The Effects of Behavioral Change in Response to Acoustic Disturbance on the Health of the Population of Blainville's Beaked Whales (Mesoplodon densirostris) in the Tongue of the Ocean

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Award Number: N0001413WX20616 / N0001412WX20919

LONG-TERM GOALS

The primary objective of this research is to:

Develop a predictive model for population health of Blainville's beaked whale (*Mesoplodon densirostris, Md*) in the Tongue Of The Ocean (TOTO), Bahamas, using data from passive acoustic monitoring collected around and during active sonar operations.

MFA sonar operations occur repeatedly on Navy ranges that are known to contain populations of Blainville's (*Mesoplodon densirostris, Md*) and Cuvier's (*Ziphius cavirostris, Zc*) beaked whales. Strandings of these species have been associated with the use of Navy sonar [1], [2]. A population of *Md* is known to use the Atlantic Undersea Test and Evaluation Center (AUTEC) range in the Tongue Of The Ocean (TOTO), Bahamas [3], and a population of *Zc* has been documented on the Southern California Offshore Range (SCORE) off San Clemente Island in California [4]. Developing a methodology for monitoring the long-term health of populations such as these, that are repeatedly exposed to sonar, is important for the continued operational integrity of these ranges.

This research focuses on *Md* at AUTEC. It combines passive acoustic data from detection of *Md* echolocation clicks and sonar, observational data from expert surface observers for group size, surface behavior, and age/sex distribution, biological data from biopsy sampling, precise ship track data from sonar operations, and mid-term (days to months)satellite tag data for animal locations and dives.

It will use these data to inform a Population Consequence of Disturbance (PCAD) model to predict the impact of repeated sonar exposure on population health.

OBJECTIVES

Same as the long-term goals.

APPROACH

Three overarching tasks must be completed to meet the objective.

1. Derive a risk function for *Md* by combining passive acoustic detection data for *Md* groups in the TOTO with sonar data archived during U.S. Navy operations.

2. Extend the data sets for an entire year to estimate the cumulative impact of repetitive sonar exposure as measured by the loss in foraging dives.

3. Develop a Population Consequences of Acoustic Disturbance Model (PCAD) framework for *Md* in the TOTO to estimate the effect of sonar on population health.

WORK COMPLETED

Risk Function

The first empirical risk function that combines both passive acoustic *Md* detection data with actual U.S. Navy sonar data has been completed. A paper has been submitted to the Public Library of Science (PLoS One) and is under final review [5].

A parametric expression was derived for the probability of disturbance (*P*)and provided as follows:

$$P[disturbance] = F(-8.073 + 5.407 RL_{rms})$$

where RL_{rms} is the received level (dB re µPa) and $F(z)$ is the cumulative normal distribution function [6].

This parametric expression was derived by fitting a Generalized Linear Model (GLM) to the original Generalized Additive Model (GAM). The GAM was fit to exposure estimates derived from passive acoustic *Md* deep foraging dive and sonar data [5]. The combined results are shown in Figure 1.

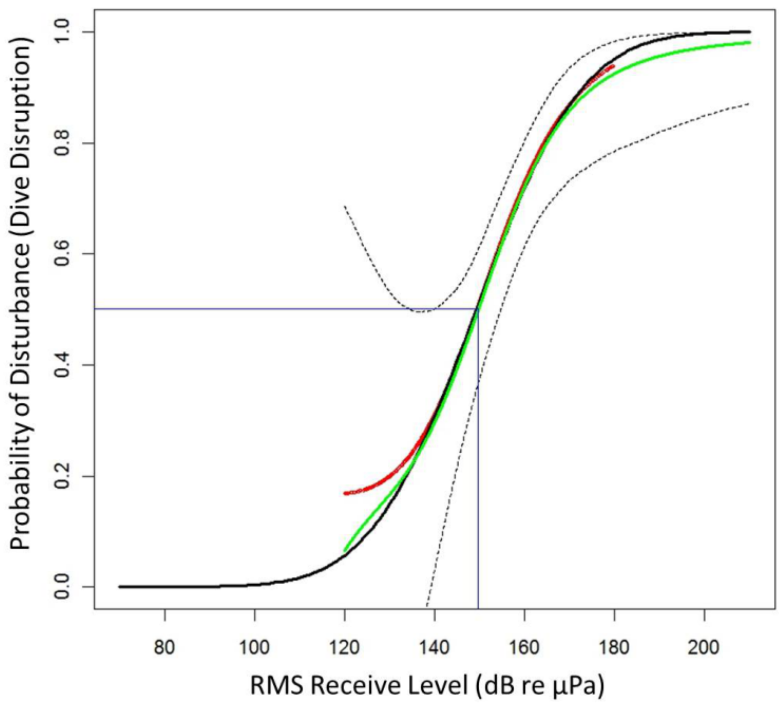

Figure 1. The probability of disturbance (D_{rms}) as a function of sonar RL_{rms}. The GAM fit to the recorded data is shown in red with the bootstrap mean shown by the green with the point-wise 95% confidence limits indicated by dotted lines from the bootstrap. The parametric GLM approximation is shown in black. There is a .5 probability of disturbance at a RL_{rms} of 149.8 dB; this is indicated in blue.

It is anticipated that the empirical risk function will replace the current criteria in the U.S. for estimating behavioral "takes" for environmental compliance modeling. With a .5 probability of disturbance at 150 dB, the function falls between the current 140 dB step function and the historical risk function with a .5 probability at 165 dB [7]. This suggests the currently used step function over-estimates the number of behavioral takes, while the historic function under-estimated the number (Figure 2).

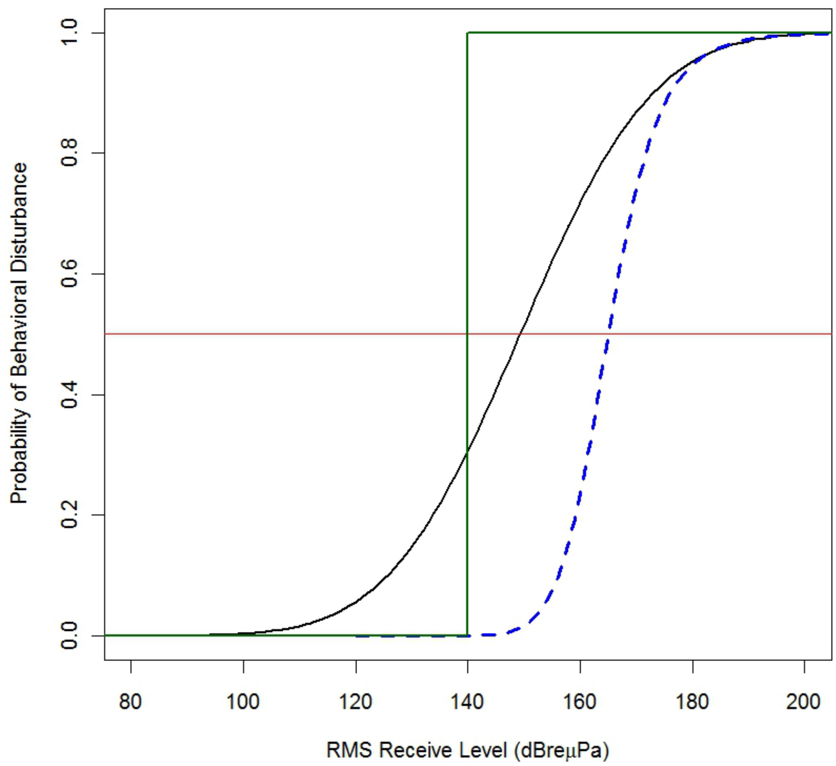

Figure 2. A comparison of risk functions relating the probability of disturbance to received level for beaked whales exposed to sonar signals. The current step function used by the U.S. Navy is shown by a green line and the historical function by a blue-dashed line. The empirical function developed in this paper is shown by a solid black line. A solid red line marks the .5 probability of disturbance.

