

# Assessing the Deepwater Horizon oil spill impact on marine mammal population through acoustics: Endangered sperm whales

Azmy S. Ackleh

*Department of Mathematics, University of Louisiana at Lafayette, Lafayette, Louisiana 70504*

George E. Ioup and Juliette W. Ioup

*Department of Physics, University of New Orleans, New Orleans, Louisiana 70148*

Baoling Ma

*Department of Mathematics, University of Louisiana at Lafayette, Lafayette, Louisiana 70504*

Joal J. Newcomb

*Naval Oceanographic Office, Stennis Space Center, Mississippi 39522*

Nabendu Pal

*Department of Mathematics, University of Louisiana at Lafayette, Lafayette, Louisiana 70504*

Natalia A. Sidorovskaia<sup>a)</sup>

*Department of Physics, University of Louisiana at Lafayette, Lafayette, Louisiana 70504*

Christopher Tiemann

*Applied Research Laboratories, University of Texas at Austin, Austin, Texas 78713*

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Long-term monitoring of endangered species abundance based on acoustic recordings has not yet been pursued. This paper reports the first attempt to use multi-year passive acoustic data to study the impact of the Deepwater Horizon oil spill on the population of endangered sperm whales. Prior to the spill the Littoral Acoustic Demonstration Center (LADC) collected acoustic recordings near the spill site in 2007. These baseline data now provide a unique opportunity to better understand how the oil spill affected marine mammals in the Gulf of Mexico. In September 2010, LADC redeployed recording buoys at previously used locations 9, 25, and 50 miles away from the incident site. A statistical methodology that provides point and interval estimates of the abundance of the sperm whale population at the two nearest sites is presented. A comparison of the 2007 and the 2010 recordings shows a decrease in acoustic activity and abundance of sperm whales at the 9-mile site by a factor of 2, whereas acoustic activity and abundance at the 25-mile site has clearly increased. This indicates that some sperm whales may have relocated farther away from the spill. Follow-up experiments will be important for understanding long-term impact.

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## I. INTRODUCTION

The aim of this study is twofold: (1) To develop a statistical methodology that utilizes passive acoustic data to obtain point and interval estimates of marine mammal population densities; (2) to apply this methodology to data collected before and after the 2010 spill in the Gulf of Mexico (GoM) and assess the impact of the spill on the population of endangered sperm whales. Our work on the statistical estimation of population density is motivated by a recent paper of Marques *et al.*<sup>1</sup> and statistical methods introduced for visual surveys, although several advancements have been implemented and are discussed here. Despite the fact that

the accuracy of density estimates based on acoustic cue counting is strongly dependent on the parameters of the model (such as the proportion of false positive detections, detection probability, etc.), this paper focuses on the comparison of estimated abundance between different regions before and after oil spills. The average regional population density with a 95% confidence interval is obtained by a bootstrap method<sup>2</sup> and provides reliable information for assessing the oil spill impact on the sperm whale population in the Northern GoM.

Oil spills have a major environmental impact on marine life,<sup>3,4</sup> and the Deepwater Horizon (DWH)/Macondo Well incident site, in particular, is in an area populated by the GoM's resident population of endangered sperm whales.<sup>5</sup> According to a NOAA Fisheries report, the sperm whale population in the Northern GoM is estimated to be 1665

<sup>a)</sup>Author to whom correspondence should be addressed. Electronic mail: nas@louisiana.edu

with a potential biological removal level of 2.8, defined as “the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population.”<sup>5</sup> Thus, even small ecological damage to the stock may have serious implications. Until recently visual observation data were the main source of information for statistical models to estimate the abundance of marine mammals in the ocean,<sup>5,6</sup> but this approach is very costly in terms of ship time and human observer involvement. The amount of collected data and their quality are strongly dependent on weather, daylight conditions, and species type (for instance, beaked whales are very difficult to observe even in calm sea-state 1 conditions).<sup>7</sup> The population estimates for species that do not exhibit well-identifiable visual cues (water spouting, fluking, jumping) and spend a long-time in deep dives are questionable. (The average sperm whale foraging dive lasts ~45 min, and more than 70% of their time is spent underwater;<sup>8,9</sup> the average beaked whale dive is 50 min long, 10 times a day, and they generally rest below the surface.<sup>10</sup>) As sperm whales spend over 70% of their time in deep dives more than 100 miles away from land, visual observations of them and mortality counts are limited and difficult to use for the assessment of ecological damage.

However, sperm whales and other deep-diving marine mammal species produce powerful sounds (echolocation clicks and foraging buzzes) unique to their species throughout their dives,<sup>9,10</sup> and in the last several years analysis of these sounds has been introduced as a new tool for abundance estimation when visual observations are limited or unavailable.<sup>1,11</sup> There are several major advantages with the new approach: (1) Animals do not need to be seen for abundance estimations, so weather and visibility conditions become irrelevant, (2) passive acoustic systems can record data over an extended period of time without human involvement, so annual, seasonal, and even daily abundance trends can be inferred, (3) many existing deep ocean acoustic observational systems can provide baseline and needed data for regional abundance estimates and stock health, (4) acoustic data can also provide insight into the assessment of causes for observed population trends through the analysis of anthropogenic noise level, prey capture calls, female–male–calf call ratios, etc.

Only a few case studies to obtain quantitative density estimates based on counting acoustic cues have been published in the literature, with the most advanced work presented by Marques *et al.*<sup>1</sup> on an estimation of Blainville’s beaked whale density over a 6-day period in the spring of 2005 in the Bahamas. Long-term monitoring of endangered species abundance based on acoustic recordings has not yet been pursued, so this paper reports the first attempt to use multi-year passive acoustic data to study the impact of the 2010 oil spill in the GoM on the population of endangered sperm whales. Prior to the spill the Littoral Acoustic Demonstration Center (LADC) had collected acoustic recordings near the spill site in 2001, 2002, and 2007.<sup>12,13</sup> These baseline data now provide a unique opportunity to better understand how the oil spill affected marine mammals. In

September 2010, LADC redeployed acoustic recording buoys at previous sites 9, 25, and 50 miles away from the DWH. A comparison of the 2007 and the 2010 collected data sets shows that the estimated abundance of sperm whales at the nearest 9-mile site decreased by a factor of 2, whereas it clearly increased at the 25-mile site.

