarthy et al., 2011; Moretti et al., 2014). A similar result was found for the same species at the Pacific Missile Range Facility (PMRF) in Hawaii (Manzano-Roth et al., 2016), indicating a consistent response to this type of noise stressor by this species.

Improvements in detection, classification, and localization capabilities have broadened the scope of these opportunistic studies to monitor more species. Herein, we focus on minke whales (*Balaenoptera acutorostrata*), which can be difficult to track in this area both visually (due to their relatively low profile in the water, low visibility blows, and short surfacing intervals) and with telemetry devices

(due to the difficulty of approaching close enough to tag). Minke whales are of interest because they were involved in the multispecies stranding event in The Bahamas in 2000 (Balcomb & Claridge, 2001), and they are among the most abundant and wide-ranging baleen whales (Bannister, 2018). Only relatively recently has a boing sound, which has been heard around Hawaii for many years, been attributed to minke whales (Rankin & Barlow, 2005). These minke whale calls are detected seasonally in this area, and it is suspected they may be made only by sexually active males for the purposes of breeding. The ability to detect and classify these vocalizations using PAM allows this species to be studied and monitored over relatively large spatial and temporal scales in locations where it would be difficult to study them using any other method.

The limited number of CEE studies on minke whales (four whales tagged, two of which were exposed to naval sonar signals as part of two different CEEs, summarized together in Kvadsheim et al., 2017) showed similar behavioral responses across tagged individuals. Neither of the exposed whales demonstrated a dive response, but both initiated an avoidance response, with one individual greatly increasing its horizontal speed away from the source (Kvadsheim et al., 2017). Kvadsheim et al. (2017) relate these responses to those documented for other baleen whales whereby foraging disruption has been the most commonly observed response (e.g., Goldbogen et al., 2013; Sivle et al., 2016). Wensveen et al. (2017) note the heterogeneity in behavioral responsiveness that has been observed between and within baleen whale species; notwithstanding this, minke whales do appear to be sensitive to mid-frequency sonar activity (Kvadsheim et al., 2017).

Despite the small sample size, these CEE results allow us to predict that minke whales may exhibit an avoidance response in relation to sonar that can be investigated at broader scales using PAM. The PMRF range has been recording minke whale calls from underwater range hydrophones since 2002. Martin et al. (2015) used these data to estimate the density of calling whales before, during, and after Navy training activities based on acoustic localizations. They found that there was a significant decrease in the density of calling whales in response to the activity.

The aim of this study was to examine the spatial distribution of acoustic tracks before, during, and after U.S. Navy training activities to determine whether there was a change in the overall spatial distribution of calling minke whales in response to sonar and, if so, to identify specific areas of distribution change. To achieve this, we examined minke whale call data from PMRF in

relation to U.S. Navy training activities but in a spatially explicit framework. Advances in acoustic processing have resulted in localizations being associated with one another to generate acoustic tracks for individual whales (Helble et al., 2015, 2016; Klay et al., 2015; Henderson et al., 2018). Recognizing individual localizations as part of a track has allowed us to account for the non-independence in the time series of localizations of the same individual. These efforts complement the CEE studies, which have limited sample size, while allowing us to examine the effects of actual Navy training activities at realistic spatial and temporal scales.

Methods

Study Area

Data from 47 bottom-mounted range hydrophones on PMRF, approximately centered on the area where U.S. Navy training occurs offshore the island of Kauai (Figure 1), were the focus of the analysis. The range hydrophones are time-synchronized, are nominally separated from one another by 5 to 7 km, and monitor an area of approximately 1,200 km². Minke whale calls can be localized throughout the range and up to approximately 20 km outside the boundaries of the range, but localization accuracy decreases as distance from the edge of the range (hydrophones) increases (Helble et al., 2015). In addition, although internal studies using *in situ* noise conditions indicate that minke whale calls made on the range are (almost) certain to be detected and localized (Helble et al., 2019), the signal-to-noise ratios of calls outside the range decrease with increasing distance away from the hydrophones, and some such calls will be missed, especially in noisy conditions. For this study, we assumed that all calls within a defined study area were detected and localized accurately; hence, we defined a conservative study area as the area encompassing the hydrophone array plus a buffer zone out to approximately 5.5 times the water depth of the hydrophones in all directions. The 5.5 times the water depth is a proxy for a reliable acoustic path (Urick, 1983; Rui et al., 2012) and has been observed in PMRF data as the distance at which the direct path signal is weaker than the first bottom-surface multipath for the minke whale boing call. Internal studies also suggest that calls originating within this area have enough signal excess such that no calls are masked even in the highest noise conditions (Helble et al., 2019). Only tracks inside this area were included in the analysis.

