An Ocean Observing System for Large-Scale Monitoring and Mapping of Noise Throughout the Stellwagen Bank National Marine Sanctuary

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Award Number: *N00014-07-1-1029*
http://stellwagen.noaa.gov/science/passive_acoustics.html

LONG-TERM GOALS

The original project goals were to map the low-frequency (<1000 Hz) ocean noise budget throughout the Stellwagen Bank National Marine Sanctuary (SBNMS) ecosystem, identify and quantify the contributing sources of anthropogenic sounds within that ecosystem, and determine whether or not such noises have the potential to impact endangered marine mammals and fishes that use the Sanctuary.

OBJECTIVES

This project represented a high-level, integrative 'bench mark' study aimed at characterizing the marine acoustic environment and the health of an urbanized, productive ecosystem, SBNMS. The primary products are a suite of tools designed to be transferable to other ecological regions and an extensive database specific to the project. These included both mechanisms for data collection and analysis as well as a conceptual framework for integrating and interpreting the scientific results.

APPROACH

Data from arrays of Marine Autonomous Recording Units (MARUs), deployed since December 2007 under this NOPP grant gathered low-frequency (< 2000 Hz sampling rate) and mid-frequency (< 10000 Hz sampling rate) acoustic data within the sanctuary for a 30-month period, ending May 2010. In previous years we focused on building tools to represent the communication space of North Atlantic right whales and to quantify the influence of the noise from AIS-tracked vessels on the whales' acoustic environment. In FY13, we finalized the tuning of our tools so that they could process larger amounts of acoustic data, including the occurrences of multiple whale species and multiple types of vessels. We added North Atlantic fin, humpback and minke whales to the list of vocally active baleen whales under consideration. For right whales and humpback whales, we added multiple call types representing different seasonal acoustic behavior and different frequency bands . We also added fishing and whale-watching vessels to AIS-tracked vessels. Data on the expected distributions and acoustic behaviors of the four species of baleen whales were merged with acoustic signature and movement data of the three vessels types to quantify the potential for ocean noise to mask each species and different call types within species. This study was co-managed by Cornell University Laboratory of Ornithology's Bioacoustics Research Program (Cornell), NOAA Fisheries' Northeast Fisheries Science Center (NEFSC) and NOAA NOS's Stellwagen Bank National Marine Sanctuary (SBNMS). For Cornell, Dr. Christopher Clark was responsible for the original derivation of communication space and acoustic ecology concepts and acoustic masking metrics, while Dr. Peter Dugan and Dimitri Ponirakis were responsible for streamlining the analysis tools to quantify, map and animate these concepts into data products that were then transferred to NEFSC. For NEFSC, Dr. Sofie Van Parijs, Dr. Danielle Cholewiak and Denise Risch, as well as NOAA-sponsored Scholars and interns were responsible for interpreting the Cornell whale and vessel noise analyses data products into biological values. For SBNMS, Dr. Leila Hatch and Michael Thompson were involved in the analyses of the AIS, fishing vessel and whale watching data.

WORK COMPLETED

From December 2007 to May 2010, consecutive arrays of MARUs were deployed to record continuously at 2-10 kHz sampling rates for approximately 90 days at a time, in geometries designed to acoustically detect and locate vocally active whale and fish species within sanctuary waters. Continued efforts during 2011-12 had three main foci: 1) develop an semi-automated analysis framework in which multiple data layers can be combined to calculate Communication Space and Masking Metrics (CSM) for selected marine animals; 2) implement these tools to evaluate CSM for multiple mysticete species that are vocally active within the SBNMS; 3) augment the existing AIS vessel track data with fishing vessel tracks and whale watching tracks into the CSM process.

Four mysticetes species occur annually within the study area, including North Atlantic right, humpback, minke, and fin whales. For fin and minke whales, one-week periods representing their periods of peak occurrence were chosen for analysis. For North Atlantic right whales, two one-week periods were chosen for analysis, representing periods when two different sound types, the up-call and gunshot, were predominant. For humpback whales, two one-week periods were also chosen, representing a change in the predominant sound type from social calls to song, as well as a change in relevant vessel activity to represent periods with high whale-watching activity. The resultant dataset selected for detailed analyses, which was quite ambitious, included a total of six 1-week periods, four whale species and six different sound types (Table 1).Ultimately, one day from each of the 1-week periods was chosen for the final combined analyses as being representative for each species/call type.