Cumulative Effect

With the development of a risk function, the probability of disturbance can be applied to exercises over an entire year. M3R detection archives were collected over two years [5]. The archives contain the detection reports from the M3R FFT-based detector along with detections from an *Md* linear matched filter-based detector. Together, these archives provide a complete year of *Md* and sonar detections from which both sonar transmissions and vocalizing *Md* groups were be isolated [8], [5]. A generalized analysis block diagram is provided in Figure 3.

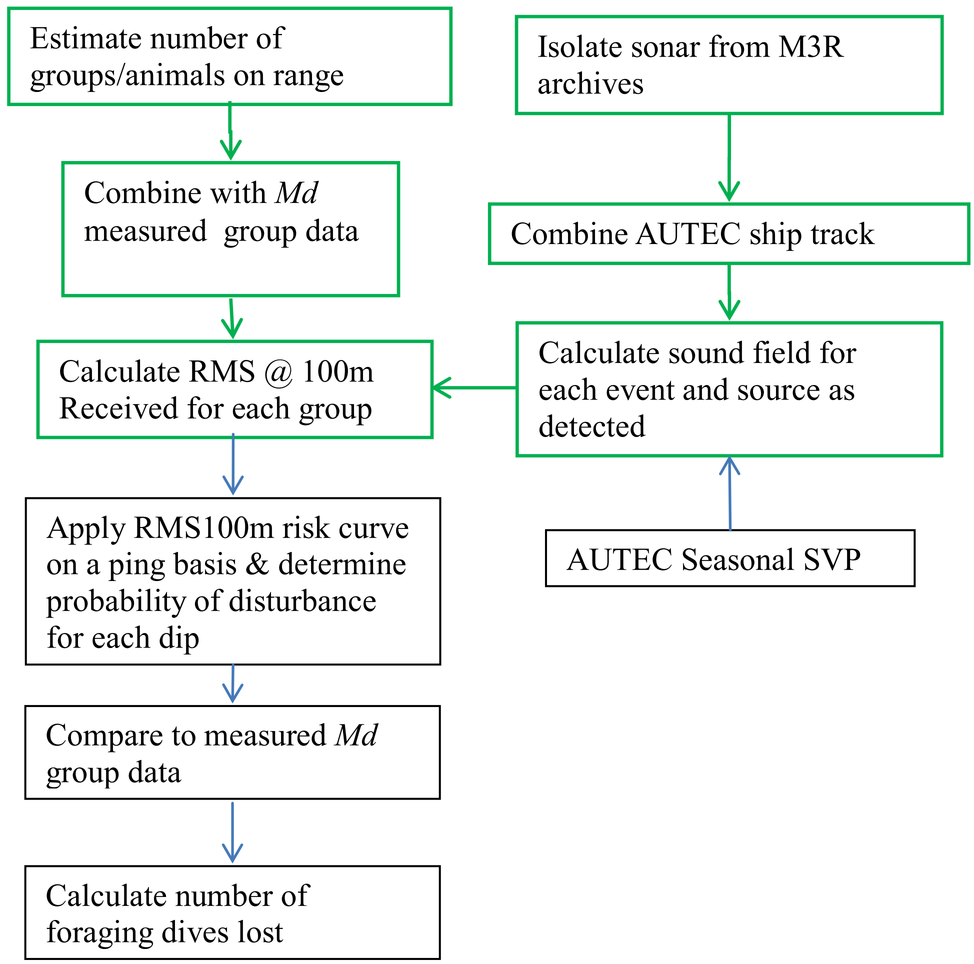

Figure 3. General framework for analysis for Md dives lost due to sonar exposure at AUTEC. Green boxes represent steps completed to-date.

As with the derivation of the risk function, groups of *Md* were detected from the archives and the hydrophone central to the group was assigned (Figure 4). For times during operations, sonar pings and sonar type were also detected. Ship tracks were obtained from AUTEC and sonar data were associated with the transmitting platform. In addition to high level sources such as the SQS-53C, that dominate SCC operations, from which the risk function was derived, numerous dipping helicopter sonar and DICASS sonobuoys are operations are present in the data.

These data were then used as input to the propagation model CASS/GRAB [9] and the RMS received level on all hydrophones was estimated. From these data, the receive level for each group on range will be calculated and the risk curve applied to using a stochastic approach to determine whether or not the group was disturbed. The number of dives lost for each exercise will be tallied. These data will be compared directly to the measured *Md* group data collected during these operations to help validate the model by comparing the number of animals that continue to vocalize during exposure to the number predicted by the model.