The remainder of this paper is structured as follows. Section II describes the deployment of the LADC passive acoustic system [the Environmental Acoustic Recording System buoys (EARS buoys)] in the vicinity of the oil spill site and presents details of the acoustic data processing to infer information about sperm whale acoustic activity by detecting and counting numbers of emitted echolocation clicks per unit of time (click density). In Sec. III the extracted click density distributions are statistically analyzed and fitted by power law functions. In Sec. IV the statistical model of the population density estimation based on acoustic cues is described and applied to acoustic data. Point estimation as well as interval estimation results are also discussed.

## II. PASSIVE ACOUSTIC DATA COLLECTION AND PROCESSING

LADC possesses multi-year pre-spill passive acoustical data in the vicinity of the DWH site collected as a part of an effort to study acoustic phonation and to develop acoustic individual identification methods for the GoM sperm and beaked whales.<sup>12,13</sup> These data were collected in 2001 (active recording period July 18–August 29), 2002 (active recording period August 28–October 23), and 2007 (active recording period July 6–July 14). In Fig. 1(A) the circles indicate three experimental sites used in 2001 and 2002; locations were chosen for their high concentrations of visually observed sperm whales, as reported by NOAA. These sites are about 50 miles away from DWH [a fire symbol on Figs. 1(A), 1(C)]. Squares indicate the northern and southern locations of EARS buoys in the 2007 experiment, about 9 and 25 miles from DWH, respectively. These locations were chosen for the relatively high density of visual observations of GoM beaked whales. Three EARS buoys were deployed in a triangular configuration at each 2007 location for tracking capabilities. Figure 1(B) shows the extent of imaged surface oil on June 14, 2010, during the active oil spill, as a green overlay. Supported by the NSF RAPID program, in September 2010 LADC scientists returned to the previous experimental sites aboard the Greenpeace ship “M/V Arctic Sunrise.” Three pairs of the LADC EARS buoys were redeployed, one pair at each previous location [marked as pins in Fig. 1(A)] 9, 25, and 50 miles away from the DWH site.<sup>14</sup>

The EARS buoys recorded continuous acoustic data for 12 days each at a 192 kHz sampling rate. The first buoy at the Northern site was deployed on September 9, 2010; and the last one was deployed on September 12, 2010 at the Western site. All buoys were successfully recovered during a following cruise in October, 2010. However, the initial post-experimental data quality check revealed that one of the buoys at the northern site started malfunctioning after several hours of recordings, so the data from this buoy were not used in the analysis. A typical EARS buoy deployment

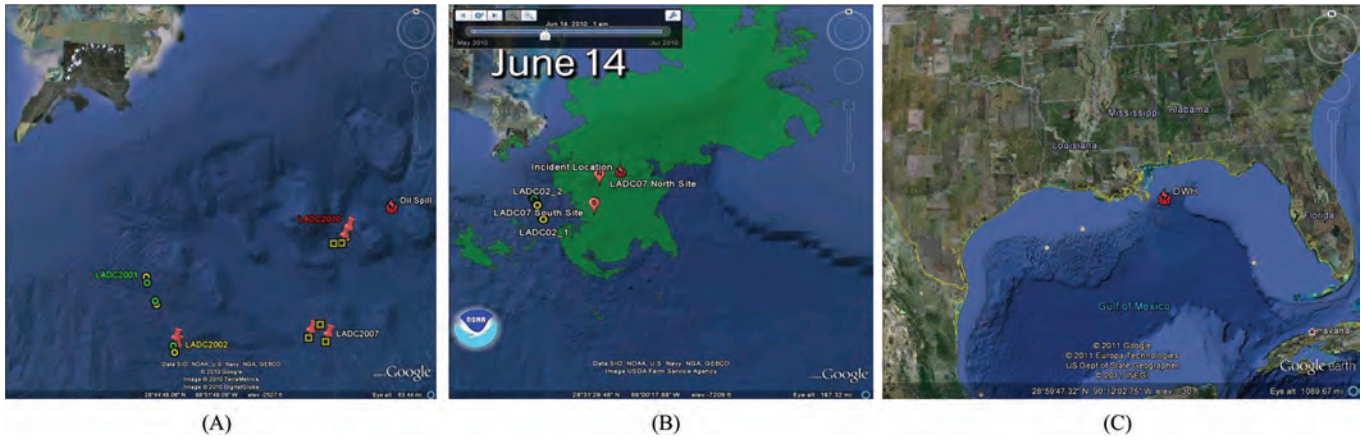


FIG. 1. (A) Location of the LADC experiment sites in 2001 (green circles), 2002 (yellow circles), 2007 (yellow squares), and 2010 (red pins). A fire symbol denotes the DWH incident site ( $28^{\circ}44'12''$  N,  $88^{\circ}23'14''$  W). Yellow squares indicate the northern and southern locations of EARS with about 9 and 25 miles from DWH, respectively. (B) Green overlay represents the extent of the satellite imaged surface oil on June 14, 2010 (courtesy of NOAA). (C) Geographic location of the oil spill site relative to the Louisiana and Mississippi coasts. These maps were produced using GoogleEarth.

assembly is presented in Fig. 2. Recording hydrophone (just above EARS buoys) depths were about 1 km at the northern and southern sites and 800 m at the shallower Western site to target the foraging depths of sperm and beaked whales.

The data processing system consists of two main components: (1) The detection and counting of acoustic signals of a particular species and (2) inserting acoustic cue counting results into a statistical model to estimate species regional abundance. GoM sperm whales (which are predominantly females with calves) produce three main types of acoustic signals: Regular clicks for orientation and

long-range prey echolocation, buzzes for short range prey echolocation before consumption, and codas for communication. The detection/counting algorithm was optimized to count echolocation clicks by using a multi-band spectral energy detector. Regular echolocation clicks have a multipulse structure of total duration between 5 and 15 ms depending on whale orientation relative to a receiver.<sup>9</sup> Inter-click interval varies between 1.0 and 1.4 clicks/s, and energy is distributed between 3 kHz and as high as 25 kHz. The on-axis monopulse click (p1 in accordance with the classification suggested by Møhl *et al.*<sup>9</sup>) spectrum is smooth and peaks at  $\sim 12$  kHz; the off-axis multi-pulse click spectra (p0, p2) have multiple peaks and notches in the 3–25 kHz band. Clicks from different marine mammal species were classified by comparing energy distribution in three bands: low (L) band (3–20 kHz—sperm whale), medium (M) band (25–55 kHz—beaked whale), and high (H) band (60–90 kHz—dolphin).