A Matlab-based, data-analysis package, referred to as SEDNA, was developed and implemented by Cornell with support from this project (Dugan et al. 2011). MARU sound data were processed to calculate RMS received levels in 1/3rd octave bands (in dB re 1 μPa). An ambient noise tool was developed to regress background noise levels against wind data obtained from local oceanographic buoys (GMOOS A01 & NDBC 44013). The resulting relationship was used to generate the present-day ambient noise level grid (*PrA*) for each analysis week.

For each species, distribution and 2-D movements of simulated animals (animats) were generated utilizing the AIM model (Ellison et al. 1999), and were subsequently imported into SEDNA. A tool was developed to spatially propagate the calls of individual vocalizing animals onto a grid of receivers, using a 17*log(Range) transmission loss model. This simple model does not take into account the site-specific bathymetry of the SBNMS area or frequency-dependent influences on sound propagation. The Bellhop sound propagation model was integrated into SEDNA and was used to recalculate all vessel source levels and received levels at each of the whale animats. It was also used to recalculate estimates of a portion of these communication space examples, which is an extremely computationally intensive process.

Multiple vessel categories, including whale-watching, fishing, and AIS-tracked vessels, were incorporated into SEDNA so that analyses could be done on a single vessel type or combinations of vessel types. For AIS-tracked vessels, event file and track figures were generated, and source levels (SL) were calculated for those vessels that passed within 3 km of an individual MARU (Figure 1).

Positional data for fishing vessels were incorporated using Vessel Monitoring System information, and simulated tracks for whale-watching vessels were generated based on known GPS data. Vessel animat files were created by recording the details of all vessels that occur within each time interval over the period of interest. Source levels were calculated for individual vessels when possible and these data were used to assign SLs to similar vessels with unknown SLs. Layers representing cumulative noise levels from all tracked vessel types (*PrS*) were generated by combining appropriate grids for each analysis period (Clark et al. 2009).

SEDNA was used to combine these data layers to generate predicted noise surfaces throughout greater Massachusetts Bay, gridded into 1 km^2 cells, for each of the six 1-week analysis periods and the frequency band for species-specific sound type of interest. CSM metrics (signal excess and masking) were calculated for each species and sound type based on the combination of appropriate layers for each period (Clark et al. 2009). An initial graphical-user-interface (GUI) was developed for the CSM to spatially visualize sound received levels, signal excess for individual senders, noise level exposure, and various temporally varying CSM metrics (Figure 2). An overall index of communication masking (Clark et al. 2009) was calculated for each scenario, species and sound type combination (n = 8) to compare the influences that various types and levels of vessel activity and background noise levels have on each of the species-specific communication contexts.

RESULTS

One day from each of six different weeks between January 2008 and December 2009 were evaluated for presence of acoustic activity by one of four different mysticete species (Table 1). Data evaluation included both manual browsing and the use of automated detectors. Acoustic presence or absence was sampled at 10-minute resolution for each of the days in the selected weeks. Overall the average percentage of 10-minute bins with acoustic occurrence ranged from 42% for humpback social sounds to 93% for fin whale 20-Hz songs.

Estimated source levels (SLs) for each sound type were calculated from measured received levels (RLs) selected from a subset of whale sounds located within or near a MARU array, based on the simple transmission loss model and the distance of the located animal from the MARU. Right whale gunshots had the highest estimated SL (206 ± 5 dB re: 1μPa; Table 1), while humpback whale social sounds had the lowest SL (162 ± 10 dB re: 1μPa; Table 1).