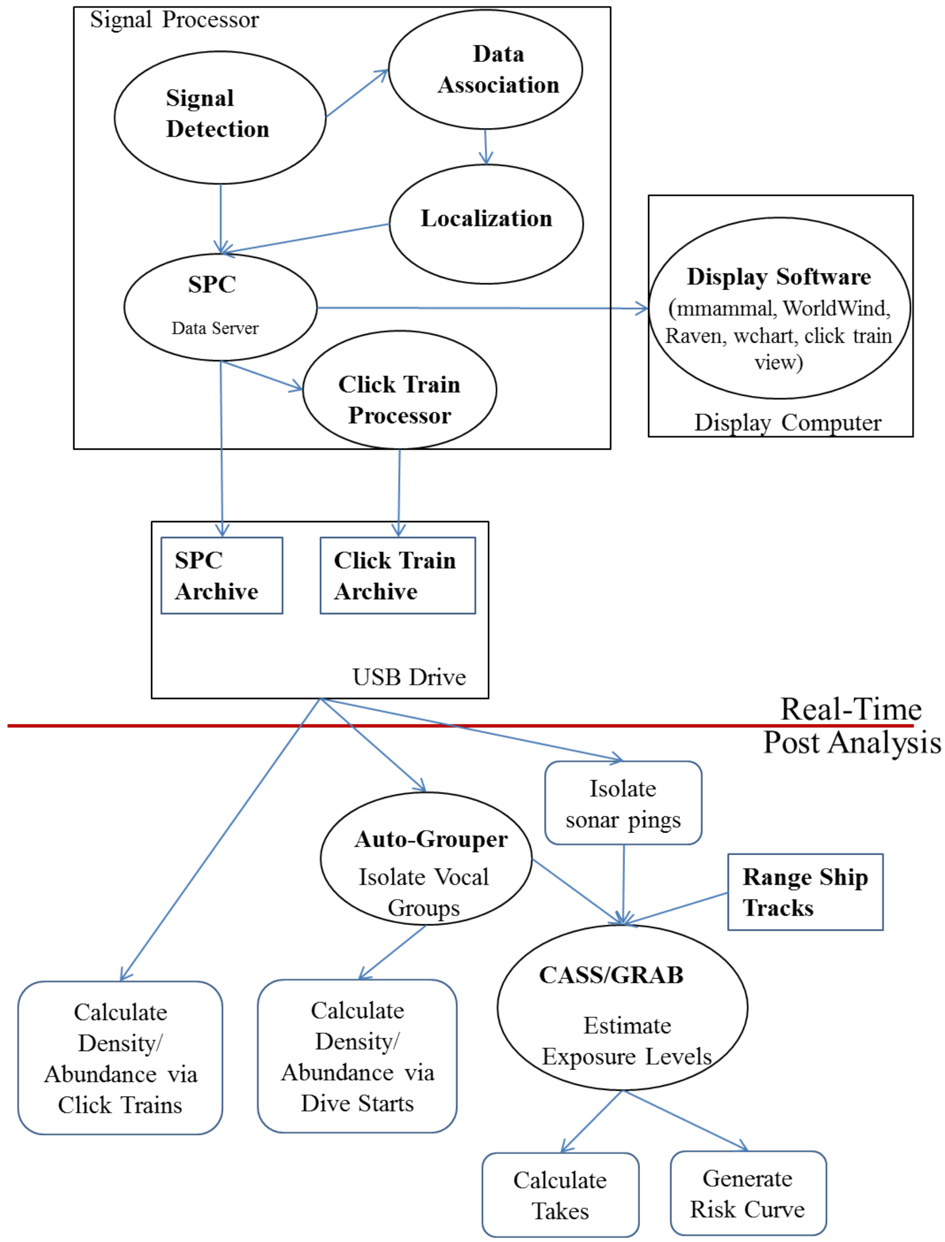

Figure 4. Data flow block diagram. Upper diagram represents real-time tools to archive required data. Bottom represents post analysis data flow. Discrete software modules enclosed within ellipses. Data are indicated in the square boxes. Manual processes are indicated by the round-corner boxes.

To date, *Md* groups and sonar transmissions for a complete year of operations have been isolated. The data have been run through the propagation model and the sound field estimated for each operation over the years' worth of data. The resulting data have been examined for overall *Md* group distribution with and without sonar. The preliminary results reinforce those reported in McCarthy et al., 2010 which suggested animals move to the periphery of the range during sonar operations (Figure 5) with a distinct preference for the western edge.

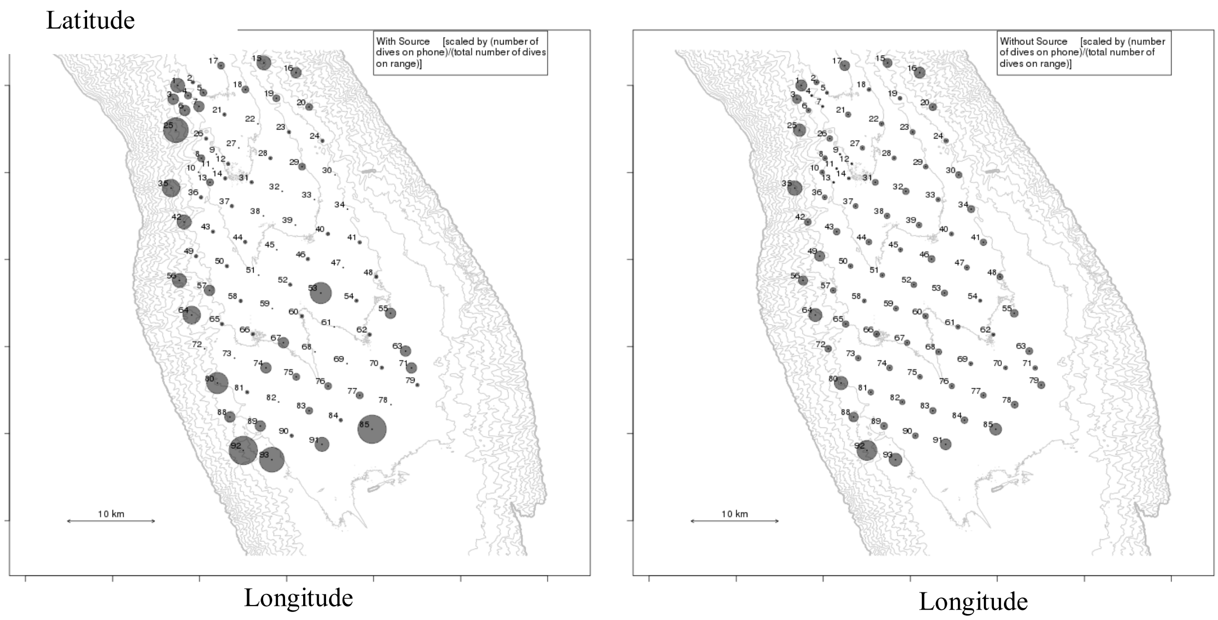

Figure 5. Distribution of Md dive starts, derived by the localization of echolocation clicks, with (left) and without (right) sonar present. The comparative distributions are represented by the size of the circle calculated by dividing the number of dive starts centered on the hydrophone divided by the total number of dive starts in the measurement period (~1 year).

These data are also being used to document animal abundance and distribution and to measure both daily and seasonal variation. Figure 6 shows the vocal activity (echolocation clicks) as a function of hour of the day.

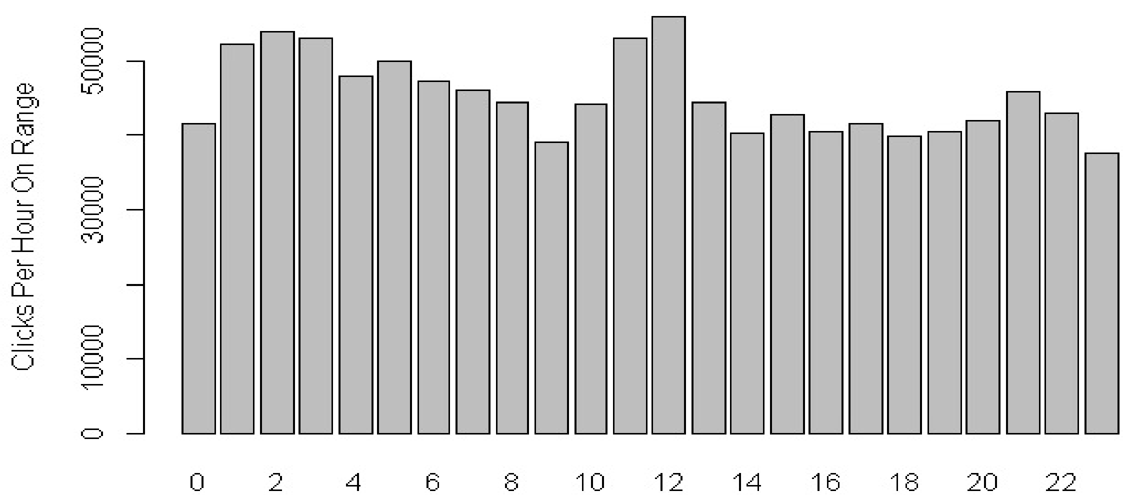

Figure 6. Mean click counts per hour derived from 14 months of data archived in 2011-2012 from all range hydrophones