Navy Sonar Training Activities

Similar types of anti-submarine warfare (ASW) training events took place over the course of 3 to

4 d in February 2014 and February 2017. Details of these Submarine Command Course (SCC) operations can be found in the Hawaii–Southern California Training and Testing Activities Final Environmental Impact Statement/Overseas Environmental Impact Statement (EIS/OEIS) (U.S. Department of the Navy, 2018). In brief, SCC training events are ASW training activities conducted under realistic scenarios and involving diverse platforms, including submarines, surface ships, helicopters, and maritime patrol aircraft. Various anthropogenic sounds of potential concern may be produced, including sounds from mid-frequency sonars and countermeasures, high-frequency sonars, torpedo sonars, and vessels and aircraft. This study did not try to investigate fine-scale interactions between these complex training events and individual whales; rather, this analysis aimed to investigate the effect of the training event as a whole on the distribution of calling whales. Therefore, for both 2014 and 2017, minke whale calls recorded on the range hydrophones were processed from a baseline period that occurred a few weeks before the event (duration = 9 d [2014], 14 d [2017]), immediately before the training event (duration = 2 d [2014], 5 d [2017]), during the event (duration = 4 d [2014], 4 d [2017]), and a few days after the event (duration = 5 d [2014], 5 d [2017]). Each of these periods was also screened for potential sonar activity by reviewing any sonar localizations present in the data, as well as reviewing the range schedule of any activities performed.

Processing of Passive Acoustic Monitoring Data

Full details of the detection, classification, and localization procedures can be found in Martin et al. (2015). In brief, the process consists of custom software both in C++ and *MATLAB* in a 3- or 4-step process. First, automated detections of various sounds in specific frequency bands are performed. In some cases, such as the minke whale boing call, a second classification stage is also performed. The third stage involves model-based localization of the detections or classifications. The fourth stage converts the localizations into individual source tracks.

In Martin et al. (2015), the fourth stage was performed using manual methods to determine when multiple localizations within certain time and space constraints constituted a whale presence. The criteria utilized in the manual process were that four localizations were required within a few hundred meters of one another within an hour and with call frequency within 5 Hz of one another (utilizing a sub-hertz spectral bin width). When the criteria were satisfied, a whale “track” was declared (as in Martin et al., 2015).

More recently, custom *MATLAB* code has been developed that semi-automatically associates call

localizations into a “track,” depending on how close together they are in time and space (Klay et al., 2015), based upon the species’ reported call rate and swim speeds. Tracks were generated using specific criteria. Herein, at least eight hydrophones had to contribute to the localization solution, the maximum time between successive calls was 40 min, the maximum change in latitude or longitude was 0.06° , and the least squares error of the actual and modeled times had to be under

0.075 s. A minimum of 12 calls were required in a track, which is based on one animal at the nominal call rate (one call/ ~ 5 min) over the course of an hour. When the resultant associated track’s call intervals closely match those reported for the species of interest, this reinforces the assumption that the associated track is real and from a single whale. Thompson & Friedl (1982) characterized the boing sound repetition interval in the Hawaii area as consisting of both a long call interval of