For each species, the numbers and distributions of animats used in the models were determined based on long-term visual sighting data collected by the NEFSC (http://www.nefsc.noaa.gov/read/protspp/mainpage/surveys/index.html). When appropriate, animat distributions were bounded within a sub-area of the study area to better reflect a species-specific distribution. Numbers of animats per day ranged from 3 (Week 1, January 2008, right whale gunshots) to 50 (Week 4, July 2009, humpback whales; Table 1).

Vessel activity varied greatly among the 6 analysis weeks. Numbers of large vessels carrying AIS carriage-A transponders ranged from 53 (Week 1, January 2008) to 93 (Week 4, July 2009). Approximately 120 fishing vessels were estimated to be active in the study area in each week; whale-watching vessels were only active in July (29 vessels) and October (5 vessels). Average calculated source levels for each of the vessel types ranged from 135-156 dB in the $1/3^{rd}$- octave bands of interest for the whale-watching and fishing vessels, and from 140 –194 dB in these same bands for AIS vessels.

The influences of different vessel types on the CSM values for each of the four species were evaluated separately for each of the three vessel classes and cumulatively for all three classes. When compared to conservative CSM values available under recent ambient noise conditions (1970's, during a period of increased levels of commercial shipping traffic), the four species of whales under present conditions were found to have lost significant percentages of their communication spaces as follows: fin whale 20-Hz song, 97%; humpback whale song, 94%; humpback whale social sounds, 68%; minke whale song, 82%; right whale up-calls, 78%; and right whale gunshots, 19%. Figure 3 shows the difference in communication masking for three species (fin, humpback and right whales). Note that contact calling right whales suffer a constant, high loss of communication space compared to the more variable masking imposed on singing fin and singing humpback whales, for which masking decreases dramatically during periods without noise from local commercial shipping. The SEDNA system allows us to quantify masking as a function of behavioral context (i.e. singing vs. calling), the number and distribution of animals of a given species that are in the area of interest, and the influence of the type, number and distribution of vessels in the area. Clearly the extent of masking was influenced by presence or absence of each vessel class. As expected, fishing and whale-watching vessels had a much lower impact on communication space loss when compared to AIS vessels. Although the numbers presented here are based on analysis days selected as representative, we believe our results are reliable representations of what will be found when years of data are processed. We expect there will be important improvements in the data products once the Bellhop propagation model, which became available to our model late in the projects, is applied to a richer data set. This will provide results that better reflect sound propagation within the study area, as well as allow comparisons to other ongoing studies using this model. Additionally, it is important to note that for these analyses we calculated the average CSM across individual "senders", and did not quantitatively evaluate masking at the population level.

Table 1. Listing of parameter values for the eight (8) communication space analysis scenario examples for four baleen species. "Date" refers to the date chosen for analysis, based on peak occurrence for each respective species. "Spec" refs to the whale species, where the fours species are: Eg (Eubalaena glacialis, North Atlantic right whale), Mn (Megaptera novaeangliae, humpback whale), Ba (Balaenoptera acutorostrata, minke whale), and Bp (Balaenoptera physalus, fin whale). "Anim/Day" refs to the number of animats (simulated whales) per day included in the analysis. "1/3-Oct CF (Hz)" refs to the center frequency, in Hz, of the selected $1/3^{rd}$-octave frequency band. "SL" refers to the median estimated RMS source level, in dB re: 1μPa, and "s.d." refs to the standard deviation, in dB, of the source level. "n" refers to the number of acoustic locations used to calculate SL estimates. The number of animats per day was chosen based on visual sighting data. Acoustic characteristics of each sound type were obtained through analysis of MARU recordings.