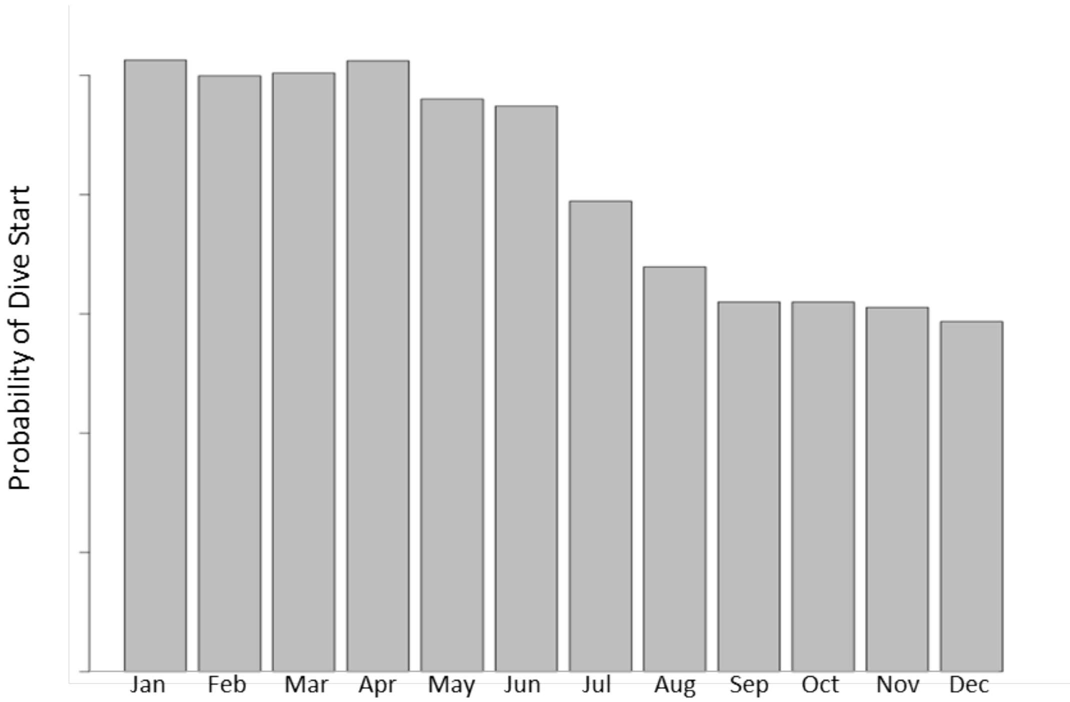

Figure 7. Probability of a dive start on any hydrophone with no sonar present derived from 14 months of data archived in 2011 and 2012

As with the empirical risk function, the probability of a dive start on any hydrophone in a 30 minute period without sonar present was calculated on a monthly basis (Figure 7). The data can also be used to map seasonal changes in distribution as well as abundance. Figure 8 shows the distribution of animals across seasons which provides insight into the *Md's* use of the habitat and the extent, if any, of seasonal variation.

These data are beginning to capture a record of long-term abundance and can be used to monitor fluctuations within the population if captured on a regular basis as part of range operations. The development and validation of passive acoustic methods for monitoring population trends is perhaps one of the most important but least considered contributions of this research.