The specifics of click detection and counting are as follows. First, a spectrogram using 512-point short-time Fourier transforms with no overlap is calculated for a given sensor's time series of continuous acoustic data sampled at 192 kHz. Each column of the spectrogram represents the frequency content in a 2.7 ms window of the signal, and for each of those windows the spectral amplitudes over a subset of frequency bins are integrated. By summing over select frequencies where content specific to a desired marine mammal species' clicks is expected, click discrimination by species can be done. In this example, a sum over frequency bins in the low band (3–20 kHz) is used in the detection of sperm whale clicks. The value of the sum of spectral amplitudes at every time window is saved, creating what will be referred to as a spectral sum time series, with one series for each of the three defined frequency bands and for each receiver.

Click detection is done through examination of the spectral sum data where brief, broadband events like marine mammal clicks will appear as relatively high and often periodic peaks in the spectral sum time series. The mean and standard deviation of a 10-min window of spectral sum data

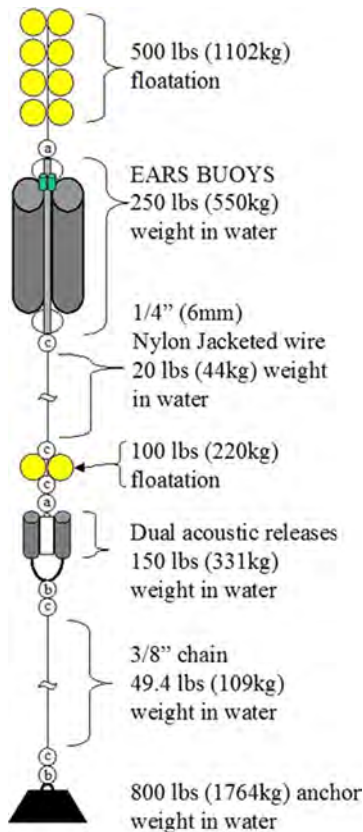


FIG. 2. (Color online) Typical EARS buoy mooring.



are calculated, and click detection is defined as any point where the spectral sum exceeds a threshold of 10 standard deviations above the mean. Human inspection and experience shows that, in the GoM environment, a 10-standard deviation threshold detects almost all clicks that are assumed to be direct acoustic path receptions of a click event while ignoring the occasional lesser-amplitude arrivals that appear to be receptions of reflected acoustic paths (multipath arrivals, or echoes). This is desirable as each click event should result in only one reported detection, not one detection for every echo that is heard. Other checks ensure that one click event spanning multiple consecutive time bins is not counted more than once.

The click detection process is applied to all three frequency bands, and there will be some occasions where a click event is seen to span more than one frequency band simultaneously. When searching for sperm whale clicks, a click event must be present in the low band only; concurrent detection in medium or high frequency bands disqualifies it as a sperm whale (but may qualify it as another species such as a dolphin). Last, the total quantity and timestamps of sperm whale click detections are passed to the statistical models.

Some results of acoustic cue counting are summarized in Fig. 3. A comparison of mean click counts per day for low band clicks at the northern and southern sites shows a decrease of 52.7% in mean acoustic activity in the low band at the closest northern site (9 miles away from the incident site) and an increase of 39.4% at the southern site (25 miles away). Note that the click density is positively skewed, thus the error bars are not centered.

### III. STATISTICAL MODELING OF CLICK COUNT DATA

Figure 3 shows that the average of the acoustic activity declined at the northern site while increasing at the southern

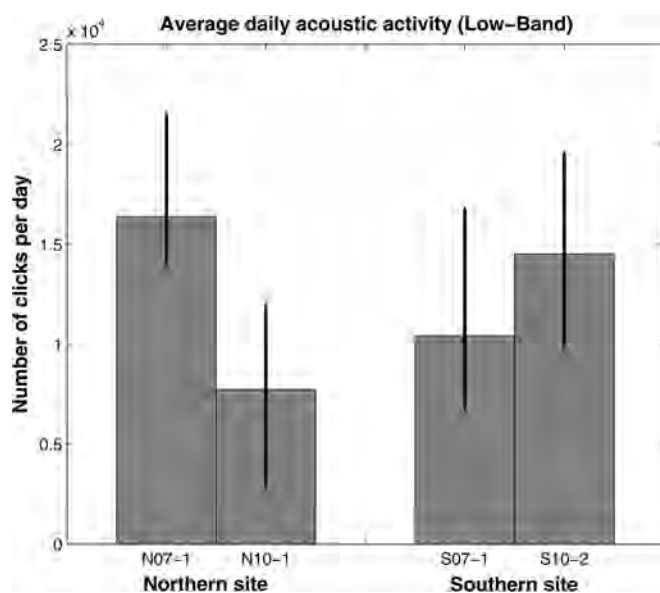


FIG. 3. Comparison of the mean click counts per day and the 95% confidence interval before and after the oil spill at the selected buoys in the northern and southern sites. Error bars shows the 95% confidence interval of the daily mean click counts. The comparison of the mean click counts using data from other buoys would give similar results.

site from the year 2007 to the year 2010. To statistically corroborate this observed pattern, in this section a probability density function that models the acoustic data for the years 2007 and 2010 at the northern and southern sites is found and compared to see if there is a significant difference between 2007 and 2010 statistical models. To that end, with the click rate data (number of observed clicks per minute), obtained as described in Sec. II, a probability density function is fit to the histograms formed for selected data sets for a specific experiment and location. The click density graphs for one 2007 buoy (marked as N07-1) and one 2010 buoy (marked as N10-1) are shown in Fig. 4 for the northern site and in Fig. 5 for the southern site (marked as S07-1 for 2007 and S10-1 for 2010). The graphs for the other buoys (2007 northern site: N07-2, N07-3; 2007 southern site: S07-2, S07-3; and 2010 southern site: S10-2) are similar in appearance. Associated histograms are shown later in Fig. 6.