Ex #	**Start**	**End**	**Spec**	**Anim/ Day**	**Sound Type**	**1/3-Oct CF (Hz)**	**SL (dB)**	**SL s.d. (dB)**	***n***
1	1/24/08	1/30/08	Eg	3	Gunshot	400	**206**	**5**	83
2	3/28/09	4/3/09	Eg	89	Up-call	160	**165**	**4**	353
3	4/12/09	4/18/09	Mn	6	Song	80	**170**	**3**	140
4	4/12/09	4/18/09	Mn	6	Song	240	**175**	**4**	140
5	7/16/09	7/22/09	Mn	50	Social	80	**164**	**6**	20
6	7/16/09	7/22/09	Mn	50	Social	240	**162**	**10**	20
7	10/3/09	10/9/09	Ba	9	Song pulse train	125	**163**	**4**	87
8	12/23/09	12/29/09	Bp	4	Song 20-Hz pulse train	20	**180**	**5**	215

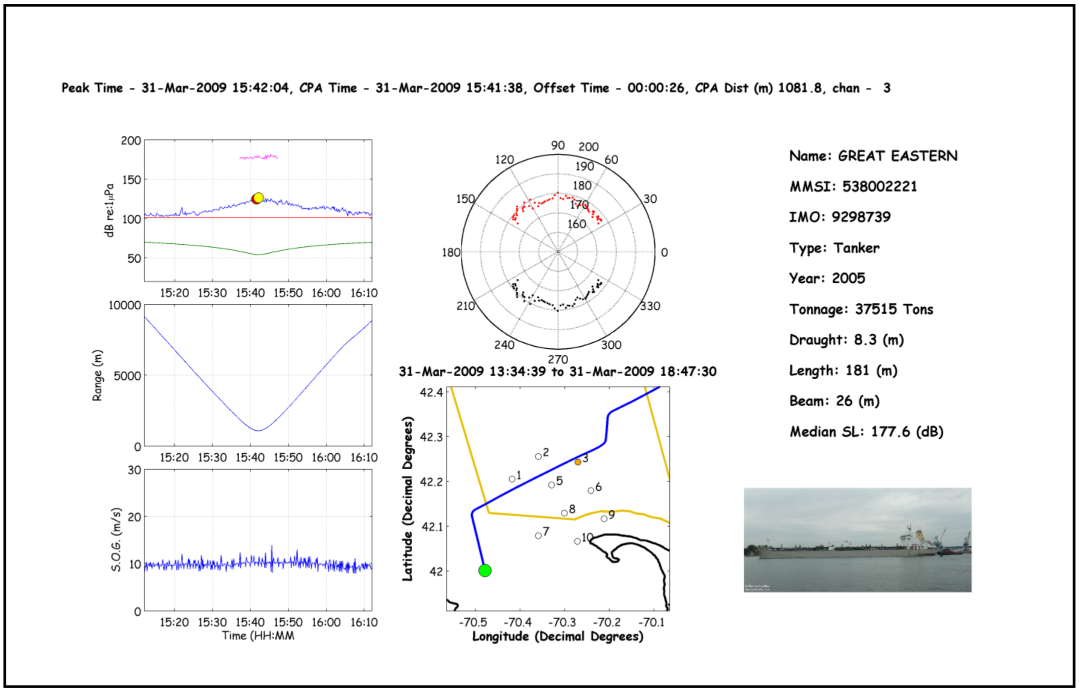

Figure 1. Example of a SEDNA-generated data chart for a single AIS-tracked vessel. Three left column panels from top to bottom show the RMS received level (dB rms re: 1µPa) on a single MARU, MARU-to-vessel range (m) as a function of time, and vessel speed-over-ground as a function of time. Two mid-column panels from top to bottom refer to the relative MARU-to-vessel bearing as a function of time and the track of the vessel relative to the MARU array and the MARU (in red) at the time of the vessel's closest approach. The right panel lists publicly-available data for the vessel and a picture of the vessel.