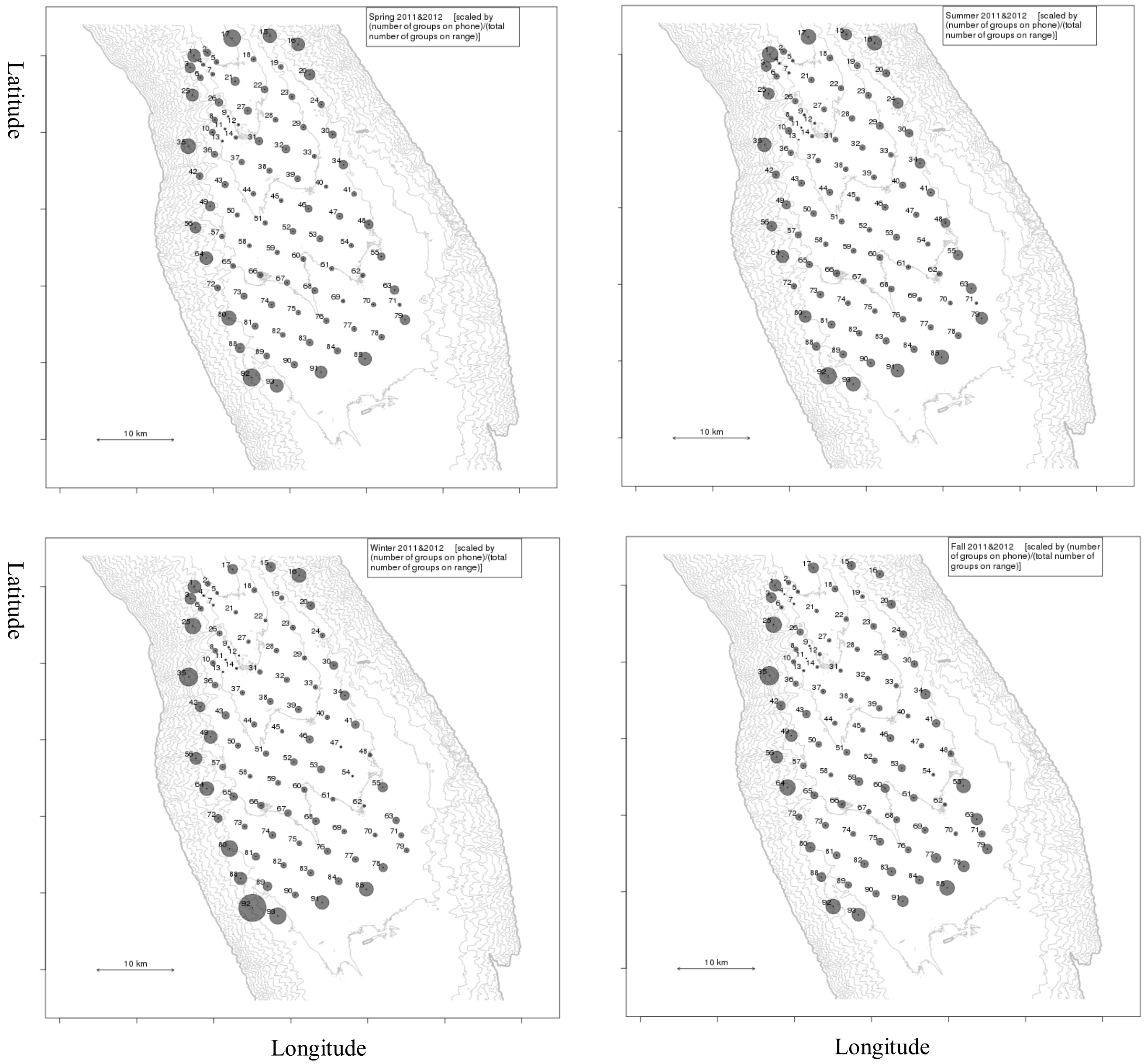

Figure 8. Md spring (upper left), summer (upper right), winter (lower left), and fall (upper right) seasonal distribution depicted by the size of the circle (hydrophone centered dive starts divided by the total number of dive starts).

With data from lower level sources, it may be possible to combine the data with obtained from multi-ship soanr operations to extend the empirical risk function. A combined analysis has begun. An initial fit or the data as compared to the original curve gernerated with data from loud surface ship operations is given in Figure 9.

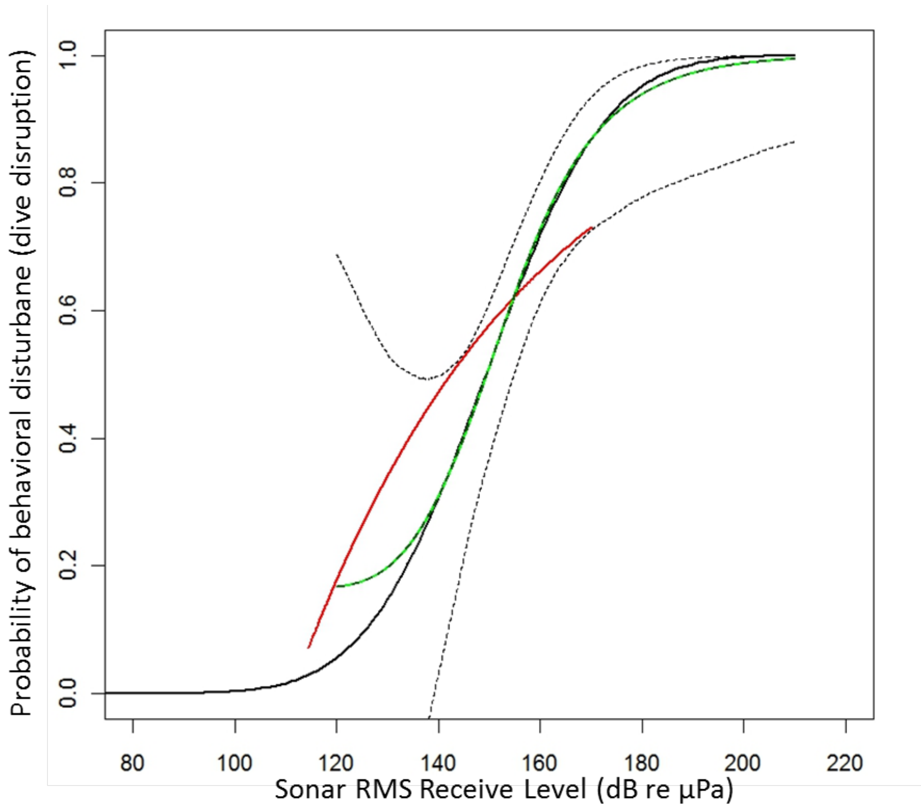

Figure 9. The probability of behavioral disturbance (dive disruption) as a function of sonar RL_{rms}. The GAM fit to the recorded data is shown in green-dashed point-wise 95% confidence limits indicated by dotted lines from a bootstrap analysis. The parametric GLM approximation is shown in black. The preliminary GAM fit to lower level dipping helo and DICASS sonobuoy data is shown in red.

PCAD Model

A generalized beaked whale PCAD model which uses an energetics approach along maternal lines was documented by New et al. in 2013 [10]. This model must be adapted for the year of *Md* cumulative passive acoustic dive data for the population of animals in the TOTO were the loss of foraging dives will be used as a proxy for calorie loss. The risk function quantifies the probability of a behavioral disruption (dive start) at a given level of sonar exposure. However, the exact nature of this disruption remains an open question. Field tests are underway at AUTEC to quantify this loss. Dive recording satellite tags are being attached to *Md* ahead of multi-ship sonar operations (Figure 10).

Md groups are being detected and localized using M3R passive acoustics. An observer RHIB is then vectored to the animals in an attempt to attach a satellite tag [11], [12]. To date three tags have been attached ahead of multi-ship sonar operations. Two were dive recording tags. These tags support the inference from passive acoustics that animals move tens of kilometers away from the sonar sources during exposure, and return later.