It will be demonstrated that the click rate histograms tend to follow a “power law” pattern. Let a particular location and observational time be fixed and let X be an event of

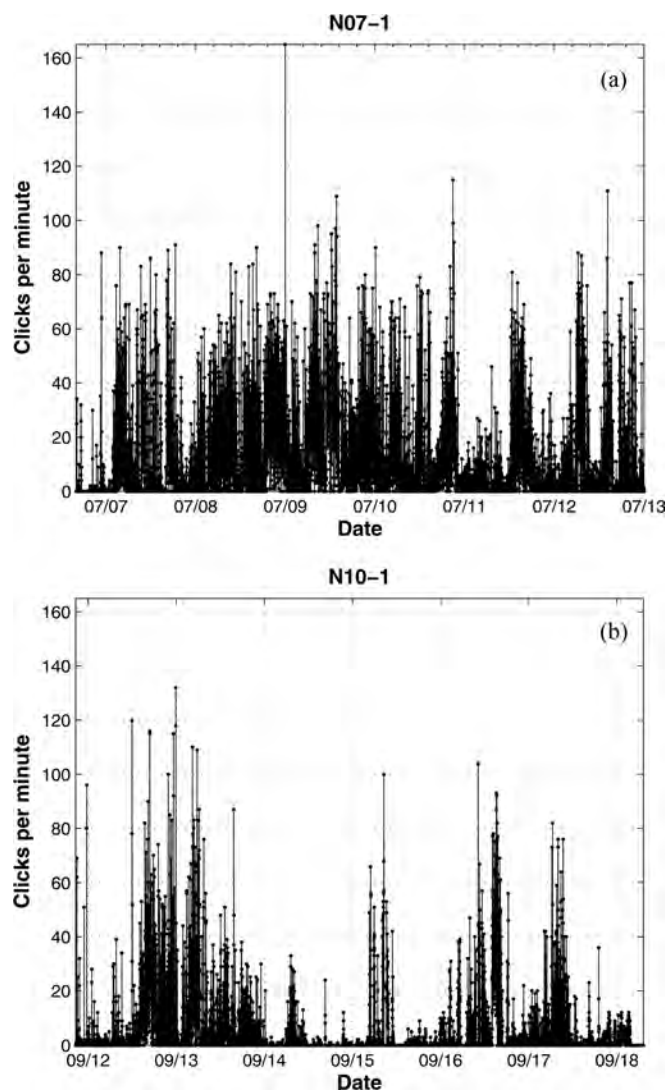


FIG. 4. Click counts per minute: (a) For one 2007 buoy (titled as N07-1) and (b) for one 2010 buoys (titled as N10-1) in the northern site.

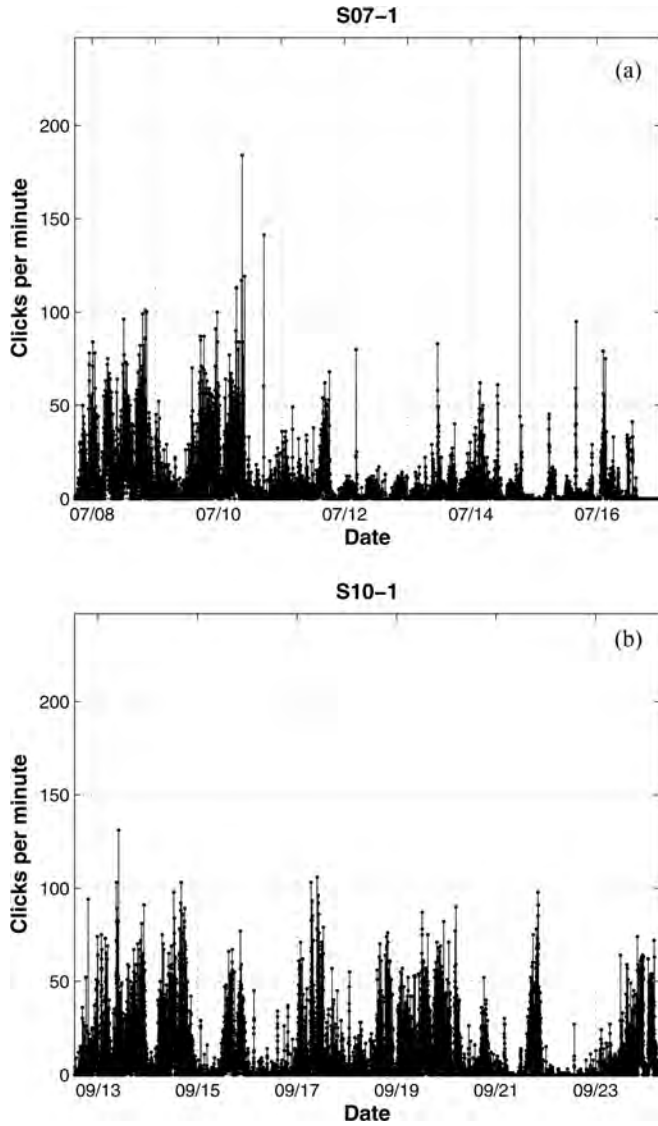


FIG. 5. Click counts per minute: (a) For one 2007 buoy (titled as S07-1) and (b) for one 2010 buoy (titled as S10-1) in the southern site.

the number of clicks observed per minute. Then the power law probability density function<sup>15</sup> is

$$P(X = x|\theta) = \frac{k(\theta)}{(1+x)^\theta}, \quad x = 0, 1, 2, \dots, \quad (1)$$

where  $k(\theta)$  is a normalizing constant, i.e.,  $k(\theta) = \left(\sum_{x=0}^{\infty} (1+x)^{-\theta}\right)^{-1}$ .