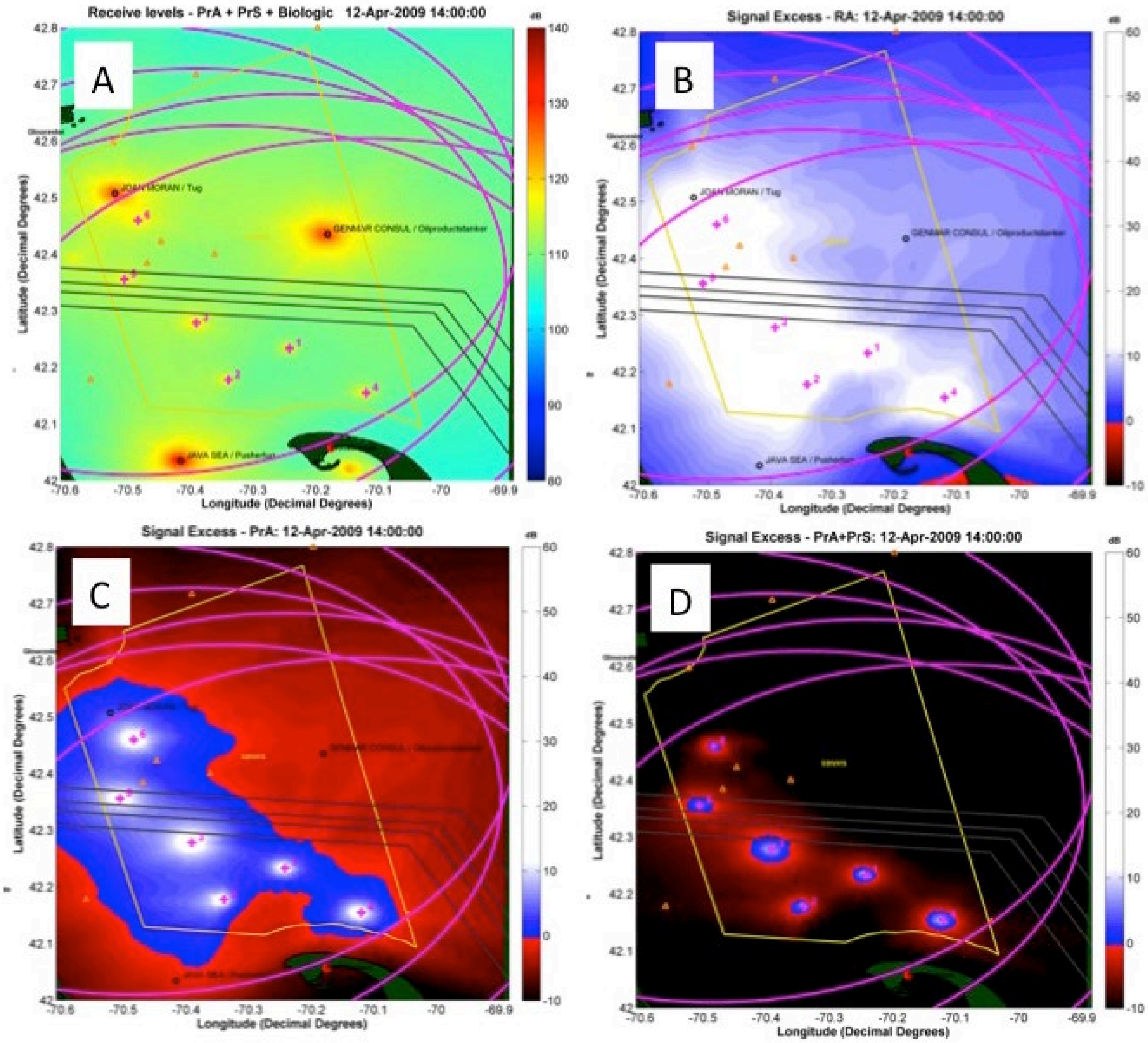

Figure 2. Example of the SEDNA-based visualizations of communication masking for six humpback whale singers on 12 April 2009 in the SBNMS study area. A) the spatially summed received levels from AIS-tracked, fishing, and whale-watching vessels; song from six humpback whale singers; and present ambient sound, with a color scale in dB re 1 µPa; B) the modeled signal excess for the six humpback singers under recent historical ambient noise (RA) conditions, with a color scale in dB; C) the modeled signal excess for the six humpback singers under present average ambient noise (PrA) conditions, with a color scale in dB; and D) the modeled signal excess for the six humpback singers under present ambient noise (PrA) and all present vessels (PrS) conditions, with a color scale in dB. Values for signal excess below zero indicate that an individual singer cannot be heard above the background noise (i.e. 100% masking). In this example, all six singers are at least partially acoustically connected under historical ambient noise (B) and present ambient noise (C) conditions, but are acoustically isolated from one another under when the cumulative noise from all vessel types (PrS) is added to present average ambient noise (PrA) conditions (D). In this example, the present cumulative noise condition (D) resulted in an average of 99% communication masking, with the lowest value of 93% for any 10-minute period.

