FINAL REPORT
Population consequences of acoustic disturbance of Blainville's beaked whales at AUTEC

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LONG-TERM GOALS

Atypical strandings and behavioral responses of beaked whales have been associated with the use of navy mid-frequency active (MFA) sonar (e.g. Simmonds and Lopez-Juraco 1991, Evans and England 2001, McCarthy et al. 2011, Tyack et al. 2011). Yet MFA sonar operations occur repeatedly on Navy ranges that are known beaked whale habitat. The Bahamas Marine Mammal Research Organisation (BMMRO) has been studying Blainville's beaked whales (*Mesoplodon densirostris*) beaked whales in the Bahamas (Claridge 2006, 2013), including a population found at the US Navy's Atlantic Undersea Test and Evaluation Center (AUTEC) range. These data are providing critical information on demography and behavior, which are directly being used in the Population Consequences of Acoustic Disturbances (PCAD) project. The long-term goal of PCAD is to develop a methodology for monitoring the long-term health of populations that are repeatedly exposed to sonar. This work is important for the continued operational integrity of navy ranges.

OBJECTIVES

The overall objective of PCAD is to develop a methodology for evaluating and monitoring the health of whale populations on navy ranges and, in this case, to apply this to Blainville's beaked whales at AUTEC. The specific objectives for BMMRO are to provide and, in some cases, analyze longitudinal data to investigate aspects of the life history and behavior of this species. These data are needed to inform the population consequences model, thus forming a critical part of the PCAD project (for full details of the project, see the PCAD Working Group reports).

APPROACH

The PCAD model is based on a framework (Figure 1) developed by the National Research Council (NRC) Committee on Characterizing Biologically Significant Marine Mammal Behavior (NRC 2005).

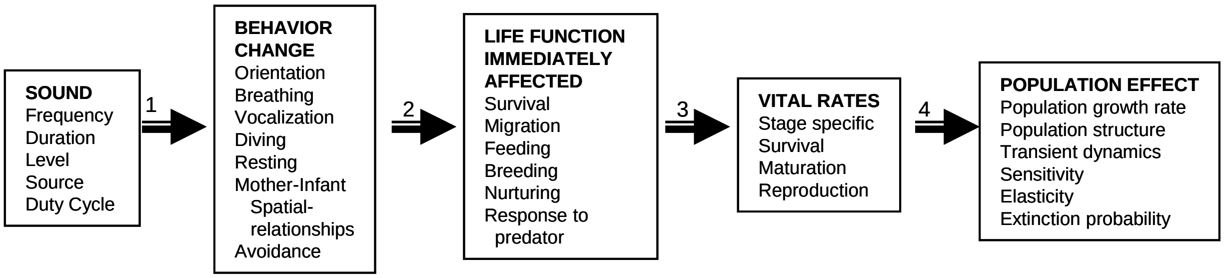

Figure 1: The PCAD (Population Consequences of Acoustic Disturbance) framework (from NRC 2005).

The ONR PCAD Working Group is developing the beaked whale PCAD model for AUTEC. This model links changes in diving behavior to changes in body condition, and changes in body condition to vital rates (particularly calf survival and pregnancy) to estimate the population level effect of these changes. BMMRO has been conducting population demographic studies on Blainville's beaked whales at AUTEC where sonars are used regularly and 170 km away at Abaco where sonar use is limited. There is very limited movement of individuals between these two sites (Claridge 2013), so the Abaco site has been used as a "reference" population for baseline demographics. This approach has been critical to the development of the PCAD model for AUTEC. The key components that BMMRO has contributed which directly inform the model are the following:

1. **Survival:** estimates of sub-adult and adult survival rates at Abaco to provide a baseline for AUTEC.
2. **Maturation:** observed age at sexual maturity at Abaco to provide a baseline for AUTEC.
3. **Reproduction:** observed inter-calf interval, age at which calves separate from the mother, and calf survival at Abaco to provide a baseline for AUTEC.
4. **Population age structure:** estimate of the proportion of calves, sub-adults and adults at Abaco and AUTEC to compare fecundity and calf survival at both sites.

In addition, BMMRO has provided information that helps the interpretation of potential behavioral changes. This includes:

5. **Mother-infant spatial relationships**: analysis of the vocal behavior of mother-calf pairs at AUTEC to learn what age calves produce echolocation clicks and to determine their spatial relationship with the mother at depth.