Note that one must have  $\theta > 1$ , otherwise the series  $\sum_{x=0}^{\infty} (1+x)^{-\theta}$  does not converge. Although the previous model (1) has provided a good fit for the 2007 data sets (i.e., for the histograms for N07-1–N07-3 and S07-1–S07-3) and the 2010 southern data set (i.e., for S10-1, S10-2), it failed to do so for the 2010 northern data set, i.e., for N10-1, which indicates that the N10-1 data set is different from the others. The histogram for the N10-1 site shows a higher concentration of 0 (no) click events. Therefore, a more general power law model<sup>15</sup> is adopted as

$$P(X = x|\theta, b) = \frac{k(\theta, b)}{(b+x)^\theta}, \quad x = 0, 1, 2, \dots, \quad (2)$$

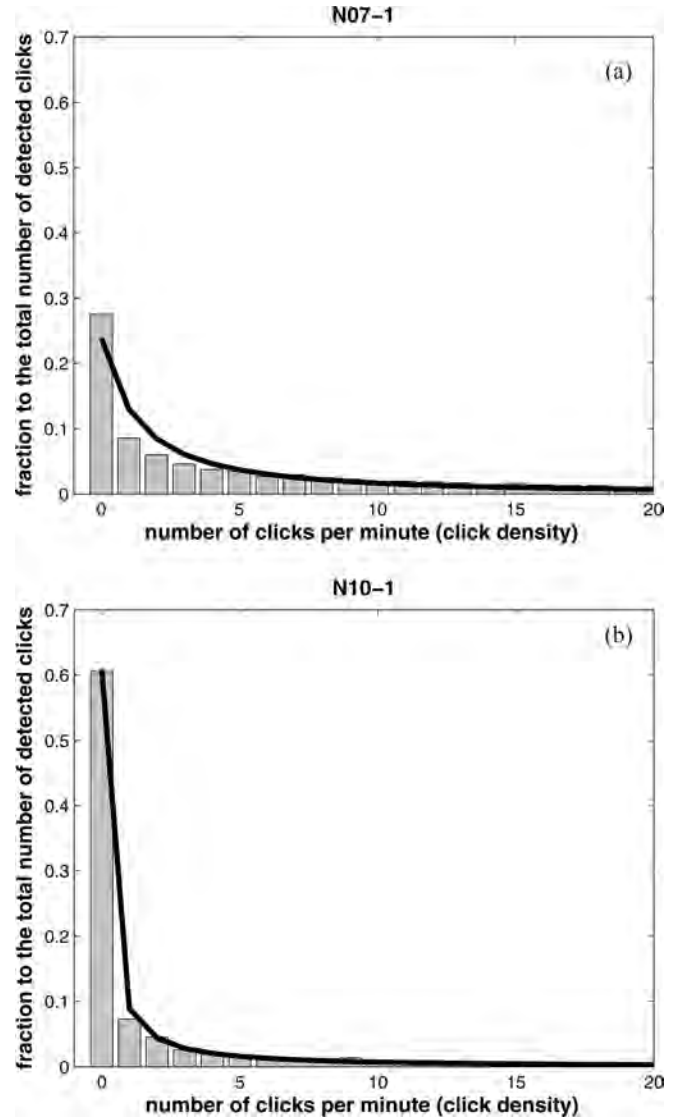


FIG. 6. The histogram and power law fitting curve: (a) For one 2007 buoy (titled as N07-1) and (b) for one 2010 buoy (titled as N10-1) in the northern site.

where the extra parameter  $b$  brings more flexibility in the model to fit the N10-1 data set. The parameter space for model (2) is  $\Omega = \{(\theta, b) | \theta > 1, b > 0\}$  and  $k(\theta, b) = \left(\sum_{x=0}^{\infty} (b+x)^{-\theta}\right)^{-1}$ .

For a given data set with random observations  $x_1, x_2, \dots, x_n$  of the number of clicks recorded at  $n$  consecutive minutes, the log-likelihood function is

$$\begin{aligned} L^*(\theta, b|x_1, x_2, \dots, x_n) &= \ln \left( \prod_{i=1}^n k(\theta, b) / (b+x_i)^\theta \right) \\ &= \sum_{i=1}^n (\ln(k(\theta, b)) - \theta \ln(b+x_i)) \\ &= -n \ln \left( \sum_{i=0}^{\infty} (b+i)^{-\theta} \right) \\ &\quad - \theta \sum_{i=1}^n \ln(b+x_i). \end{aligned} \quad (3)$$

The estimates of the parameters  $b$  and  $\theta$ , henceforth denoted by  $\hat{b}$  and  $\hat{\theta}$ , are to be obtained by maximizing the

previous log-likelihood function  $L^*$ . However, maximization of  $L^*$  with respect to  $\theta$  and  $b$  simultaneously runs into the “saddle point” or “ridge line” type problem, where  $L^*$  is monotonically increasing with respect to  $b$  and  $\theta$ .

To resolve the previous problem of estimating the parameters  $b$  and  $\theta$  by maximizing  $L^*$ , a different approach is used. For a fixed  $b$ ,  $L^*$  is maximized with respect to  $\theta$ , and the optimal value of  $\theta$  thus obtained, which depends on  $b$  and is called  $\hat{\theta}(b)$ . With the pair  $(b, \hat{\theta}(b))$ , the expected number ( $E$ ) of observations with value  $X=x$  is now computed as

$$E = nP(X = x | b, \hat{\theta}(b)), \quad (4)$$

where the expression  $P(X = x | b, \hat{\theta}(b))$  is the same as the one in Eq. (2) with  $\theta = \hat{\theta}(b)$ . The expected number ( $E$ ) of observations in the category  $X = x$  is then matched with the observed numbers ( $O$ ) of observations, i.e., observed frequency of  $X = x$ , and the “goodness of fit” statistic  $G$  is computed as  $G = G(b) = \sum_x (E - O)^2 / E$ , which is a function of  $b$ . The optimal value of  $b$ , i.e.,  $\hat{b}$ , is now obtained as the one that minimizes  $G$  with respect to  $b$ . Table I summarizes the estimated values of the parameters  $b$  and  $\theta$  for eight data sets.

The modified power law function fit (with parameters in Table I) of click density histogram data is shown in Fig. 6 for the northern site. The histograms and power law fitting curves for buoys in the southern site are all similar to each other; the fitting curves for all buoys will be shown in Fig. 7.

To take a closer look at the differences between the northern and southern sites, all the power law fittings for the northern and southern sites are overlaid in Fig. 7. Apparently, the power law functions in the northern area show a sharp difference between years 2007 and 2010, whereas the fitting functions in the southern area are similar. Acoustic activity of sperm whales at the site closest to the DWH incident site has considerably changed between 2007 and 2010, but no obvious differences are observed at the southern site. This change reflects into the population density estimates as presented in the next section.

#### IV. ESTIMATION OF POPULATION DENSITY

In this section the estimation of a change in regional population density of sperm whales from acoustic cue counts is discussed. Once a particular region with an area  $a$  in the

TABLE I. The estimated values of the parameters  $\hat{b}$  and  $\hat{\theta}$ .