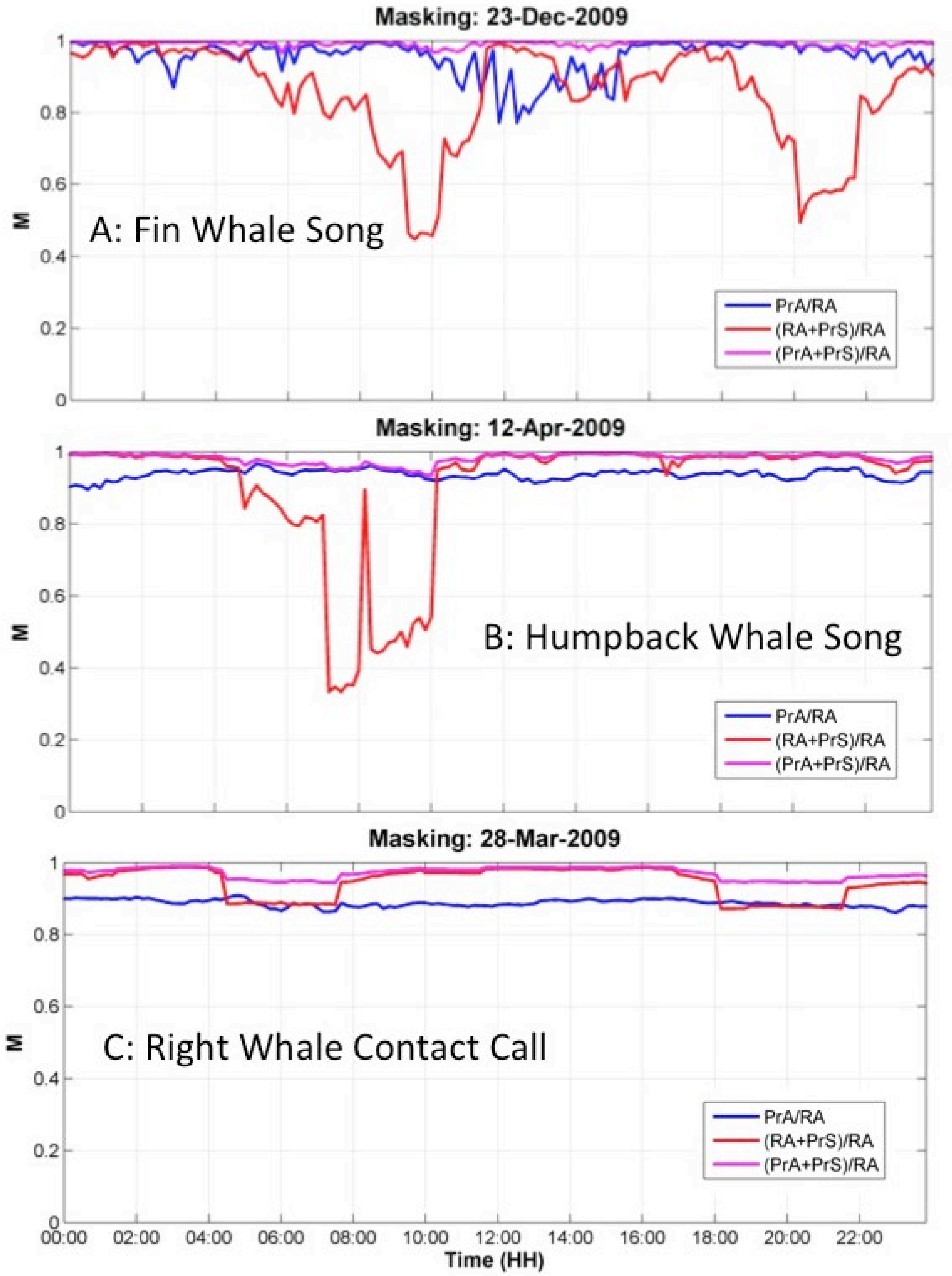

Figure 3. Examples of index of communication masking metric (M) during representative 1-day sample periods for a common form of acoustic communication by three species of whales that frequent the SBNMS area: A) singing fin whales (n =4) , B) singing humpback whale (n = 6), and C) up-calling right whales (n =3). The three colored data lines represent the level of masking under current ambient noise conditions relative to a recent historical ambient noise level (dark blue, PrA/RA), the day's vessel traffic and recent historical ambient noise levels combined relative to recent historical ambient noise level (dark red, (RA +PrA)/RA), and present day ambient and the day's vessel traffic relative to recent historical ambient noise level (pink, (PrA +PrA)/RA)).

IMPACT/APPLICATIONS

National Security

The Stellwagen NOPP Project produced a preliminary suite of transferable tools for assessing contributions from several sources of noise to an underwater noise budget. These tools are valuable for assessing and contextualizing the place-based environmental influences of commercial vessel traffic, seismic airgun surveys for oil and gas, and defense-related activities. Over this final period of the project the technical effort focused on: a) validating the analytical mechanisms for measuring received level and calculating estimates of source level; b) ways to expand and streamline the SEDNA GUI; and c) advance the application of these acoustic masking metrics and concepts so as to be included in processes by which to adequately assess the consequences from and influences of anthropogenic sounds on marine environments.

Quality of Life

By describing and assessing the influences of changes in the acoustic environment for marine animals over biologically-relevant scales, this project will better inform managers and the general public regarding how best to minimize and/or mitigate the costs of human activities that introduce noise into coastal marine environments. Tools created as part of this Stellwagen NOPP research can be used by various stakeholders (i.e., governmental agencies, ocean user groups, environmental consultants, environmental advocacy organizations, and private citizens) to ensure that chronic, sub-lethal anthropogenic impacts associated with human activities (i.e. shipping noise, offshore energy development and operations) are included in national, regional and international marine spatial planning initiatives.

