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

Christopher W. Clark
Bioacoustics Research Program, Cornell Laboratory of Ornithology
159 Sapsucker Woods Road, Ithaca, NY 14850
phone: (607) 254 2405 fax: (607) 254-2460 e-mail: cwc2@cornell.edu

William T. Ellison
Marine Acoustics, Inc.
809 Aquidneck Avenue, Middletown, RI 02842
phone: (401) 847-7508 fax: (401) 847-7864 e-mail: bill.ellison@marineacoustics.com

Leila T. Hatch
Stellwagen Bank National Marine Sanctuary, NOAA National Ocean Service
175 Edward Foster Road, Scituate, MA 02066
phone: (781) 545-8026 fax: (781) 545-8036 email: leila.hatch@noaa.gov

Richard L. Merrick
Northeast Fisheries Science Center, NOAA Fisheries
166 Water Street, Woods Hole, MA 02543
phone: (508) 495-2291 fax: (508) 495-2032 email: richard.merrick@noaa.gov

Sofie M. Van Parijs
Northeast Fisheries Science Center, NOAA Fisheries
166 Water Street, Woods Hole, MA 02543
phone: (508) 495-2119 fax: (508) 495-2258 email: sofie.vanparijs@noaa.gov

David N. Wiley
Stellwagen Bank National Marine Sanctuary, NOAA National Ocean Service
175 Edward Foster Road, Scituate, MA 02066
phone: (781) 545-8026 fax: (781) 545-8036 email: david.wiley@noaa.gov

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LONG-TERM GOALS

The project goals are 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 represents 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 will be a suite of tools designed to be transferable to other ecological regions and an extensive database specific to the project. These will include both mechanisms for data collection and analysis as well as a conceptual framework for integrating and interpreting the scientific results.

APPROACH AND WORKPLAN

Well-established passive acoustic technologies and a mixture of existing and newly-developed analytical methods are applied to meet the goals of this project. Arrays of Marine Autonomous Recording Units (MARUs), deployed since December 2007, are gathering low-frequency acoustic data within the sanctuary for a continuous 30 month period. MARU data are used to calculate the spatial and temporal variability of the noise field and to detect and localize vocally active baleen whales and fish species. This project has developed methodologies that combine MARU data with commercial ship track data from the US Coast Guard's Automatic Identification System (AIS) to calculate the noise budget contributions from vessels within and outside the sanctuary. Data on the distributions and acoustic behaviors of ships and marine animals are merged in order to investigate the potential for ocean noise to mask animal sounds and/or otherwise impact vocally-active species. These data are then input into tools built as modifications either to the Acoustic Integration Model/AIM (Frankel et al. 2003) or as Matlab (The Mathworks, Inc. 2006) plug-ins that interface with an open-source sound analysis platform called XBAT (http://xbat.org/home.html; Figueroa 2008). Additionally, data from visual sighting efforts and digital tags (Johnson & Tyack 2003) placed on individual humpback whales are used to improve parameter values of whale distribution, 3-D whale movements and behavioral responses.

This study is 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). Dr. Christopher Clark's team at Cornell supply calibrated MARUs, synchronize acoustic data files, and develop analysis tools for quantifying and mapping of ocean noise. Dimitri Ponirakis is a central member of the Cornell analysis team. Dr. William Ellison and Dr. Adam Frankel at Marine Acoustic Inc. collaborate with Cornell to upgrade AIM for vessel noise and total noise spatio-temporal calculations and mapping. Dr. Sofie Van Parijs oversees NEFSC's project responsibilities, including refurbishment of MARUs, partial staffing of field work, and whale and fish detection and distribution analyses. Denise Risch is a central member of the NEFSC team, which also includes several NOAA-sponsored Hollings Scholars and graduate students. Dr. Leila Hatch oversees the SBNMS's project responsibilities, including hiring of the vessel and staff, scheduling of MARU field work, analysis of AIS data and other vessel GPS data, analysis of DTAG data, website and case study development and producing annual and final reports. Michael Thompson and Dr. Danielle Cholewiak are central members of the SBNMS team.
Between October 2009 and April 2010, 3 consecutive MARU arrays will be deployed, each collecting 2-3 months of data to address temporally and spatially-specific analytical goals. In the upcoming year, detection and localization efforts will focus on building a detector for non-song in humpback whales using three identified tonal call types and linking acoustically located/tracked right, minke and fin