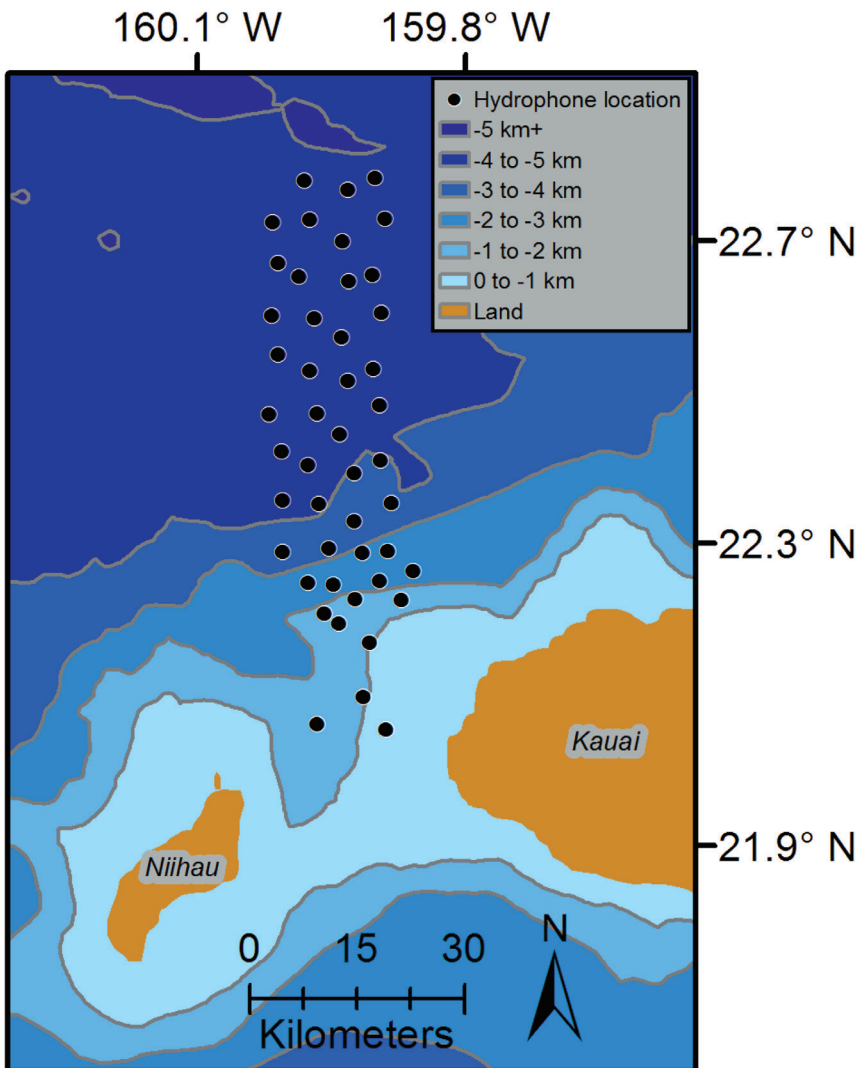


Figure 1. Approximate locations of 47 recorded broadband hydrophones at the Pacific Missile Range Facility (PMRF) in Kauai, Hawaii. These hydrophones have the frequency response necessary to detect minke whale (*Balaenoptera acutorostrata*) boing calls. Bathymetry contours were adapted from Amante & Eakins (2009).

6 min (± 30 s) and shorter mean call intervals of 19 and 30 s for two boing sound trains, respectively. They hypothesized that the 6-min call interval was for single whales and that call interval was closer to 30 s when more than one whale was present. However, little is known about minke whale group sizes on breeding grounds, and it is likely that animals are either solitary or in groups of two to three whales (Perrin et al., 2018).

This same localization association method has also been applied to surface ships performing active sonar training where the precise satellite tracks of the surface ships were known, and these have been compared with associated tracks derived from mid-frequency active sonar (MFAS) detections on the range hydrophones. For ships, the satellite tracks and associated acoustic tracks matched very closely (within 50 m for the majority of localizations). The whale track data were used in the statistical analysis.

Statistical Analysis

For the purposes of analysis, the data were divided into three phases within each year: (1) Before, (2) During, and (3) After. The Before phase included all data from the baseline period as well as the days immediately prior to the start of the sonar activity (initial model results indicated no statistically significant difference between the baseline period and the days immediately before the sonar activity and, therefore, the data from these periods were combined into the Before phase for the analysis described herein). The During phase included all data from the time of the first sonar transmission until 24 h after the last sonar transmission; and the After phase included all data collected more than 24 h after the last sonar transmission (limited to 5 d in both years). We chose to include 24 h after the last sonar transmission in the During phase for two reasons. First, we wanted to ensure vessels participating in the training activity had adequate time to depart the area; and second, we wanted to determine whether any change in the spatial distribution that occurred in the During phase had returned to the distribution observed in the Before phase beyond 24 h after sonar activity had ceased. The During phase was relative to specific MFAS sources, primarily surface ship hull-mounted MFAS (i.e., AN/SQS-53C) with a center frequency of approximately 3 kHz and a nominal source level of 235 dB re 1 μ Pa at 1 m (U.S. Department of the Navy, 2018), but also active MFAS sonobuoys (e.g., AN/SSQ-62) and helicopter (helo-) dipping MFAS sonar (AN/AQS/22). These sources could occur concurrently or separately, but the distinction was not made for this analysis, and all periods and sources of MFAS were utilized. There were no acoustic data indicative of sonar activity in Before and After periods.

The data were analyzed as a binary logistic regression using generalized estimating equations (GEEs; Hardin & Hilbe, 2012), with “presence” (coded as a 1) or “absence” (coded as a 0) of each localized whale vocalization within each acoustic track as the response variable, various spatially and temporally referenced variables as potential explanatory variables (see below), and individual track as the panel structure (i.e., allowing for spatial and temporal correlation in the location of presences). Presences were the individual localizations within each track ($n = 29,725$). For each presence, a corresponding absence was generated at the same time point by randomly simulating a location within the survey area from a uniform distribution on latitude or longitude, following the method used by Russell et al. (2016). These are known as *pseudo-absences* or the *background sample*. They can be thought of as a representative sample of locations from the space available to each vocalizing animal and, therefore, as a method of communicating to the model the contrast between the locations that animals vocalize at and the locations that are broadly accessible to them in their environment (Beyer et al., 2010). Unlike Russell et al. (2016), who assumed each pseudo-absence came from a different animal (thereby inflating the error degrees of freedom in the analysis), we conservatively assumed the absences come from different animals but in blocks corresponding to the actual tracks (i.e., there were 312 tracks and 312 absence “tracks”).