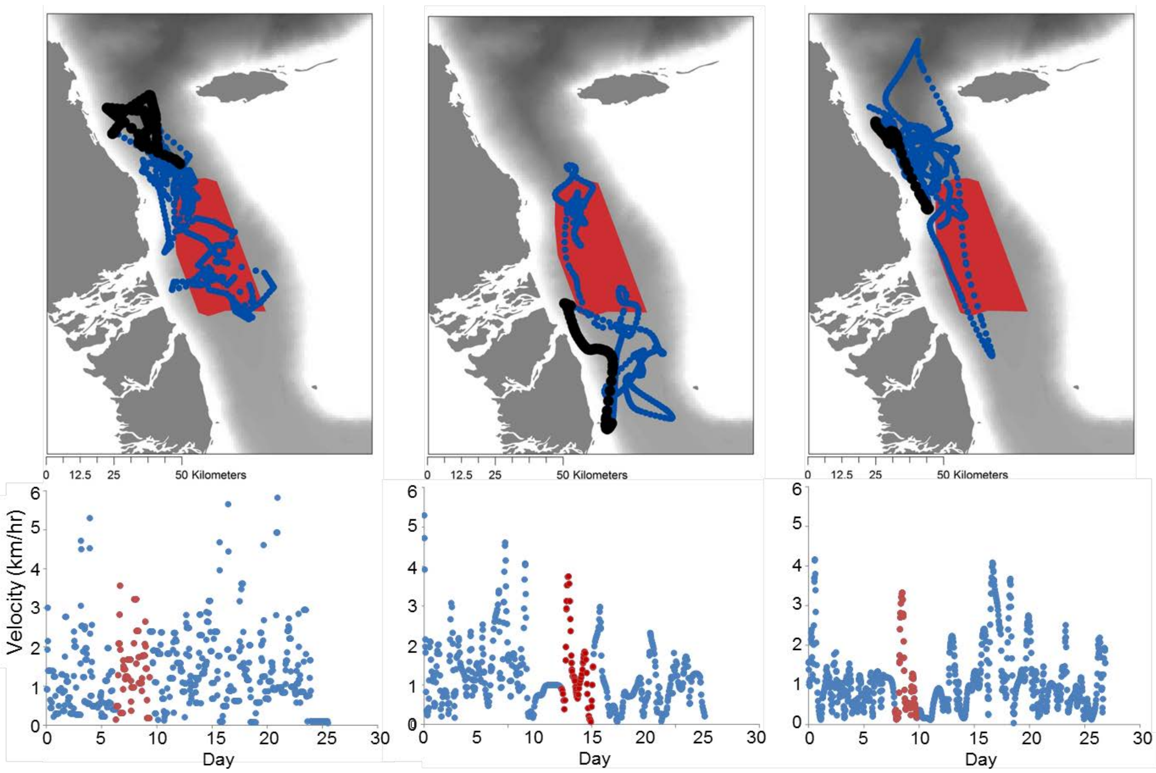

Figure 10. Md movement tracks (top row) of three animals (left to right) tagged on the AUTEC range (red) around MFA sonar operations in May 2009 (left) and 2012 (mid and right); with estimated locations before and after exposure marked in blue and locations during exposure in black. Estimated displacement velocity of the whales is given in the lower plots, with data collected during exposure marked in red. Location and velocity estimates were calculated by fitting a continuous-time correlated random walk model [13] to locations derived from tag transmissions to the Argos satellite system (http://www.argos-system.org), smoothing across the estimated errors for the Argos locations. (Unpublished data., Durban et al., 2012).

Tags have also been placed on animals outside the TOTO off Abaco and Eleuthera Islands (Figure 11). These are thought to represent separate population as our ongoing study indicates the animals in the TOTO represent an isolated population cluster, with no documented movement away from Tongue of the Ocean [3], [14], [15]. Of note, neither photo-identification (over 8 years) or telemetry data (over 4 years) have documented any exchange between whales using TOTO and those using the coastal waters off Abaco and Eleuthra Islands to the North. The animals at the Abaco site (150km to the North) are rarely exposed to MFA sonar, and thus provide a potential “control” population to which data from the TOTO population can be directly compared. Initial comparison of demographic composition has revealed a lower proportion of calf and immature whales at AUTEC/TOTO, an initial indication of a possible population-level response to cumulative sonar exposure [3]. This highlights the value of the multi-disciplinary study, with the collection of biological observations alongside tag deployments and passive acoustic monitoring.

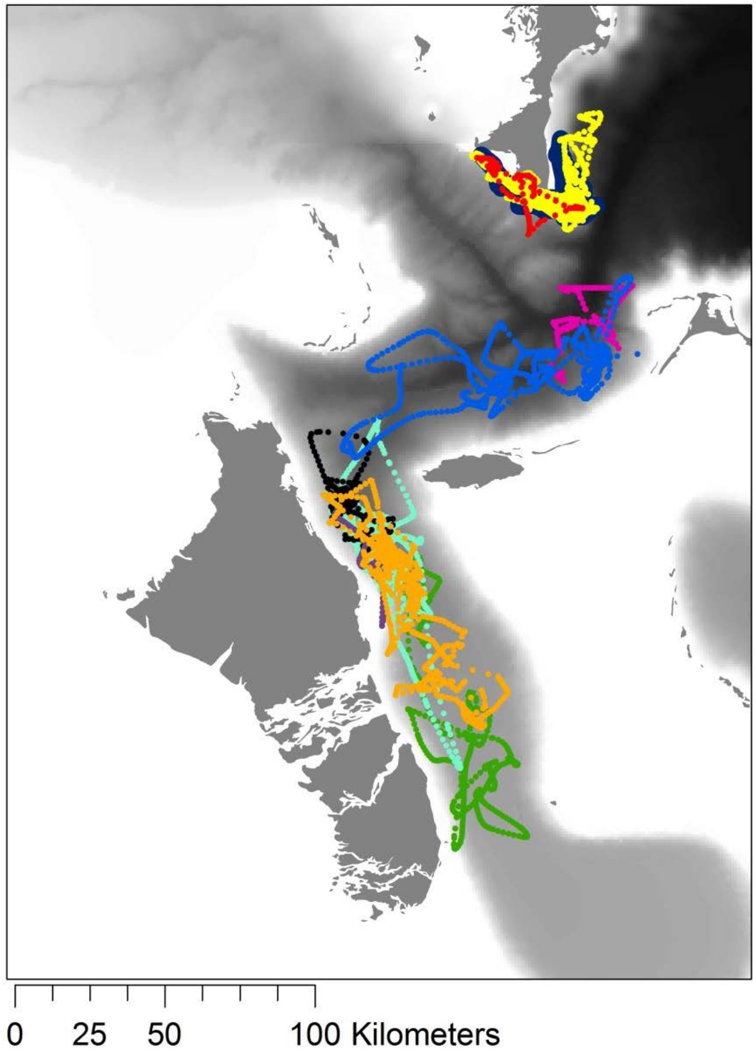

Figure 11. Md tracks derived from satellite LIMPET tags placed on 11 different whales (different colors) between 2009 and 2012 throughout the Great Bahama Canyon, including TOTO / AUTEC Tracks were estimated by fitting a continuous-time correlated random walk model [13] to locations derived from tag transmissions to the Argos satellite system (http://www.argos-system.org), smoothing across the estimated errors for the Argos locations. Based on unpublished data (Durban et al., 2012).