whale groups to visual sightings to validate acoustic patterns and behaviors. Analysis methods and tools built in AIM and Matlab/XBAT will continue to be fine-tuned to increase their efficiency and accuracy. Data from other research conducted in greater SBNMS waters (e.g., additional MARU arrays deployed by Cornell in Massachusetts and Cape Cod Bays, NEFSC-led regional right whale aerial surveys, SBNMS vessel-based large whale surveys and right and humpback whale DTag efforts) will be further integrated to inform parameter settings in these new tools. Methods to quantify communication masking impacts and assess responses of vocally-active whales to changes in ambient noise will be further developed and implemented over wider spectral, longer temporal and larger spatial scales. In addition to ongoing presentations at workshops, meetings and conferences, interfaces with outside databases will be further formalized and publications will be submitted to highlight emerging results.

WORK COMPLETED

Since December 2007, consecutive arrays of MARUs have been deployed to record continuously at 2 kHz for 90-100 days in geometries designed to detect, localize and track vocally-active whale and fish species during time periods of local abundance within sanctuary waters. Additional oceanographic data collected by CTD during each deployment and retrieval, data from transmission loss/calibration experiments, and analyses-in-progress are compiled and updated via a project-wide, internet-accessible database system.

Field experiments were conducted (5 October 2008 and 18 July 2009) to empirically measure and more accurately model sound transmission loss (TL) within the array area. Analyses and comparison of acoustic data to different sound propagation models was undertaken in AIM, focusing on shallow-water conditions. MARU received sound levels (RLs, dB re 1 µPa) were measured for 1/3rd octave frequency bands spanning center frequencies 200-1000Hz using LTSpec, a customized tool written in Matlab (Cortopassi 2007). Playback source levels (SLs, dB re 1 µPa) were calculated for 0.5-second time slices centered around 6 different frequencies. All measurements were corrected for background noise. Additional field and laboratory efforts were undertaken to more extensively calibrate the equipment used in sound production, recording and acquisition.

Analysis efforts in 2008-9 expanded a framework initially developed in 2007-8 to integrate results from whale detection/localization/tracking, ship tracking, MARU received levels and physical environmental variables (wind, sediment type, CTD etc.). AIM was used to create predicted species-specific RL gridded surfaces throughout greater Massachusetts Bay over the course of a month based on multiple empirical datasets. The 90x90 gridded modeling area covered 10,980 km^2 (90 km latitude, 122 km longitude).

RLs at MARU locations were calculated for species-specific frequency bandwidths (i.e., right whale contact calling, 71-224 Hz) and three 1/3rd octave bandwidths (center frequencies at 20, 100, and 800 Hz). Total bandwidth RLs were also broken down into percentages of the time period analyzed, with RL thresholds for 5%, 25%, 50%, 75% and 95% of the sampling period reported. These calculations were performed using LTspec. For 10-minute data samples recorded at the MARUs nearest to two oceanographic buoys in Massachusetts Bay (GMOOS A01 and NDBC 44013) in April 2008, 5% RL thresholds in the 71-224 Hz band were regressed against recorded wind speeds (meters/second per 10-minute). The resulting relationship was used to estimate wind-generated noise throughout the modeling area.