Potential predictor variables were “phase of study” (Before, During, and After), “longitude,” “latitude,” “year,” “ETOPO1 water depth” (obtained from NOAA, <https://www.ngdc.noaa.gov/mgg/global/global.html>; Amante & Eakins, 2009), and “distance from the estimated center of ship activity” in each year. The latter was based on an estimated mean center point (in longitude and latitude) of all ship activity on the range within the time frame of the training event in each year. Spatial contribution of the non-ship sources was not included in this metric for multiple reasons (e.g., the source levels of the other sources are considerably less than the ship hull-mounted sonar, and the amount of sonar activity from the other sources is much less than the hull-mounted sonar). The continuous variables were modeled using B-splines (e.g., Wood, 2017) with up to 4 degrees of freedom. The initial model included a four-way interaction term between “longitude,” “latitude,” “phase,” and “year,” and a three-way interaction term between “depth,” “phase,” and “year.” In exploratory analyses, it was found that “distance from the center of ship activity” was not retained in the same models as “latitude” and “longitude,” and that “latitude” and “longitude” produced

better fitting models; therefore, “distance from the center of ship activity” was not included in the model set. Model selection was backward, starting with the highest order interaction terms, using a $p < 0.05$ inclusion criterion (Wald test; see Hardin & Hilbe, 2012). If an interaction was retained in the model, the corresponding marginal variables were automatically retained.

The selected model was used to generate spatial prediction plots using the variables retained after model selection. In addition, to highlight the areas of greatest change, surfaces illustrating the difference in the probability of call presence (varying from -1 to 1) were generated for a series of comparisons relevant to the retained variables—for example, a surface showing difference in probability of presence for the Before vs During phases. To illustrate the uncertainty in each surface, a parametric bootstrap was undertaken where 1,000 bootstrap model coefficients were generated from the selected model using the model coefficients and variance-covariance matrix. Surfaces were then reconstructed for each bootstrap and, hence, a bootstrap surface of differences could be calculated. Regions of significant difference could then be identified by considering cells that were in the extreme lower and upper 2.5% of the bootstrap sample.

All statistical analyses were conducted in *R*, Version 3.4.4 (R Core Team, 2018) using the ‘geepack’ package (Højsgaard et al., 2006).

Results

The detection, classification, and localization algorithms resulted in the derivation of 116 tracks for 2014 and 187 tracks for 2017 within the boundaries of the study area. In 2014, there were 58 tracks in the Before phase (over 11 d), 19 in the During phase (over 4 d), and 43 in the After phase (over 5 d). Only four tracks extended over more than one phase. In 2017, there were 137 tracks in the Before phase (over 19 d), 23 in the During phase (over 4 d), and 32 in the After phase (over 5 d). Five tracks extended over more than one phase. The training activities that coincided with the During phases were comparable across the 2 y, both in terms of the center of ship activity (difference of 6.13 km) and the level of activity during the training exercise (relating specifically to hull-mounted MFAS, active sonobuoys, and helo-dipping sonar). In 2014, there were 20 bouts of sonar activity, with a cumulative duration of 21.4 h (mean = 64.3 min; SD = 56.8 min); while in 2017, there were 25 bouts of sonar activity, with a cumulative duration of 17.9 h (mean = 43.1 min; SD = 24.0 min).

The selected model retained both the four-way interaction term between “latitude,” “longitude,”

“phase,” and “year” ($p < 0.001$) and the three-way interaction term between “depth,” “phase,” and “year” ($p < 0.001$). All terms marginal to these interactions were also retained, but for clarity, we only provide p values here for the top-level interaction terms. The marginal R^2 (Zheng, 2000) for the selected model was 0.151. As it can be hard to interpret model outputs when interaction terms are included, we produced a series of spatial prediction plots to illustrate the results (Figures 2 & 3). “Depth,” like “latitude” and “longitude,” is essentially acting as a spatial descriptor. Minke whale acoustic presence was predicted over much of the range in the Before phase in both years (Figure 2). There were some differences in the overall distribution of calls within the range in the Before phase, with a patch of low probability toward the northeast in 2014, which was not apparent in 2017. Differences such as this likely explain the retention of “year” in both interaction terms. The spatial distribution of probability of acoustic presence was notably different in the During phase compared with Before for both years (Figure 2), with probabilities close to zero particularly in the southeastern part of the range, around the center of the ship activity. High probabilities of acoustic presence were predicted in the northwest in 2014 and the north and northeast in 2017, again highlighting another difference between the years. The distribution of probability of acoustic presence in the After phase was more similar to the Before phase in both years compared with the During phase, but there was still a low probability predicted for the southeastern corner (Figure 2).