A current effort within NOAA heavily relies on the tools developed from this and other related projects to map the sound field throughout the US EEZ and provide these metrics and maps alongside existing and improved density models of cetaceans.

Science Education and Communication

A total of eleven (11) publications in scientific, peer reviewed journals and one book chapter. One defining and presenting the analytical paradigm by which to calculate and quantify communication masking as a result of cumulative noise from commercial ships. One applying these concepts and the analytical paradigm to communication masking of North Atlantic right whales over a one month period based on these NOPP data. Five papers on baleen whale occurrence and distribution, including humpback whale seasonal singing rates, acoustic tracking, and response to an anthropogenic stimulus; right whale long-term seasonal occurrence; and a description of minke whale call types and occurrence. One paper investigated applying new localization techniques to baleen whales, and the book chapter discussed the use of acoustic techniques for density estimation. Several manuscripts will be forthcoming over the next year, including a one on calling behavior of individual minke whales (accepted, in press), one on right whale abundance estimation, one evaluating multi-year baleen whale occurrence, and one on transmission loss, all for the SBNMS study area. Project PIs highlighted this work at the North Atlantic Right whale consortium meeting (New Bedford, MA; 6-7 November 2013). Three different technical competitions in 2013 used the acoustic data and our annotations of validated right whale contact calls as the basis of detection-classification competitions; a) Kaggle-1, an open, online competition hosted and supported by Kaggle and Marinexplore.com; b) Kaggle-2, an open competition associated with the first Bioacoustics Workshop at the International Conference on Machine Learning (ICML, Atlanta, GA, 2021 June 2013); and c) 6th International Workshop on Detection, Classification, Localization, & Density Estimation, St. Andrews, Scotland, 12-15 June 2013.