Location/time	$\hat{b}$	$\hat{\theta}$
N07-1	1.9770	1.4809
N07-2	1.3860	1.2312
N07-3	1.4960	1.3793
N10-1	0.2409	1.1940
S07-1	2.1350	1.8057
S07-2	1.4860	1.7470
S07-3	0.8670	1.4881
S10-1	0.3340	1.1091
S10-2	0.6510	1.2634

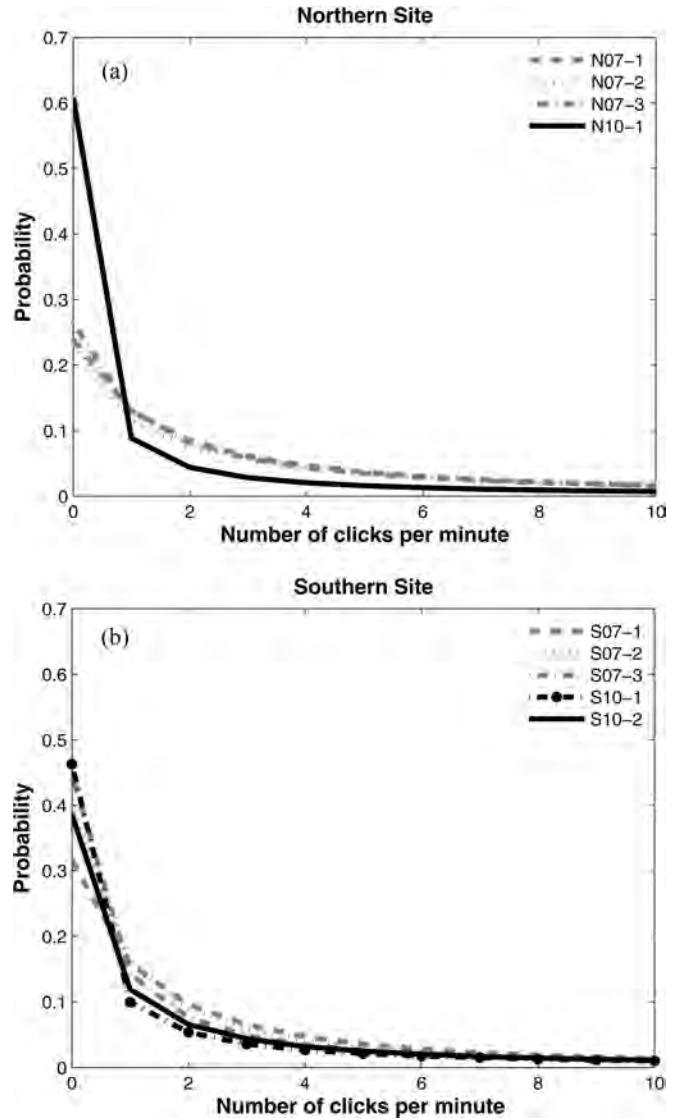


FIG. 7. Comparison of the power law fittings for the (a) northern and (b) southern sites. Dark lines correspond to the 2010 data set.

ocean is identified, the density  $D$ , which is defined as the number of animals per unit area  $a$  is  $D = N/a$ , where  $N$  represents the total number of animals in the region within area  $a$ . If  $n$  animals are detected in the target area visually or acoustically, then an estimate of  $D$  is given by Buckland *et al.*<sup>6</sup> as  $\hat{D} = n/(aP)$ , where  $P$  represents the probability (estimated) of detecting a given animal in the target area. Intuitively this can be justified as

$$D = \frac{N}{a} = \frac{nN}{a n} = \frac{n}{a} \frac{1}{n/N} = \frac{n}{aP}, \quad (5)$$

where  $P = n/N$  is the probability of detecting a given animal through a sample of size  $n$  from a population of size  $N$ . Note that a sample of size  $n$  can be selected from a population of size  $N$  in  $\binom{N}{n}$  ways, where

$$\binom{N}{n} = \frac{N!}{n!(N-n)!}, \quad 0 \leq n \leq N.$$

If a particular animal needs to be included for sure in the sample, then the remaining sampled animals are chosen in  $\binom{N-1}{n-1}$  ways. Thus  $P = \binom{N-1}{n-1} / \binom{N}{n} = n/N$ .

Following Marques *et al.*,<sup>1</sup> a population estimate based on detected acoustic cue count is given by

$$\hat{D} = \frac{n_c(1-c)}{\pi\omega^2 P(Tr)}. \quad (6)$$

Here  $n_c$  is the number of detected cues over a time period  $T$ ,  $c$  denotes an estimated proportion of false positive detection,  $r$  is an estimated cue production rate by a single mammal (i.e., expected number of cues per unit time).

$$\begin{aligned} P &= \int_0^\omega \text{Prob}(\text{a cue is detected} | \text{the cue is generated at a distance } y) \times \text{Prob}(\text{the cue is generated at a distance } y) \\ &= \int_0^\omega p_y h(y) dy, \end{aligned} \quad (7)$$

where  $p_y$  gives the probability a cue is detected given that the cue is generated at a distance  $y$  and  $h(y)$  gives the probability of the animal being at a distance  $y$ . There are several approaches that can be used to estimate  $P$  for a particular area. The first procedure requires the use of a considerable number of tagged animals in a survey area and relates sensor detection events to the sounds produced by tagged animals to estimate  $p_y$  and  $h(y)$ .<sup>1</sup> No concurrent tagging was conducted during LADC deployments. The second approach implies a localization of an animal producing each detected cue<sup>16</sup> that is a computationally and operator-time costly procedure. The third approach is based on modeling an animal sound production<sup>17</sup> and employing propagation models and the sonar equation to predict a probability of detection at a sensor location relative to animal locations.<sup>18</sup> The last approach is subject to availability of environmental data (sound speed, bathymetry) and the animal's beam pattern (usually derived from tagged data that are absent for GoM). In this article we use an alternative methodology for estimating  $P$ , as described in the following.