While Figure 2 shows the overall predicted probability of acoustic presence, Figure 3 illustrates where the main differences are in the spatial surfaces and where these differences are significant (as determined by the parametric bootstrap; i.e., where the 95% confidence bounds on the bootstrap differences do not include zero). In both years, there was a large area near the center of ship activity where the probability of call presence was significantly lower in the During phase compared with the Before phase. In 2014, there was very little area with significant increase in the probability of acoustic presence; while in 2017, there were a few patches where predicted probability of acoustic presence was higher in the During phase compared with the Before phase (Figure 3). The comparison of the spatial distributions in the After phases vs the During phases revealed a significant increase in the probability of call presence in the After phase in the regions where there had been a significant decrease in the During phase (Figure 3). This decrease and increase nearly balanced one another for 2014, resulting in very small areas of significant difference between Before and

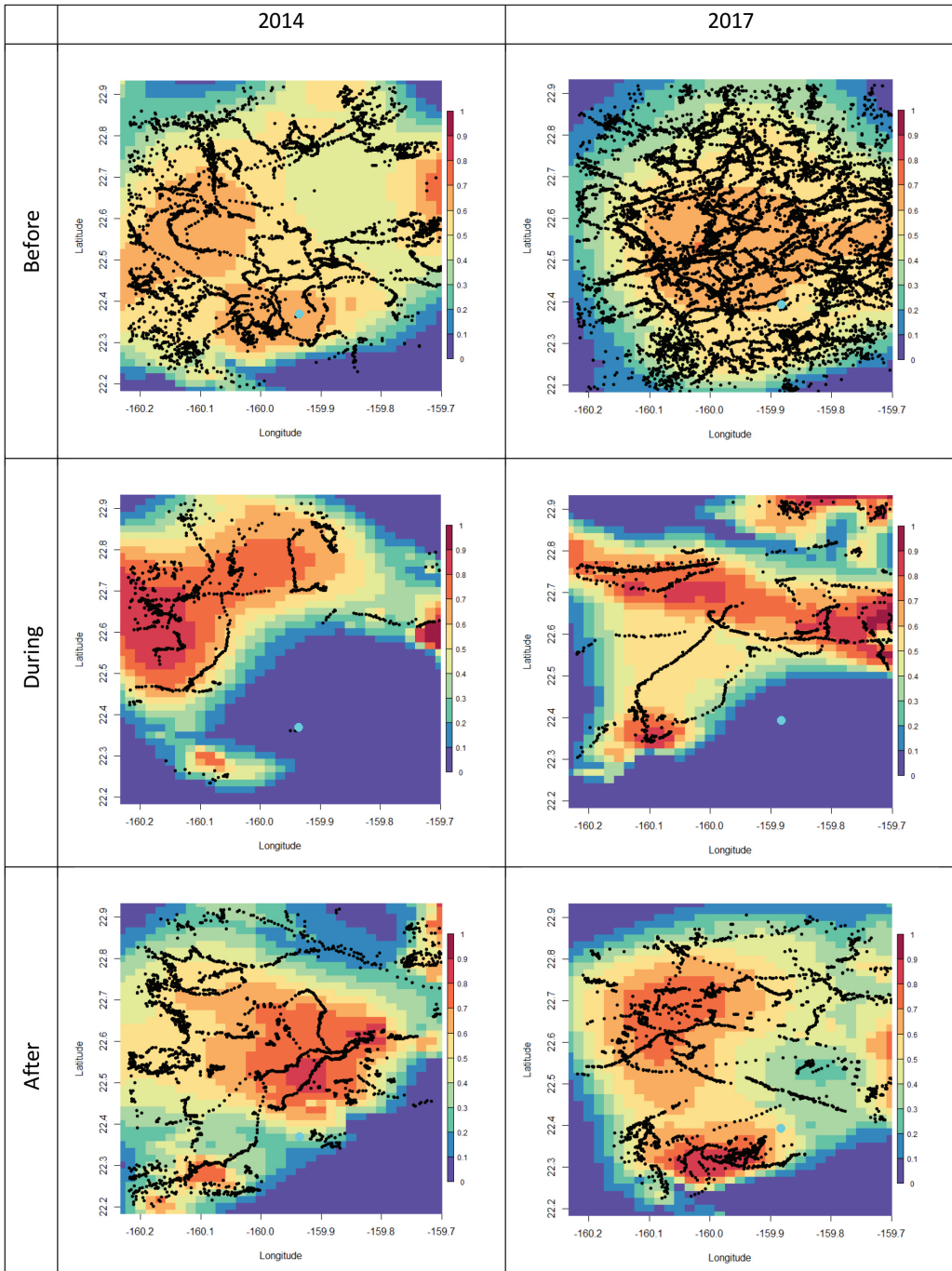


Figure 2. Minke whale tracks (black) overlying prediction surfaces from the selected model. The surfaces represent predicted probability of presence, with cool colors representing low probability of presence and warm colors representing high probability of presence. The left plots relate to 2014, and the right plots relate to 2017. The top panel shows Before, the middle panel shows During, and the bottom panel shows After. The cyan dot represents the estimated mean center of ship activity for that year (not included in the final model). Note that the data collection effort differed across years and phases, which is reflected in the number of whale tracks in each plot.