Whale and fish detection and localization analyses continued with the implementation and further development of species-specific automatic detector tools. Data collected between December 2007 and May 2008 were used to build and test efficiency of detectors for minke whale pulse trains, as well as fin and humpback whale song. All automatic detectors, including the one previously developed for right whale up-calls (ISRAT, Urazghildiiev & Clark 2006), were run on data from April 2008. Data from July 2008 were used to identify non-song calls for humpback whales to enable improved characterization of species presence during the summer months when foraging is predominant and singing is minimal within SBNMS. XBAT and the Correlation Sum Estimation (CSE) Tool (Fristrup & Cortopassi unpublished) were used compute locations (x, y) of calling fin and right whales in December 2007-April 2008. Localization of right whale up-calls was used to identify the spatial and temporal characteristics of vocalizing groups (termed ‘acoustic groups’) present within the array. SLs for up-calls from acoustic groups located in April 2008 were calculated in AIM using their RLs and locations.

April 2008 MARU-derived acoustic detections of right whales were integrated with April 2008 visual sightings from NOAA Northeast Fisheries Science Center’s aerial survey efforts to create a course estimate of density and distribution of calling right whales within greater Massachusetts Bay over this time period. AIM was used to model the acoustic behavior and movement of these right whales as “animats” [1] over the month, with calling intervals and SLs informed by MARU-located acoustic groups. The total area modeled was subdivided to create localized regions with perpetual lower and higher right whale densities, based on the observed acoustic and visual detections. AIM was then applied to predict the month-long 10-minute time-series of RLs from calling right whales within the 71-224Hz band over the gridded surface.

All AIS data collected in 2008 were analyzed to determine the number, size, type/cargo, and identity of all vessels transiting the sanctuary using methods described in Hatch et al. (2008). Closest points of approach (CPAs) to MARUs were determined for all AIS-tracked vessels transiting greater sanctuary waters in April 2008. For ships passing <5km from MARUs, RLs were calculated for the right-whale specific low-frequency bandwidth (71-224 Hz) and AIM was applied to calculate vessel SLs. For ships passing >5km from MARUs, SLs for vessels of the same type measured during other NOPP monitoring periods or from previous SBNMS-based studies (Hatch et al. 2008) were used. AIM was then applied to predict the month-long time-series of RLs from each AIS-tracked vessel within the 71-224Hz band over the gridded surface. Matlab was used to sum all vessel RL fields to create a gridded surface representing the total contribution from large commercial ships to the area’s noise budget. Finally, Matlab was used to sum the calling right whale, shipping noise and wind-generated noise gridded surfaces to create an empirically-based, 10-minute resolution animation of total noise throughout the modeled area.

An index of right whale communication masking representing the portion of right whale communication space that is unavailable for communication was developed (Clark et al. in press) and implemented for April 2008 within greater Massachusetts Bay. For each receiver grid point in the modeled area (n=8100) and for each 10-minute sample (n=4320), the index was calculated as the relative difference between the communication space available to all calling right whales under wind-generated noise only and the communication space available to all calling right whales under conditions of wind-generated noise plus noise from large commercial shipping. The index varied between 0 and 1, where 0 represented no communication masking from shipping noise, and 1

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[1] Animats are artificial animals with positional and movement data governed by AIM parameters (Frankel et al. 2003).

represented full communication masking from shipping noise realized within the sampled time and area.

General levels of calling activity, represented by numbers of right whale calls detected by individual MARUs, were compared to ambient noise measurements. Continuous MARU data for the month of April were divided into 15-minute bins (n=2880) and RLs for two broad frequency bandwidths (30-1000Hz and 30-400Hz) as well as for 1/3rd octave bands were calculated for each MARU using LTspec. Numbers of right whale up-calls were quantified in 15-minute bins for each MARU. All detected calls were reviewed by hand to remove false detections.

The tracking tool ISRAT_LT (Urazghildiiev unpublished) was used to create predicted tracks of acoustic groups based on the timing of located calls and known right whale swimming speeds. AIM was used to estimate RLs from AIS-tracked commercial ships at locations where acoustic groups were located.