Note that  $p_y$ , which depends on  $y$ , is like the probability of "success" taking a value between 0 and 1. On the other hand,  $h(y)$ , the unconditional probability density function of an animal presence at a distance  $y$ , must integrate to 1 over the interval  $(0, \omega)$ . For  $p(y)$ , we require that it is 1 at  $y=0$ , and 0 at  $y=\omega$ , and it is a decreasing function of  $y$ , where  $\omega$  is the maximum distance beyond which EARS cannot detect any cue. We use two general types of  $p_y$ , satisfying the previous conditions, in our estimation: (1)  $p_y = \{\exp(-y/\beta) - \exp(-\omega/\beta)\} / \{1 - \exp(-\omega/\beta)\}$  for  $\beta > 0$ ; (2) Linear, that is,  $p_y = 1 - (y/\omega)$ . For  $h(y)$ , Marques *et al.*<sup>1</sup> used  $h(y) \propto y$ , but we generalize it by taking  $h(y) \propto y^d$  for  $d > 0$ . That is,  $h(y) = (d+1)y^d/\omega^{d+1}$ .

Even though no one knows for sure what is the most appropriate value of  $d$ , and the correct structure of  $p_y$  is

Then  $Tr$  is the total number of cues produced by an animal over a time period  $T$ , and  $n = n_c(1-c)/(Tr)$ . A target region is considered as a circular area centered at the buoy location with the maximum detection radius of  $\omega$ ; thus  $a = \pi\omega^2$ .

Formula (6), as discussed by Marques *et al.*,<sup>1</sup> provides a point estimate of the population density in a circular horizontal area. Formula (6) is used for point estimation purposes, however our approach and assumptions to derive a suitable estimate of  $P$  are different, as discussed in the following. In passive acoustic detection studies, an animal can be identified by a cue only. Therefore,  $P$  represents the estimated probability of detecting a cue. Hence,

unknown, the estimate of  $D$  is derived for various combinations and applied for both pre-spill data and post-spill data, as the acoustic detection techniques used are the same, to see if the density values are different. Note that the availability of population density estimates for previous years based on visual surveys can aid in the selection of appropriate parameters.

Interval estimation of  $D$  to obtain the accuracy of estimates, is different from the one followed by Marques *et al.*,<sup>1</sup> where the authors used the first order delta (FOD) method to approximate the variance of  $D$ .<sup>2</sup> The FOD method states that if  $X$  is a random variable with finite mean  $\mu_x$  and variance  $\sigma_x^2$ , then for a differentiable function  $g$ , which does not vanish at  $\mu_x$ ,

$$\text{Var}(g(X)) \approx (g'(\mu_x))^2 \text{Var}(X) = (g'(\mu_x))^2 \sigma_x^2. \quad (8)$$

Taking the natural logarithm on both sides of Eq. (6), one gets

$$\begin{aligned} \text{Var}(\ln \hat{D}) &= \text{Var}(\ln n_c) + \text{Var}(\ln(1-\hat{c})) + \text{Var}(\ln \hat{r}) \\ &\quad + \text{Var}(\ln \hat{P}). \end{aligned} \quad (9)$$

Applying result (8) for  $g(X) = \ln X$ , Eq. (9) now yields

$$\begin{aligned} \text{Var}(\hat{D}) / \left( E(\hat{D})^2 \right) &\approx \text{Var}(\hat{n}_c) / (E(n_c))^2 \\ &\quad + \text{Var}(1-\hat{c}) / (E(1-\hat{c}))^2 \\ &\quad + \text{Var}(\hat{r}) / (E(\hat{r}))^2 \\ &\quad + \text{Var}(\hat{P}) / (E(\hat{P}))^2. \end{aligned} \quad (10)$$

Expression (10) is essentially the same as expression (4) of Marques *et al.*<sup>1</sup> However, all the variance components on the right-hand side of Eq. (10) cannot be obtained or estimated



accurately for our study. The data collection method (or the sampling method) of Marques *et al.*<sup>1</sup> is different from this one as some animals were also tagged in their study. As simultaneous animal localization was not implemented in this study, which can be very time consuming to implement for each cue detection event, cue detection records do not tell how far the animal is from the EARS hydrophone when a cue is detected.

Because of the above-mentioned difficulties in estimating the variance of  $\hat{D}$  directly, a bootstrap technique is proposed for estimating the variance of  $\hat{D}$ .<sup>2</sup> The formula for  $\hat{D}$  in Eq. (6) gives only a point estimate of the population density at a specific location of area  $a$ . It also depends on the time period  $T$ , and hence  $\hat{D}$  should be treated as an average instantaneous density over a period of time  $T$ .

In this estimation the proportion of false positive detections  $\hat{c} = 0.059$  is obtained from the comparison of manual and automatic detections. Cue production rate  $\hat{r} = 1.22$  clicks per second per whale and detection range  $\omega = 20$  km, are taken from the literature on sperm whales.<sup>8,19</sup> Throughout this section, the units of the population density are numbers of whales per 1000 km<sup>2</sup>.

Using the formula of  $\hat{D}$  in Eq. (6), the hourly population density estimate is obtained for various  $\beta$  (the scale parameter) in the exponential model, as well as the linear model used for  $p_y$ . The hourly estimates are then averaged to obtain a single value point estimate of population density for each location and each survey. For example, if  $\hat{D}_1, \hat{D}_2, \dots, \hat{D}_k$  are the hourly estimate of  $D$  over  $k$  consecutive hours, then  $D$  is estimated by  $\bar{D} = \sum_{i=1}^k \hat{D}_i/k$ , where each  $\hat{D}_i$  is obtained by using formula (6) with  $T = 60 \text{ min} = 1 \text{ h}$ .