TRANSITIONS

Quality of Life

Methodologies developed for this project were also used to evaluate impacts associating with the construction and operation of two offshore liquefied natural gas terminals adjacent to the SBNMS. As the contractor responsible for evaluating the acoustic impacts of these terminals and as a result of this NOPP-funded research, Cornell continues to develop new ways of calculating and articulating the contributions of multiple types of noise sources to the noise budgets in the area. Additional contracts to provide passive acoustic monitoring in Arctic waters coincident with seismic exploration for oil and gas resources have also received the benefit of these NOPP tool developments.

Science Education and Communication

The Stellwagen Bank Sanctuary's website and the Northeast Fisheries Science Center's website were supplemented to provide information on the project and noise in the marine environment (http://stellwagen.noaa.gov/science/passive_acoustics.html; http://www.nefsc.noaa.gov/psb/acoustics/psbAcousticsNOPP1.html). Between October 2010 and September 2011, the Stellwagen NOPP project was highlighted in several public media pieces. *National Geographic* magazine ran an article entitled "Quieting Noisy Oceans" January 2011 that addressed this work. An article in Scientific American entitled "Noise Reduces Ocean Habitat for Whales" highlighted communication masking research in the sanctuary, including a video of sound in the sanctuary (October) http://www.scientificamerican.com/article.cfm?id=noise-reduces-ocean-habitat-for-whales. An article on the website Scienceline.org on right whales, acoustic impacts and sanctuary research addressed this work http://scienceline.org/2011/06/looking-for-admiral/ . New Scientist published a story that appeared in June on ocean noise pollution, predominantly focused on shipping, which highlighted the work in the sanctuary http://www.newscientist.com/article/mg21028165.200-software-simulator-tracks-undersea-noise-pollution.html. Project PIs highlighted this project's results in multiple forums, including the 3rd Symposium of the Acoustic Communication of Animals, which included workshops on Acoustic

Ecology (Ithaca, NY; 1- 5 August 2011), the Detection, Classification and Localization workshop (Mt. Hood, OR; 22 – 25 August 2011), the 6th International DCLDC workshop (St. Andrews, Scotland; 12-15 June 2013; the First Bioacoustics Workshop at the ICML (Atlanta, GA; 20-21 June 2013); and the 20th Biennial Conference on Marine Mammals (Dunedin, New Zealand, 9-13 December 2013).

RELATED PROJECTS

The Stellwagen NOPP Project is related to a database development project, a cumulative impact mapping project, collaborative dialogue with the population modeling project (http://www.onr.navy.mil/en/Science-Technology/Departments/Code-32/All-Programs/Atmosphere-Research-322/Marine-Mammal-Population.aspx) and a NOAA working group project aimed at mapping the sound field and cetacean densities and distribution throughout the US EEZ. Additionally, the dataset from this project will be part of a upcoming large-scale analysis of right whale migration throughout the western North Atlantic Ocean.

Sofie Van Parijs is working on the realization of a standardized acoustic database with collaborators at Scripps and the NOAA Science Centers, is PI on a recent NOPP database grant and together with Chris Clark, and is collaborating closely with a recent NOPP OBIS-SEAMAP grant awarded to Pat Halpin. The Massachusetts Oceans Partnership is engaged in mapping the annual cumulative impacts of human activities on the marine environment from the Commonwealth's shoreline to the boundaries of the US Exclusive Economic Zone. Through collaboration with researchers based at the National Center for Ecological Synthesis and Analysis (NCEAS; Santa Barbara, CA), information from the Stellwagen NOPP project is informing a preliminary representation of noise from large commercial shipping in these maps. The NOAA Marine Mammal and Sound Working Groups (Underwater Sound-field Mapping and Cetacean Distribution and Density Mapping) represent a NOAA-led effort to develop geospatial products and tools for representing human-induced noise and important areas of cetacean activity throughout the US EEZ. These efforts integrated expertise and support from multiple agencies within the USG as well as multiple universities and private consulting companies. The continuation of this project includes drafting guidelines for NOAA's Ocean Noise Strategy. Several of the PIs on this project are leading and participating in this effort and the experience gained through this NOPP project is and will continue to provide guidance for integrating information on noise and cetacean activity and interpreting the results for management.

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