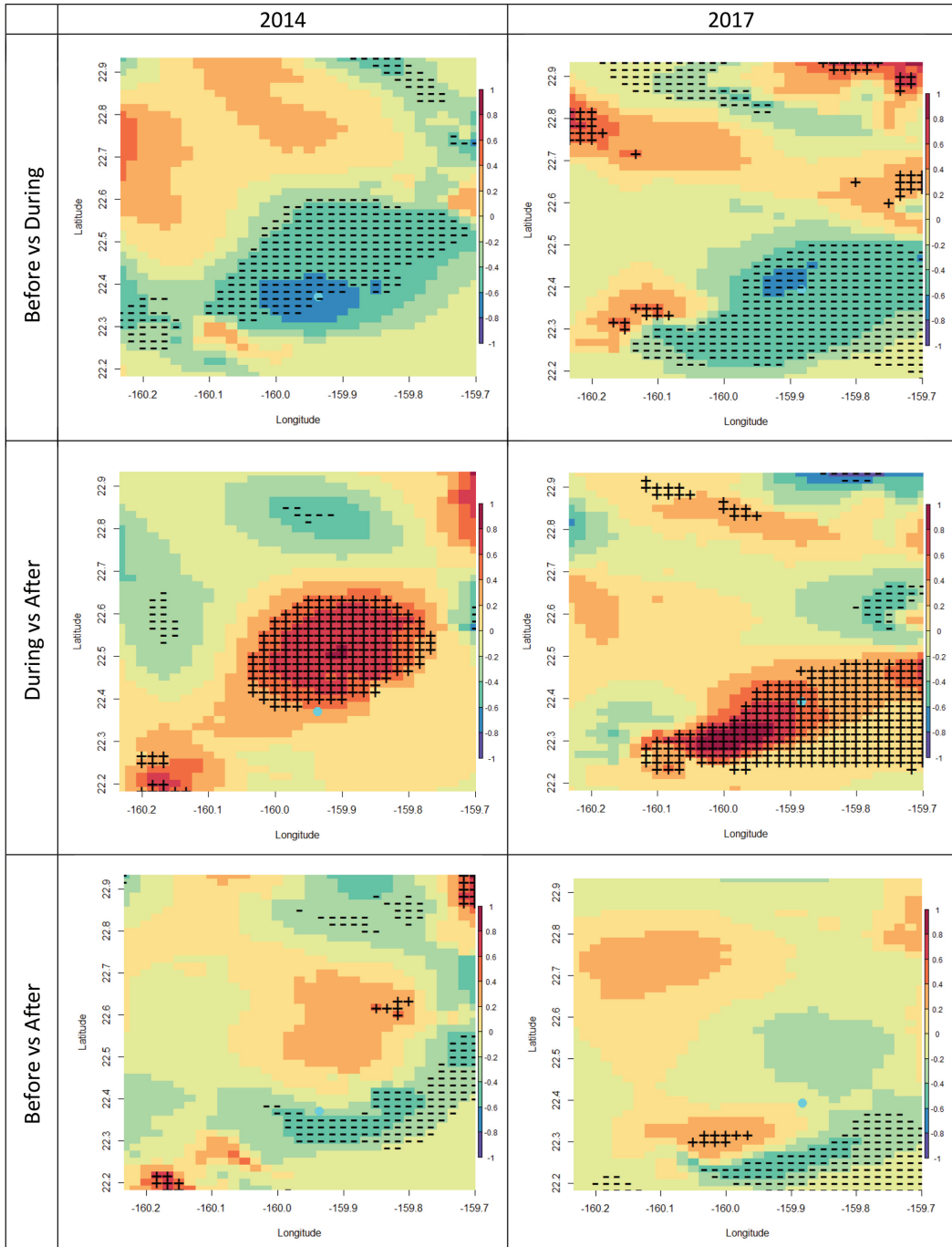


Figure 3. Point estimate surfaces of differences between phases for which cool colors relate to a decrease in presence from one phase to another and warm colors relate to an increase in presence. “+” indicates regions with a significantly higher probability of presence, and “-” indicates regions with a significantly lower probability of presence as estimated by the parametric bootstrap. The left plots relate to 2014, and the right plots relate to 2017. The top panel shows the difference between Before and During, the middle panel shows the difference between During and After, and the bottom panel shows the difference between Before and After. The cyan dot represents the estimated mean center of activity for that year (not included in the final model).