WORK COMPLETED

1. Adult and sub-adult survival rates (Abaco)

An open population model that parameterizes emigration from and re-immigration back into the Abaco study area was fitted to sighting history data compiled for each individual, starting from the time of first capture (i.e. photo-identification) through each annual interval (e.g. Whitehead 1990, Ford et al. 2007, Matkin et al. 2012). Model parameters also included capture probability when in the area, in addition to survival and recruitment. To explore age and sex structured heterogeneity in Blainville's beaked whales, the re-immigration model was fitted to photo-identification data with separate parameter vectors for four different age / sex classes: sub-adult female, sub-adult male, adult female and adult male (e.g. Ford et al. 2007). The photo-identification dataset consisted of high-quality photographs of 75 individual Blainville's beaked whales which were collected off Abaco during an annual sampling interval from May – August, 1997 – 2011. (For complete details of the modeling approach, see Claridge 2013).

2. Maturation age (Abaco)

To examine the age at the onset of sexual maturity, analyses of photographs of individual Blainville's beaked whales photographed off Abaco were carried out to assign age and sex classes to individuals throughout the sighting record (1997-2012). There were six individuals first observed as calves that were re-sighted repeatedly over 9 – 14 years, four of which (three females, one male) were monitored until sexually mature, which provided information on the minimum age at sexual maturity. Detailed examination of the individual sighting histories of these six whales was undertaken. Once the age of each of these calves was assigned, this formed the timeline on which to assign ages at the different stages of their maturity (see Claridge 2013 for further details).

3. Reproductive rates (Abaco)

Life history information has been collected for Blainville's beaked whales at Abaco over seven years. The reproductive histories for adult females that had more than one calf over the study period were used to determine inter-calf intervals, age at mother/calf separation and annual calf survival. Three calves were known to be less than 1 month old when first observed and these animals were tracked for more than 2.5 years, which helped define the criteria for estimating the age of the others. These criteria included size relative to its mother, pigmentation, spatial relationship with its mother, and scarring patterns. Using sightings of the mother with and without its calf then allowed the age at which calves separated from their mother to be determined. Finally, calf survival (φ) was calculated by dividing the number of calves that were observed post-weaning by the total calves born, and annual calf survival was calculated as $\varphi^{1/\text{age at weaning}}$.

4. Population age structure (Abaco and AUTEC)

We estimated the age composition for Blainville's beaked whales in two areas of equal size (~300 km^2) at Abaco and at the AUTEC range to compare population age structure on and off a navy range. We then fit a Bayesian multinomial model of photographically-determined age-class counts to photo-identification data collected from 2005-2010 at both sites.

5. Mother-infant spatial relationships (AUTEC)

To investigate mother-infant spatial relationships at depth (i.e. while the mother is foraging) we began by determining what age young Blainville's beaked whales are (first) recorded vocalizing, and whether these vocalizations differ to those produced by their mothers. For this analysis, the Marine Mammal Monitoring on Navy Ranges (M3R) group provided acoustic recordings from AUTEC when visual observers confirmed that the group composition was made up solely of a mother-calf and when acoustic recordings were made in the absence of any other whales within a three-hydrophone radius around the focal area (equivalent to six nautical miles distance). These criteria were met on three occasions (Table 1).

Table 1. The dataset used for analysis, detailing three encounters with a mother-calf pair, the estimated age of the calf, the date of the encounter, the duration of the visual encounters and recordings, the number of clicks detected by the PAMGUARD beaked whale detector, and the number of hydrophones that recorded vocalizations during each encounter.

Ref.	Age of calf	Date	Duration of visual encounter	Duration of recordings	# Clicks	# Hyd.
1	~ 1 week	1-Oct-2008	41 mins	45 mins	117	4
2	2 – 3 months	25-Jul-2012	62 mins	11 mins	61	2
3	18 months – 2 years	1-Oct-2008	28 mins	37 mins	2259	5

To identify if more than one animal was vocalizing, which in these recording contexts would indicate the calf was vocalizing, each acoustic file was visually inspected, examining waveform and spectrogram views in Adobe Audition CS6 (4096 point FFT with a 75% overlap and Hamming window). Times were noted for the start and end of periods of silence, periods whether only one animal was clicking, and periods when there were overlapping click trains, indicating more than one animal was clicking. Potential differences between mother and calf vocalizations were investigated using Principal Components Analysis (PCA) to provide a visual representation of the clicks detected by the PAMGUARD software (www.pamguard.org, Gillespie et al., 2008). The variables used for the PCA analysis included the -3 dB and -10 dB bandwidths, duration, peak frequency, sweep rate, and the starting frequency of the click. Negative sweep rate clicks were removed from the dataset. PCA, using standardized variables to account for different measurement scales of click parameters, was performed using the statistical software R (R Core Development Team 2010).