RESULTS

Observed RLs from the TL experiment on 5 October 2008 were compared to those predicted by three models of sound propagation (Bellhop, Kraken and Parabolic Equation)[2]. The Parabolic Equation model (PE version 5.0, Zingareli et al. 1999) was found to best replicate the observed data. In addition, range-averaging (Harrison and Harrison 1995) was implemented to evaluate correspondence between observed vs. predicted measurements within 1/3rd octave bands (Figure 1). As seen in Figure 1, range-averaged PE was found to simulate the sound propagation characteristics of the SBNMS with a high degree of accuracy.

Figure 2 shows the distribution of AIS-tracked large commercial vessels in April 2008 within the modeling area. Of the 144 unique vessels identified, 33% were tugs/tows, 23% were cargo ships, 22% were tankers, 16% were law enforcement, military, construction or research vessels, 4% were fishing boats and 4% were cruise ships, pleasure craft, ferries or sailboats[3]. 30 of the 144 vessels were found to contribute insignificantly to RLs in the modeling area. Thus, the transiting activity of 114 vessels was modeled, with 50 vessels passing within 5km of MARUs, providing transit-specific SL estimates.
Fin, right, and humpback whales were detected every day within the April 2008 MARU array (Figure 3). While no minke whales were detected, additional analyses have demonstrated generally low levels of acoustic detections for this species from December through April, with peaks in calling activity during August and September. Acoustic time-bearing tracks for vocal right whales were generated for each day during the December 2007-March 2008 deployment, for a total of approximately 60 groups. Multiple right whale acoustic groups were distinguished based on the location and timing of calls in April 2008. For example, 296 located calls were grouped into 23 different acoustic groups on 1 April 2008. AIM estimated the average SLs for located right whale contact calls to be 163 dB (SD +/- 4 dB) within the 71-224Hz band.
Figure 4 shows an example of the time-varying 71-224Hz and 20, 100 and 800 Hz 1/3rd octave RLs based on 10-minute samples throughout April 2008 at a single MARU location in the array. Regression

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[2] Additional AIM parameters included NOAA’s 3 arc-second bathymetry database, Consolidated Bottom Loss Upgrade (CBLUG) with Class 2 setting, and a wind speed of 10 knots.

[3] Because AIS carriage A requirements do not mandate transmitters for craft < 300 gross tons or with <165 passengers, these estimates underestimate the distributions and densities of small and mid-size vessels in the modeled area (i.e. fishing boats, pleasure craft and ferries).

analysis found a linear relationship between wind (m/s) and 5% RL, with a slope 0.1644 and intercept 96.071dB. To account for several dB of variation around this line when predicting wind-generated noise levels in the modeling area, an additional term of 1.5 x a random number drawn from distribution with a mean of zero and standard derivation of 1 was added to the equation.

Figure 5 shows the month-long summation of 10-minute predicted RLs for the 90x90 receiver grid due to wind (top left), calling right whales (top right), transiting large commercial vessels (bottom left) and the total (bottom right). The calling behavior and movements of 113 right whales were modeled based on empirical estimates that ~1/3rd of the total North Atlantic right whale population was present in greater Massachusetts Bay in April 2008. In Figure 5B, calling right whale RLs were highest in the rectangular areas determined to have the right whale densities in April 2008. Shipping noise dominates the total accrued RLs for the month. Two 10-minute snapshots from the summed RL gridded surfaces (wind, calling right whales and shipping noise) are depicted in Figure 6. The relative difference in communication space available to calling right whales during times with fewer ships (Figure 6 left) versus more ships (Figure 6 right) is visually apparent here. This relative difference is quantified by calculating the communication masking index for the entire modeling area (Figure 7). For 25% of the month, communication masking was 0.05 or lower, representing conditions close to pre-shipping ambient levels. However, for 50% of the month, communication masking was greater than 0.69, representing a loss of ~70% of the communication space that calling right whales would have had without shipping. That loss was as great as 86% for 25% of the month. Given that the modeled calling right whale density for April 2008 was arguable higher than could be justified for any other time period in the last decade and AIS-tracked vessels represent an underestimate of total vessel activity in Massachusetts Bay during right whale season, these results likely present a conservative estimate of the situation facing communicating right whales in this region.