After (Figure 3). Despite the significant increase between During and After in 2017, the comparison of Before and After for 2017 still showed a relatively large area, with lower predicted probability of call presence in the After phase, particularly in the southeast.

Discussion

This study utilized data collected on a U.S. Navy training and testing range as part of ongoing acoustic monitoring of the area to establish that there was a clear response of calling minke whales to training activities that involved sonar emission. In both 2014 and 2017, the spatial distribution of acoustically derived whale tracks changed during the training activity, with fewer tracks in the vicinity of the center of ship activity. There was evidence that the detected call presence was returning toward normal over the days following the end of the activity. Despite this clear response in the spatial distribution of calling, one drawback of PAM is that conclusions cannot be made about whether this relates to a silencing response or an avoidance response, or a combination of the two.

Our prediction, based on results from tagged whales and CEEs, is that the minke whales on the range and near the training activity would initiate an avoidance response to the training exercise (Kvadsheim et al., 2017). Our results indicate that this may indeed have been the case, particularly as there was an increase in predicted probability of acoustic presence in some northern regions of the range as well as a decrease around the center of ship activity. This might not be expected if whales near the ship activity just ceased calling temporarily without being displaced. In addition, the spatial distribution in the After phase resembled animals moving in from the edges rather than a return to normal calling behavior because the spatial distribution did not appear to have returned to pre-training conditions, even when we combined data over 5 d after training in 2017. The distribution had returned to something resembling the Before phase in 2014 when we combined data over 5 d after the training activity finished, but patches of lower presence of calling did remain.

Similarly, for harbor porpoises (*Phocoena phocoena*) exposed to pile driving, PAM studies using C-PODs showed a decrease in acoustic detections within 5 to 10 km of pile driving activity during and shortly after the activity, while detectors up to 25 km away showed a concurrent increase in detections (Brandt et al., 2011; Dähne et al., 2013). The studies concluded that the harbor porpoises had most likely moved away from the activity rather than just changed their vocal activity. That interpretation was supported in some

cases by concurrent aerial surveys (Dähne et al., 2013; Haelters et al., 2014). However, Blackwell et al. (2015) describe a dual behavioral response in bowhead whale (*Balaena mysticetus*) calling in response to airgun sounds whereby there was an increase in calling at low levels of exposure and then a decrease and cessation at higher levels of exposure. On this basis, it could be suggested that individual minke whales near the edge of the range would increase their calling rate, while those near the center would decrease their calling rate or cease calling. Unfortunately, there are no visual observation data concurrent with the acoustic data used in this study to determine whether minke whales did remain in the center of the range.

It should be acknowledged that the minke whale individuals in this study were in a different behavioral context than those minke whales reported in Kvadsheim et al. (2017), as were the other species for which similar responses on navy ranges have been reported (e.g., McCarthy et al., 2011; Tyack et al., 2011). Kvadsheim et al. (2017) presented results from individuals that were on feeding grounds and discussed the observed avoidance responses in terms of energetic costs and disruption to foraging. Studies from the AUTECH range reported avoidance responses of beaked whales based on evidence from both tagging and PAM, and they also related these responses to foraging disruption because the vocal behavior being detected was foraging clicks.

The calling of minke whales in the Hawaii region at this time of year is thought to relate to mating and, therefore, their responses may not parallel those of foraging minke whales. There is increasing evidence that the environmental and behavioral context of exposure affects responsiveness and type of response (e.g., Ellison et al., 2012; Harris et al., 2015; Friedlaender et al., 2016; Southall et al., 2019). For example, it could be hypothesized that animals would cease calling because the combined activities of a training event create an environment that is too noisy for communications—that is, it is not worth the effort for those few days (Blackwell et al., 2017). We should also consider that we are monitoring the calling behavior of males during a period in which they are primarily interested in the females and, therefore, the calling behavior of the males may be affected by behavioral responses exhibited by females. For example, if the females leave the range during the training activity, then males may either follow or cease calling until the females return.

Regardless of the mechanism underlying the change in the spatial distribution of calling, it appeared to take up to 5 d for the distribution to

return to Before conditions in 2014 and longer in 2017. This is a comparable recovery time frame as observed for beaked whales at PMRF (Manzano-Roth et al., 2016) whereby vocalizations began to increase in the After period but had not returned to Before conditions by the end of data collection (4 d after exercise), and it is thought that it may take up to 1 to 2 wks for full recovery to baseline conditions (Henderson et al., 2016). Similarly, at AUTEK, beaked whales were observed to take 2 to 3 d to return to the range following the end of an exercise (Tyack et al., 2011). There are also examples of recovery times of similar duration following displacement in response to vessels for both baleen whales (Richardson & Malme, 1993) and odontocetes (Finley et al., 1990). The effect of this behavior disruption on an individual depends on whether the behavior ceases altogether for the duration of the activity and the days following, whether the animals move elsewhere and continue the behavior in sub-optimal conditions, or whether they move elsewhere and carry on as normal. This relates to both disruption of feeding and mating behavior. Studies utilizing telemetry devices with acoustic recorders could help resolve this uncertainty, providing an indication of whether animals are ceasing calling and/or moving away and, if they are moving away, what they are doing in the new location. A better understanding of the behavior of individuals during periods of disruption would allow the evaluation of the potential for population-level consequences due to repeated exposure of individuals.