RESULTS

1. Adult and sub-adult survival rates (Abaco)

The open population re-immigration model fitted to sighting history data from Abaco allowed us to estimate annual probability of survival for sub-adult and adult sex classes (Table 2). We found heterogeneity in annual survival; female annual survival rates, both adult and sub-adult, were higher than male.

Table 2. Annual probability of survival for sub-adult and adult sex classes of Blainville's beaked whales at Abaco. Posterior medians and 90% highest posterior density intervals (HPDI) are shown.

Age Class	Posterior Median	90% HPDI
Adult female	0.984	0.949 – 0.998
Adult male	0.859	0.759 – 0.891
Sub-adult female	0.962	0.835 – 0.997
Sub-adult male	0.807	0.555 – 0.883

2. Maturation age (Abaco)

Sighting histories of Blainville's beaked whales monitored from calves to (or near) the age at sexual maturity, were compiled to determine maturation age (Table 3). One adult female followed from a dependent calf through maturity was 9 years old at the onset of sexual maturity. A minimum age at sexual maturity of 8 – 9 years was estimated for a second individual. Male Blainville's beaked whales appear to mature at a similar age to females. One male first seen as a dependent calf matured when 9 years old, but another male had not yet reached sexual maturity by age 10. This suggests some individual variation and demonstrates the need for larger sample sizes. However, age reported here should not be considered absolute because it was based on a timeline beginning from an estimated age when a calf was first sighted and none of the whales that matured during the study were first seen as neonates. Assigned age could be wrong by +/- 1 year depending on individual differences in length at birth, growth rates, and scarring patterns. (See Claridge 2013 for full details of these findings.)

Table 3. Sighting histories of Blainville's beaked whales monitored from calves to or near the age at sexual maturity.

FEMALES	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Obs. age first calving	Min. age sexual maturity
Md107	(C)	(C)	C	C	X	X	S	S	X	X	A?	X	X	X	A	(M)	15	?
Md134			(C)	C	C	C/S	X	S	X	S	A?	A?	X	A	(M)	M	12	8 - 9
Md135			(C)	C	C	S	X	S	S	X	S?	A	M	X	X	A	10	9
MALES	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Obs. age first teeth	Min. age sexual maturity
Md115				C	C	C	S	X	X	S	X	S	X	X	X	X	> 8	> 8
Md143				(C)	C	C	S	X	S	S	S	X	T	X	A	A	9	9
Md191							(C)	C	C	X	S	X	X	S	X	X	> 10	> 10

[(C) = birth year estimated based on appearance when first sighted, C = dependent calf, S = sub-adult (separated from mother, and not seen with calf (females), or teeth not erupted (males), not associated with known adults), A? = poss. adult female (≥ 9 yr old but not seen with calf), A = confirmed adult (for females includes 1 year before parturition, and for males year in which observation of teeth erupted), M = observed with calf, (M) = not seen in that year but observed the following year with a 1-year old calf , T = teeth erupted, X = not seen.]

3. **Reproductive rates (Abaco)**

Reproductive rates were determined for eight adult females that had more than one calf over the study period, totaling 18 calves. The median inter-calf interval was 3.3 years (range 2.8 – 5.1 years). Fecundity at Abaco can then be calculated by taking the reciprocal of the inter-calf interval and multiplying by 0.5 (assuming half of calves born are female) or 0.152. The median age of the calf at mother/calf separation was 2.7 years (range 2.4 – 3.1 years). Based on the number of calves re-sighted post-weaning, calf survival was calculated to be 0.8 and annual calf survival was $0.8^{1/2.7}$ or 0.921.

4. **Population age structure (Abaco and AUTEC)**

Differences were found in the population age structure at Abaco and AUTEC. A Bayesian multinomial model of age-class counts revealed that there was a high probability ($p = 0.85$ and 0.91) of a lower proportion of calves and sub-adults, respectively, at AUTEC (Figure 2). Note that p values reported here result from a two-tailed test by monitoring parameter values across 20,000 Markov Chain Monte Carlo iterations. If the probability is high that the proportion of calves (for example) at Abaco is greater than at AUTEC, p will be close to one (as is the case), and *vice versa* for p values close to zero if the statement is reversed. For adult males, the two distributions overlapped (i.e. there was no difference in proportions between areas), and $p = 0.55$.