Figure 8 shows results from preliminary analyses of right whale calling-level response to noise based on a single MARU over the month of April 2008. Average ambient noise levels were 105.4 ± 5.3dB re: 1µPa (min: 96.2dB, max: 133.2 dB). Overall, 10% of the time periods had received sound levels less than or equal to 100dB re: 1µPa (n=277 bins), while 2% of the time periods had received sound levels greater than 120dB (n=58 bins). A total of 5420 right whale calls were detected on this channel for the month. Calling activity varied from 0 - 43 calls per time bin, with an average of 1.9 ± 4.5 calls. Calls were detected in 25% of time bins (approximately 180 hours with detections). Data from the first week of April were examined using cross-correlation analyses to investigate the relationship between numbers of calls and ambient noise measurements over 8 hour time lags. Correlation values were 0.1 or less, which was not considered to be significant. However, calling activity on individual days showed greater correlation to ambient noise conditions; these relationships are being explored with further data analyses. The resultant ambient sound level data in the 30-400Hz band and right whale calling data are being used to create a time series model to determine whether calling activity varied under different noise conditions.

Figure 9 shows preliminary results from the integration of the one MARU- tracked acoustic group of right whales and AIS-tracked cargo ship (MV Teng He). AIM calculated a maximum RL of 105dB re: re: 1µPa for acoustic group during the ship's passage. Possible changes in movement and vocalization behavior of acoustic groups relative to RLs from nearby ships are now being evaluated.

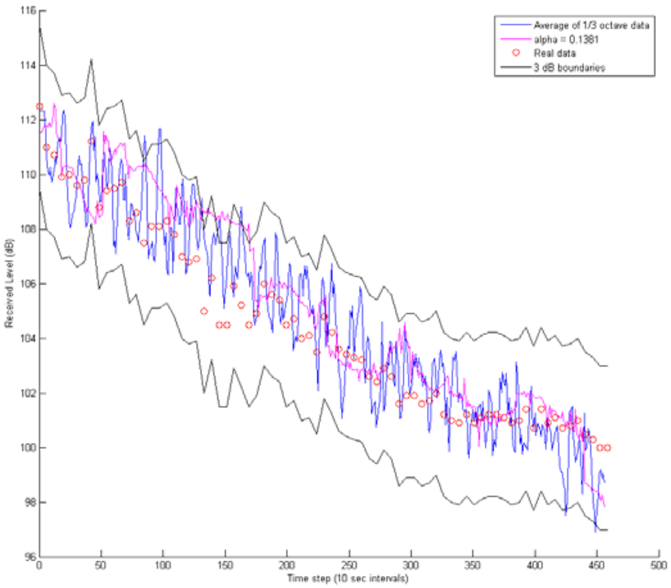

Figure 1. Comparison of 10-second 100Hz 1/3rd octave empirical MARU RLs (red dots) and AIM-predicted (Parabolic Equation Model) RLs for the 83 minute period following the close approach of the M/V Everlast on 27 December 2007. 100 Hz single frequency propagation modeling shows considerable variation (blue line), while range-averaged predictions for the 100Hz 1/3rd octave band (magenta line) show less variation and are a better match to the measured data. Furthermore, range-averaged data almost always fall within 3 dB of the measured data (black lines).