The retention of “year” in both interaction terms indicates inter-annual variability in the presence and distribution of calling whales across all phases. This is in agreement with Martin et al. (2015) who found year-to-year variability in the density of minke whale calls between 2011 and 2013, and Henderson et al. (2016) who found inter-annual variability in detection of Blainville’s beaked whale vocalizations on PMRF over the same period. This variability could be due to many factors, including environmental conditions, background noise levels caused by natural sources, changes in population numbers, presence of other species, or differing levels of human activity in the area. It is important to recognize this variability in baseline presence and distribution because ignoring it may lead to wrongly associating a change in distribution with human activity (Henderson et al., 2016). However, in all of these studies, it has been found that despite the differences in baseline across years, there was a change in the metric of interest during training activities.

“Latitude,” “longitude,” and “depth” were found to be better spatial predictors than “distance to the center of ship activity” in each year. There

are a few potential reasons for this finding. First, the “distance to the center of ship activity” metric relates to a single location on the range that represents the centroid of the activity over the entire training period which may not be representative of the spatial spread of ship activity over the range or indeed of sonar use. For example, the spatial distribution of different MFAS sources in each year may result in different spatial patterns of response due to variable responsiveness to, for example, hull-mounted MFAS vs helicopter-dipping MFAS (Falcone et al., 2017). Second, the covariate included in the model was “distance to this location,” which assumes that any response in relation to distance would be equal in all directions. Looking at Figures 2 and 3, the redistribution of calling appears non-isotropic, with a greater probability of call presence in the north in the During phase than in the southern portion of the range. Third, the location was very similar across the 2 y, and so there was little to be gained from this covariate over “latitude” and “longitude.” Perhaps looking at data from a year where the “distance to the center of ship activity” differs substantially from that in 2014 and 2017 may help assess the utility of this metric. Fourth, there may be environmental factors relating to “latitude,” “longitude,” and “depth” that confer a preference for particular areas within the range. We propose investigating other, more representative spatial metrics relating to aspects of the training activity, such as a spatial surface of cumulative intensity, but note that national security restrictions on the details of the training activities may limit the options available.

The statistical analysis framework used here—the logistic regression based on observed call locations (presences) and random locations (pseudo-absences)—has the disadvantage that the number of pseudo-absences chosen is user-defined but affects the results (Warton & Shepherd, 2010—in the context of temporally uncorrelated data), so it needs to be considered carefully. An alternative approach is to specify the observed locations as a realization from a point process model (Johnson et al., 2013), with an underlying intensity function that varies according to covariates such as “latitude,” “longitude,” and “phase.” That alternative framework would use only the observed locations as input, bypassing the need to consider pseudo-absences; a disadvantage is that computation is more difficult.

The analysis herein focused on differences in space use between the different phases of the naval exercises. An alternative is to focus on differences in the trajectory formed by successive localizations—for example, differences in speed or tortuosity between the Before, During, and After phases. Such an approach would allow the incorporation

of more time-varying covariates relating to the exposure context such as “source type,” “the distance between individual whales and vessels/sonar sources,” “metrics of received level,” and “information on whether vessels are heading toward or away from individual whales.” This may allow us to explain some of the variability in responsiveness that has not been investigated here such as the difference in response between years. Such analyses have been performed using animals fitted with position- or displacement-sensing tags using, for example, hidden Markov modeling (Isojunno & Miller, 2015; DeRuiter et al., 2017). Visual studies of theodolite-tracked individuals (e.g., Malme et al., 1984; Dunlop et al., 2017) have also been used to look at changes in trajectories in relation to a disturbance source. This finer-scale approach, using acoustically derived tracks, is the subject of an ongoing study.

The findings presented herein expand on previous analysis of the density of calling minke whales in relation to naval training activities on PMRF (Martin et al., 2015). We have shown that there is a spatial shift in calling behavior on the range During training activities compared with Before, and that this extends for a number of days after the activities end. While we are unable to conclude categorically that this relates to a movement away from the range rather than a cessation of calling, there are indications from this and other studies that an avoidance response is a likely explanation. This is an example of data from an opportunistic exposure study complementing data from controlled exposure studies, and extending over larger spatial and temporal scales than practical in CEEs.

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