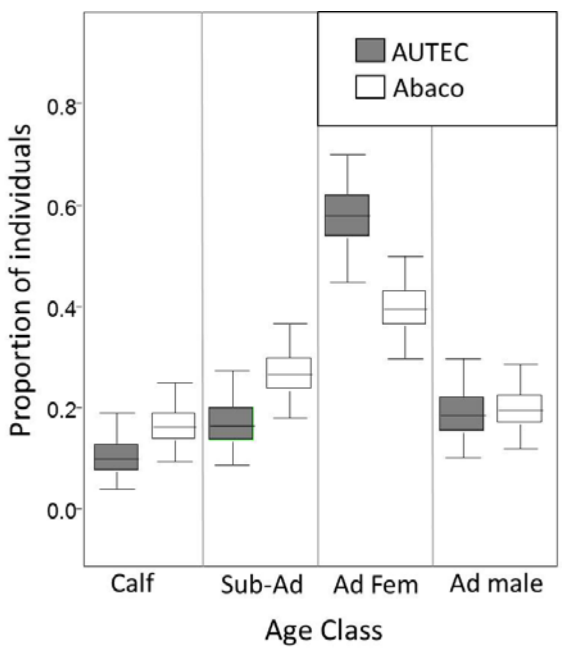

Figure 2. Plot produced from multinomial model of age-class counts by encounter day at Abaco and AUTEC (2005-2010).

5. **Mother-infant spatial relationships (AUTEC)**

The recordings from the encounter of a mother and her neonate (Reference 1, Table 1) never displayed more than one animal clicking at any time (Figure 3). In contrast, the recordings from the encounter where the calf was around 3 months old (Reference 2, Table 1) contained some overlapping clicks, indicating that both animals were clicking at some points. The recordings from the encounter with the oldest calf (Reference 3, Table 1) contained the largest percentage of overlapping clicks. No differences were found using visual PCA scatterplots to distinguish between a mother and her calf's clicks, so there were no differences in vocalizations of the mother and its calf evident in these analyses.

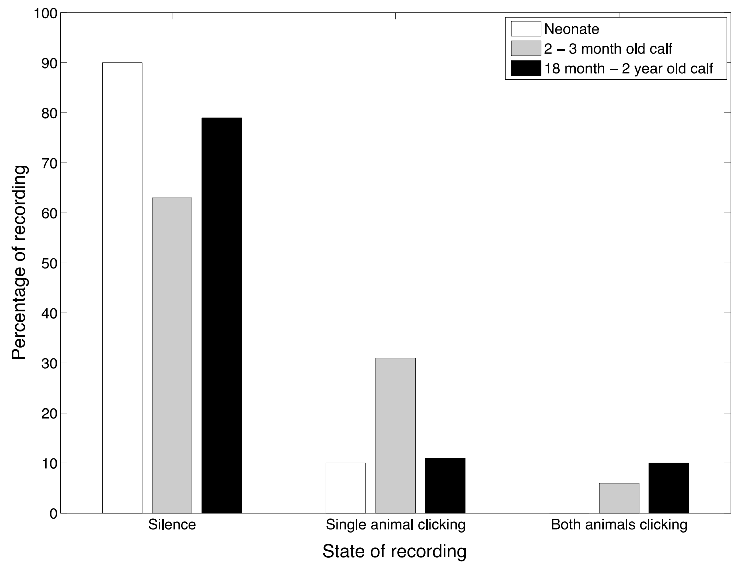

Figure 3. The difference in the contents of the recordings for the three mother-calf pairs, showing the percentage of the recording with no clicking, one animal clicking, or both animals clicking.

IMPACT/APPLICATIONS

Assessing population demographics of beaked whales on navy ranges is important for identifying whether population-level effects result from regular exposure to military sonars. At AUTEC, Blainville's beaked whales cease foraging and move tens of kilometres away during multi-ship sonar exercises, returning days later when the testing has ceased (Tyack et al. 2011). Higher energetic costs associated with displacement, combined with lower energy intake if foraging is disrupted, provide a possible mechanism to reduce individual condition. Energetic demands suggest this is of particular concern for lactating females, and may result in lower reproductive success and population consequences (New et al. 2013). Repeated exposure to navy sonar at AUTEC may have contributed to low fecundity and/or calf survival when compared to our reference population at Abaco. Furthermore, effects on sub-adult numbers suggest prolonged disturbance over at least the last decade which we found to be the maturation age for this species.