The hourly estimates (for a specific location, survey, and  $p_y$ —either exponential or linear) are again highly positively skewed as they are proportional to  $n_c$  (the “click rate” per minute). Therefore, a straightforward interval estimation of  $D$  by taking a 2-standard deviation range about  $\bar{D}$  does not seem logical. The theoretical model that is adopted for  $n_c$  in Sec. III also applies to  $\hat{D}_i$  as it is proportional to  $n_c$ . Even though  $\bar{D}$  is the average of the  $\hat{D}_i$ 's over a fairly large  $k$ , the distribution of  $\bar{D}$  does not seem to follow a normal distribution closely. Note that the model, that is the power law in Eq. (1) for the per minute click rate  $n_c$ , has estimated  $\theta$  ranging from 1.1091 to 1.8057 indicating that such distributions have heavy tails for which variances do not exist. [For the model in Eq. (1), the parameter  $\theta$  must be  $>2$  to guarantee that a mean exists, and it must be  $>3$  to ensure that a variance exists.] Hence, interval estimates of population density are obtained by employing the bootstrap approach as described in the following:

- (1) For a specific location and a particular survey, obtain the  $k$  (depending on the survey) consecutive hourly point estimates of  $D$  as  $\hat{D}_1, \dots, \hat{D}_k$ .  $\bar{D} = \sum_{i=1}^k \hat{D}_i/k$  is our point estimate of  $D$ .
- (2) Draw a bootstrap sample<sup>2</sup> of size  $k$  with replacement from  $\{\hat{D}_1, \dots, \hat{D}_k\}$ , and call this sample as  $\hat{D}_1^*, \dots, \hat{D}_k^*$ . Define  $\bar{D}^* = \sum_{i=1}^k \hat{D}_i^*/k$ .
- (3) Repeat step (2) for a large number ( $M$ ) of times. The obtained  $\bar{D}^*$ 's are ordered  $\bar{D}_i^*$ 's from the smallest to the largest as  $\bar{D}_{(1)}^* \leq \bar{D}_{(2)}^* \leq \dots \leq \bar{D}_{(M)}^*$ .

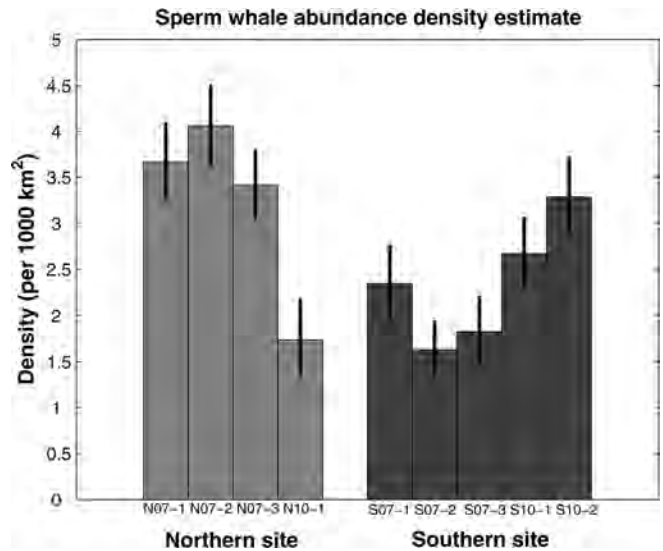


FIG. 8. The 95% confidence interval of the average hourly density for both northern and southern locations (light gray—northern sites, dark gray—southern sites; N07-1–N07-3 and S07-1–S07-3 are data for 2007; N10-1, S10-1, and S10-2 are data for 2010).

- (4) The approximation of  $(1 - \alpha)$  level confidence interval for  $D$  is obtained as  $(\bar{D}_{((\alpha/2)M)}^*, \bar{D}_{((1-\alpha/2)M)}^*)$ . Note that the bounds are the lower and upper tail  $\alpha/2$ -probability (empirical) cut-off points of  $\bar{D}_1^*, \dots, \bar{D}_M^*$ .

Using  $1 - \alpha = 0.95$  and  $M = 5000$ , the following estimates of population density are presented in Fig. 8. Here  $\beta$  and  $d$  are chosen in a way that the average density of sperm whales before the spill matches the NOAA reported population in the Northern GoM: 1665.<sup>5</sup>

The regional abundance density estimate shows a decrease in the number of sperm whales nearest to the DWH site, which exceeds statistical uncertainties and can be accepted as an existing trend.

## V. CONCLUSIONS

In this study a methodology is developed to provide point and interval estimates for a marine mammal population from passive acoustic data. Results show that both acoustic activity and abundance of sperm whales have increased in the southern site farther away from the DWH oil spill source and decreased in the northern site closest to the spill. This seems to indicate that some of sperm whales left the northern area and have possibly relocated to the southern site. At least two possible reasons, relevant to the recent oil spill, could have led to such relocation: (1) Whales moved out of the areas with high concentration of oil and pollutants and thus possible shortages of food supply or (2) increased vessel traffic led to an increase in anthropogenic noise levels to values uncomfortable for these whales. Existing acoustic data contain information to assess the validity of both hypotheses. A comparative analysis of anthropogenic noise on all three sites for 2007 and 2010 to understand the difference of noise level between the two years is planned to be done. Detection and comparative analysis of the density of characteristic short-range buzzes, produced by sperm whales right before



capturing prey, should be also attempted to understand food supply availability. The GoM sperm whales have an extensive habitat as seen from a uniform distribution of visual sightings<sup>5</sup> that gives them an opportunity for relocation. The same reaction could not be expected for other species (e.g., for beaked whales) that could be more limited in habitat extensions. Using the 2007 and 2010 data and the presented statistical methodology, the short-term abundance trends for other species (dolphins, beaked whales) need to be investigated.

The previous are two possible oil-spill related scenarios for why the sperm whale population relocated. However, we point out that other explanations, based on natural fluctuations in density, for the observed relocation may be as justifiable. For example, the trend may simply be a seasonal shift in the location of the animals within their natural range<sup>5,20</sup> due to the different period of the year the data sets were collected: the 2007 data set was collected in July, whereas the 2010 data set was collected in September. Thus far we have analyzed only two temporal data points (2007 and 2010). However the data from 2001 and 2002 partially overlap in location and collection season with the western site of the 2010 experiment. Thus, future processing of the 2001 and 2002 data sets for density estimates will perhaps provide additional information on the general variability (both in time as well as location) in sperm whale densities. Future multi-year acoustic experiments and their corresponding sperm whale abundance estimates are necessary to understand whether there is indeed an oil-spill related trend for animal relocation and density reduction or not.

As whales are positioned at the top of the food chain, any long-term effects will be significant and need to be studied. For example, studies of the resident killer whale population after the “Exxon Valdez” oil spill show that the resident population abundance has not returned to pre-spill levels 16 years after the spill.<sup>21</sup> In the case of the DWH, baseline data and an outlined methodology provide a unique basis for understanding the long-term impact of the GoM spill on the resident populations of different marine mammal species. The commitment to long-term monitoring of the effects of the GoM spill on marine mammal population will require consecutive passive acoustic experiments in the area where baseline data exist.

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