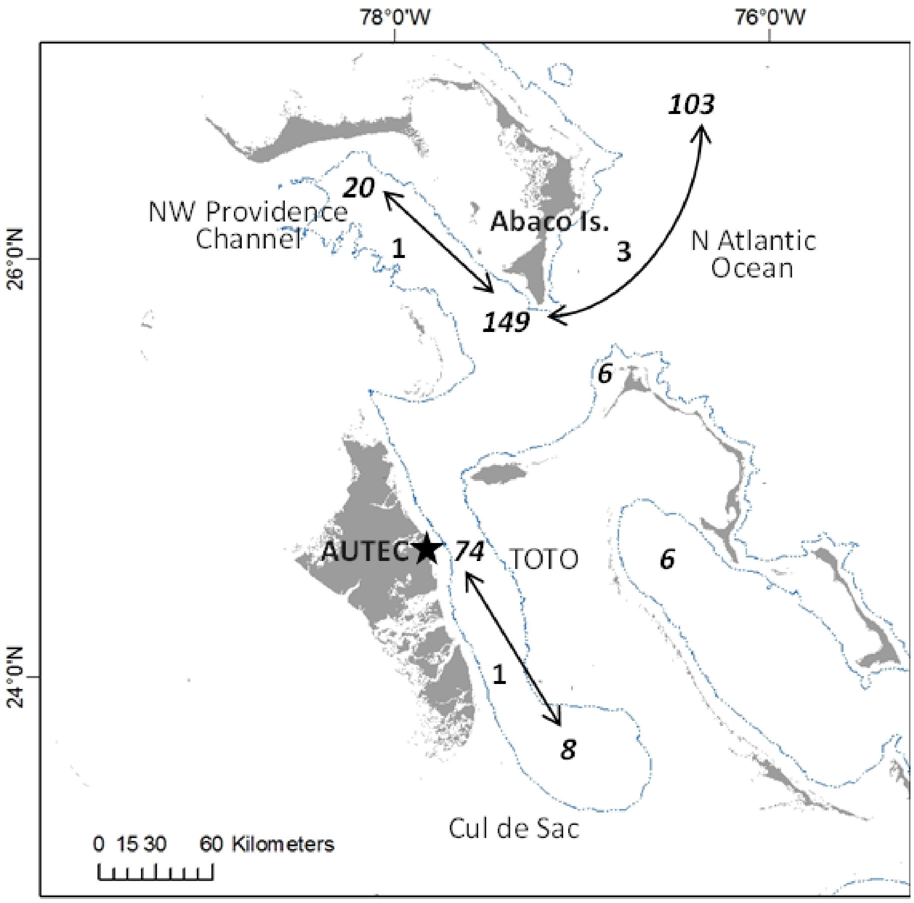

Figure 12. Movements of Md from 1992 to 2012 within and outside the Great Bahama Canyon as documented through photo-ID. Italisized numbers refer to the number of individuals identified from high-quality photographs in each area while numbers next to the arrows represent the number of individuals that have been photographed in both areas. The blue line represents the 1000m isobath

Eight of the eleven *Md* tags also collected dive-depth data, and the diving behavior from 6/8 of these are being being compared to the two depth recording tags (*Md* 2&3, Figure 10) deployed around sonar operations. This preliminary analysis shows that *Md* 3 closest to the top of the AUTEC range (presumably noisiest area, awaiting exposure levels) showed a change in diving behavior during displacement, with fewer deep dives (>1000m) and more dives to intermediate depths (500-1000m) during the mini war ("Exposed", Figure 14) compared to other times ("Non-exposed"). This likely reflects the shallower water depth in area NW of range where whale was "displaced" to.

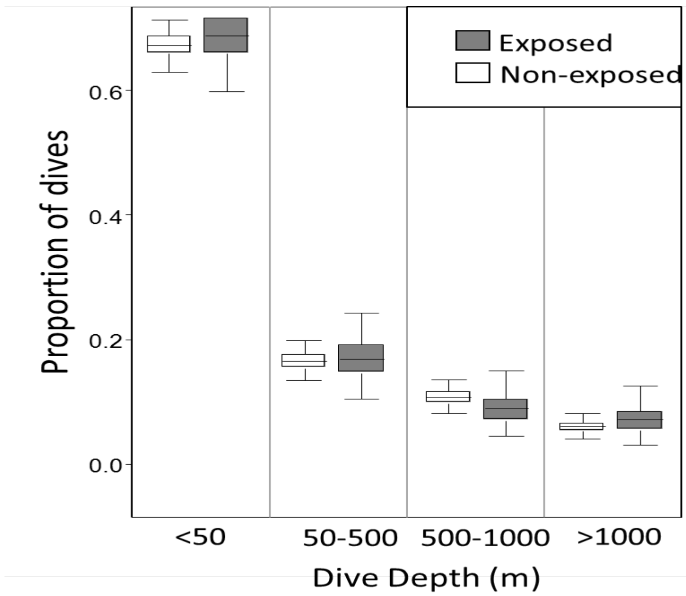

Figure 13. Dive summary for Md 2, comparing periods with and without sonar exposure. Boxes show medians, 95% probability intervals and the full distributions for proportions across 12-hour histograms for exposed and non-exposed periods (Durban et al. unpublished data).

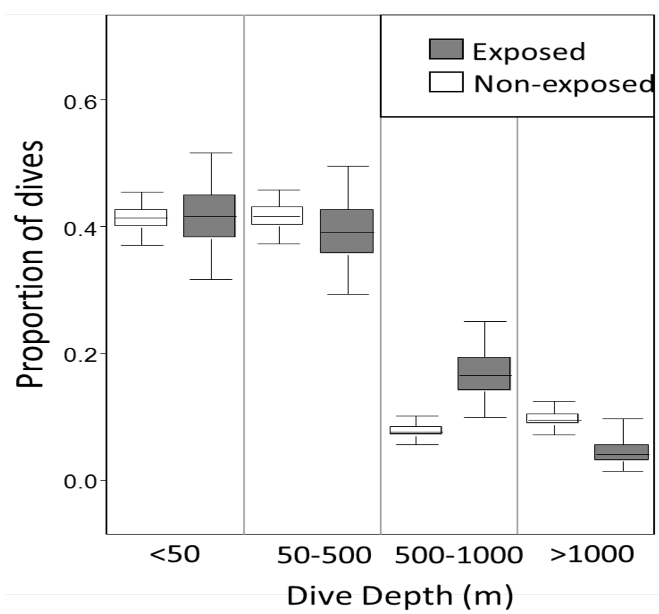

Figure 14. Dive summary for Md 3, comparing periods with and without sonar exposure. Boxes show medians, 95% probability intervals and the full distributions for proportions across 12-hour histograms for exposed and non-exposed periods (Durban et al. unpublished data).

Preliminary analysis suggests there was no obvious diving response for *Md* 2 (Figure 13) to the south of the range, which was able to stay in deeper water whereas *Md* 3 showed a decrease in dive depth (Figure 14). Dive frequency along with exposure levels are currently being analyzed.

Of note, a tagged adult male provided dive data in the absence of any tests at AUTEC (range hydrophone maintenance during deployment in July 2012 (Figure 15). This “control” whale was in the same area as used by *Md* 3 during exposed period but not as close to the shallower water at the western edge of TOTO . Most foraging dives were >1000m, more like the non-exposed deep dives of *Md* 2; not like the shallower 500-1000m dives during exposure of *Md* 3 (Figure 16).

Figure 15. Satellite track (black) of Md north or the range (red) during a range maintenance period with no operations

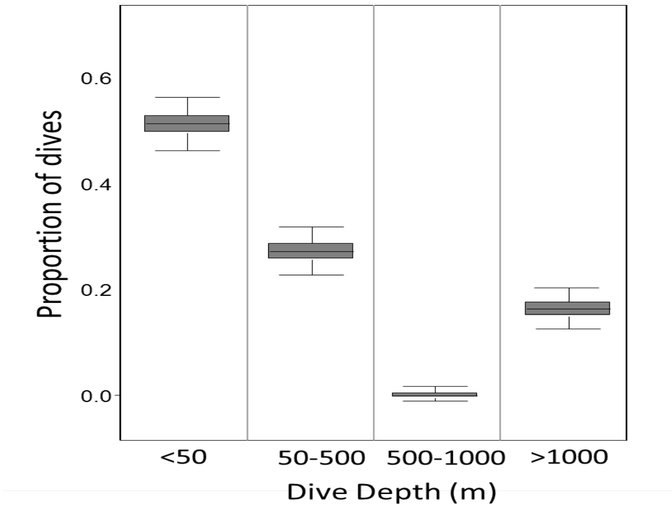

Figure 16. Dive summary for Md control.