Understanding mother/infant spatial relationships is critical to predicting the effect of disturbance on calf survival if the disturbance causes the mother and calf to separate, especially at depth. Unlike sperm whale calves that are left at the surface with babysitters while their mothers go on foraging dives (Whitehead 1996), Blainville's beaked whale calves dive in synchrony with their mothers immediately after birth (pers. obs.). We have shown in this study that Blainville's beaked whales may not be vocalizing as neonates, but around three months of age they are vocalizing and diving to the same depths as the mother. There were no differences found using visual PCA scatterplots to distinguish between a mother and her calf's clicks. Combined, these results suggest that mother-calf pairs must be maintaining close proximity while diving and disturbance that causes their separation at depth would likely result in the fatality of a calf.

We have provided new information on survival rates, age at sexual maturity, inter-calf intervals and age at which calves separate from their mother for a reference population (Abaco) of Blainville's beaked whale. These parameters are currently being used in the PCAD modelling process by building an age-structured model of population growth for Abaco as a baseline. This process is then repeated for AUTEC using the age structure we found to estimate fecundity on the navy range. Preliminary findings of the PCAD Working Group support very low fecundity at AUTEC. The next steps are to determine what level of acoustic disturbance (using dives lost due to disturbance) would be needed in order to cause such low fecundity.

Measuring the health of populations utilizing navy ranges has more relevance to the navy than simply monitoring a populations' size. The PCAD program focuses directly on that goal and represents the first attempt to combine data from various sources (visual, tag, biophysical, and passive acoustic data) for this purpose, including the long-term photo-identification and behavioral data provided by BMMRO. Using these data sets and expertise, a methodology is being developed for evaluating the population level effect of sonar on Blainville's beaked whales at AUTEC. This will be valuable to apply to other beaked whale species and in other locations, e.g. Cuvier's beaked whales, a priority species, at the Southern California Offshore Range (SCORE).

RELATED PROJECTS

Assessing Beaked Whale Reproduction and Stress Response Relative to Sonar Activity at the Atlantic Undersea Test and Evaluation Center (AUTEC)
This project is a collaborative project between BMMRO, Southwest Fisheries Science Center (Nick Kellar, John Durban) and the Naval Undersea Warfare Center (David Moretti). The goal of this study is to assess glucocorticoid levels from blubber biopsies of targeted species, to assess stress levels relative to sonar exposure. Specifically, the project aims to collect biopsy samples at AUTEC where fleet readiness training involves regular use of mid-frequency active sonars, and compare the levels to those measured in biopsies collected from control populations within the Bahamas region that are less exposed to sonar activity. In parallel, pregnancy states will be ascertained via blubber progesterone levels in both groups of animals to investigate whether there is a relationship between sonar activity, stress measures, and reproductive rates, to assess population-level impacts.

Monitoring beaked whale movements during the Submarine Commanders Course using satellite telemetry
This project is a collaborative project between the Bahamas Marine Mammal Research Organisation, Southwest Fisheries Science Center (John Durban) and the Naval Undersea Warfare Center (David Moretti). Satellite telemetry is being used to monitor the movements and diving behavior of beaked whales and other odontocete cetacean species on the US Navy's AUTEC range before, during and after sonar exercises in which multiple ships are using their tactical sonars. Field work during this project is providing opportunity to collect biopsy samples

and photo-identification data at AUTEC. This project has been supported by the US Department of Defense (NAVFAC Living Marine Resources program).

Behavioral ecology of deep-diving odontocetes in the Bahamas
This project is examining key aspects of the behavioral ecology of six Department of Defense priority species in The Bahamas. We will integrate data acquired through individual photo-identification, molecular genetics, fatty acid, persistent organic pollutant and stable isotope profiles, satellite telemetry and acoustic recordings to characterize the social structure, residency patterns, foraging ecology, and population structuring of key cetacean species. Field work during this project is providing opportunity to collect biopsy samples and photo-identification data from throughout the northern Bahamas. The project has been supported by the Strategic Environmetal Research and Development Program (US Department of Defense, Department of Energy and the Environmental Protection Agency).

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