Analyses of tag data are currently underway (Durban et al.), specifically by developing hierarchical models for relating changes in location, velocity and diving parameters to received sonar levels. Further tag deployments will use a modified program of depth-recording and transmission priorities to emphasize deep foraging dives rather than the numerous shallow/short recovery dives; the intention is to yield improved data throughput and provide consistent data as to the presence or absence of deep foraging dives. These changes are being incorporated into future tests, the next of which is scheduled for 28 October-8 November at AUTEC.

RESULTS

PCAD model development is well underway. An empirical risk function has been completed. A paper has been drafted and is in review. A year of data required to calculate the cumulative effect of sonar has been compiled. These include passive acoustic data for *Md* dive starts and sonar transmissions along with the precise ship tracks. All sources of sonar transmissions have been identified and the data sets have been combined. These data were then used in conjunction with the CASS/GRAB propagation model to estimate the sound field during each operation.

Preliminary analysis of the data is underway. As with the risk function, the data have been grouped into 30 minute periods and the maximum exposure level for each exposed *Md* group has been derived. The data are being used to document changes in abundance and distribution over the entire year and in response to sonar exposure.

The data may be used to extend the risk functions for lower exposure levels. The data have been compiled into a usable format and an initial GAM fit to the data was completed.

A model with combines the data to estimate the cumulative number of dives lost over the year along maternal lines is under development. Once the results of the model are available, the generalized beaked whale PCAD model [10]will be modified to accept the *Md* data from AUTEC. This will complete the process and provide a framework for long-term monitoring of population health.

The precision of the model depends heavily on the ability to predict the level of dive loss due to sonar exposure. There is an active program underway at AUTEC to attach dive recording satellite tags to *Md* around sonar operations. To date, three depth recording tags have been place on animals in the TOTO, two around operations, and one with no sonar present. Placement of these tags is extremely difficult since the animals are deep diving, have cryptic surface behaviors do not present a large surface profile. Multiple tests with an emphasis on tag placement are planned within the next two years, but there are no guarantees.

An additional data gap exists regarding the distribution of prey. Both the passive acoustic and tag data indicate that animals are displaced during sonar operations. If they continue to forage but there is a reduction in available prey off-range, where they may be forced to forage in shallower water and reduced depths, this displacement may be significant. During the BRS in 2008, prey field mapping with a surface transducer was undertaken and the data were compared to the distribution of *Md* groups as derived from M3R passive acoustics [16]. No subsequent effort has been made to map deep (>800m) benthic prey at AUTEC. Of particular importance would be mapping prey along the western edge of TOTO where whales appear to be displaced to during periods of sonar use on the AUTEC range.

IMPACT/APPLICATIONS

This effort is focused on developing a means of estimating the population health of *Md* in the TOTO. The long-term monitoring of cetaceans in areas of repeated sonar use is a mandated component of the Navy's environmental compliance requirements. If successful with *Md*, this methodology can be adapted to other Navy ranges and sonar-sensitive beaked whale species including Cuvier's (*Ziphius cavirostris*) beaked whales at SCORE.

RELATED PROJECTS

Marine Mammal Monitoring on Navy Ranges (M3R)

The basic opportunistic passive acoustic data with and without MFA sonar present for vocalizing groups of *Md* are being collected through the M3R program. Two major multi-ship sonar exercises per year at AUTEC will be monitored. The program is also providing the basic signal processing infrastructure and algorithms which make the collection and analysis of these data possible. This includes isolation of the sources present, their location, and transmission durations. These data are then being integrated with precise AUTEC vehicle track which allow an understanding of the interaction of active sources with ship movements relative to vocalizing and tagged animals. This attention to context is extremely important and is often overlooked in the discussion of interaction of sonar and marine mammals.

The ability to obtain precise ship track and at the same time extract precise detail as to the use of MFA sonar is unprecedented. Depending on the circumstances, some data may be classified. M3R is providing the necessary processes to handle these data in the appropriate manner and providing the final outputs via the specified Navy release chain.

M3R is providing in-kind support in excess of $200K per year. These data are also being used as part of the LATTE program the results of which will be incorporated into this program.

The ONR PCAD Working Group

ONR has funded the University of California, Santa Barbara (led by Erica Fleishman) to convene a collaborative Working Group of researchers (including two of the PIs on this proposal) who will cooperate and meet regularly to examine the population-level effects of sound exposure on marine mammals. The objectives of that group include, but are not limited to:

- Explore how the conceptual model developed by the NRC committee might be translated into a formal mathematical structure
- Consider how the above model might be parameterized with existing or emerging data on the responses of large vertebrates to disturbance
- Define conceptual approaches for investigating transfer functions (e.g., time-energy budgets, trait-mediated responses)
- Expand work by the NRC to include sensitivity analyses on different transfer functions
- Outline exploratory models that might be used to model transfer functions, synthesize existing knowledge, examine potential mechanisms, or inform research and management efforts

The Working Group meets at 6-monthly intervals and has already developed PCAD-style models for elephant seals and coastal bottlenose dolphins, and will begin the development of a similar model for beaked whales at its spring 2011 meeting. The mathematical structure developed by the Working Group will be applied as part of this program. Two of the PIs associated with this proposal are members of the Working Group and they will ensure that the project's outputs are harmonized with the needs of the Working Group.

Density Estimation for Cetaceans from Acoustic Fixed sensors (DECAF)

One required input for the proposed project is an estimate of the number of animals present within the AUTEC range under different circumstances (for example, before, during and after exercises). Methods for estimating absolute animal density from fixed hydrophone data have been developed under the above project, and applied to estimate beaked whale density (and hence numbers) at AUTEC. This project, which will finish in May 2010, was co-funded under the National Oceanographic Partnership Program by the Joint Industry Program of the Association of Oil and Gas Producers and by the National Oceanographic and Atmospheric Administration; the project budget is US$1,500K.

Linking Acoustic Tests and Tagging using statistical Estimation: Modeling the Behavior of Beaked Whales in Response to Medium Frequency Active Sonar (LATTE)

Another essential input is an estimate of the behavioral response of beaked whales at AUTEC, in terms of their change in diving behavior and location. Methods to estimate this using combined tag and passive acoustic data are being developed in the LATTE project, which runs from April 2010 to March 2013. The output will be a statistical description of the animal behavioral response, produced using all available relevant data. The framework used to produce the parameterized model can be used in the project proposed here to further refine the parameter estimates as new data are produced. The LATTE project is funded by ONR and has a budget of US$1,250K.

The Way They Move

The LATTE project is leveraged on parallel work taking place at the University of St Andrews to develop statistical methods for fitting movement models to tag data from mammals. This project is funded from September 2008 to August 2011 by the UK Engineering and Physical Science Research Council, with a budget of approximately US$650K

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