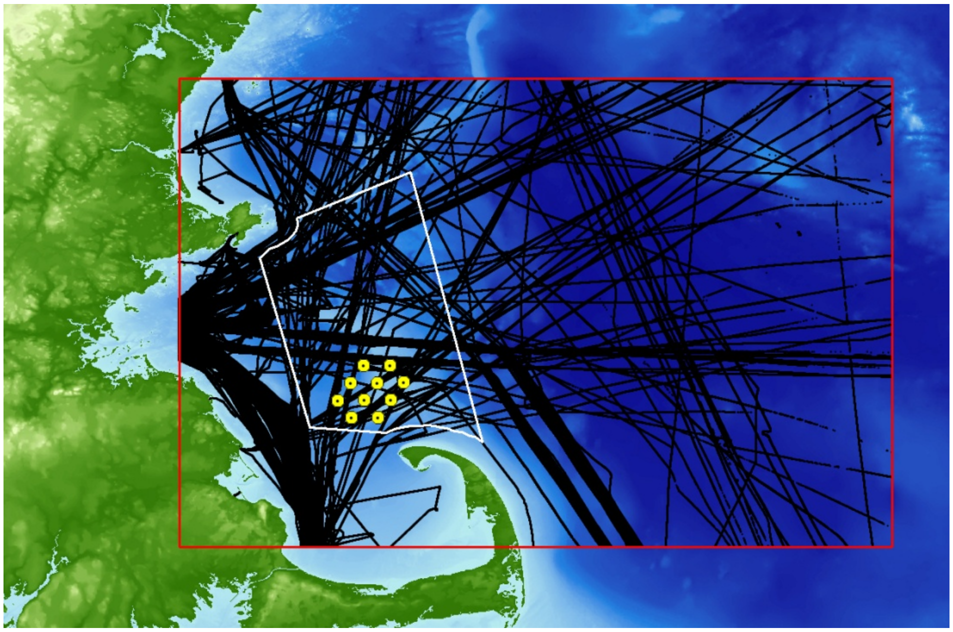

Figure 2. Distribution of 144 AIS-tracked large commercial vessels (black lines) that transited the modeling area (red boundaries) in April 2008. The locations of the bottom-mounted MARUs that were recording during this period (yellow dots) and the boundaries of the Stellwagen Bank National Marine Sanctuary (white) are also indicated.

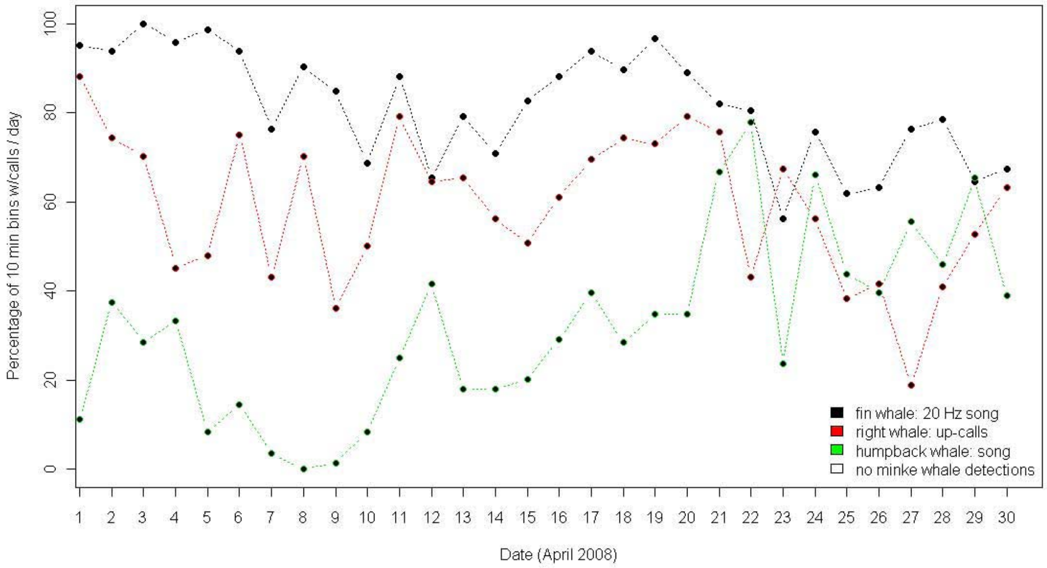

Figure 3. The percentages of 10-minute bins per day throughout the month of April 2008 in which North Atlantic fin, right, and humpback whales were acoustically detected on a single MARU within the array shown in Figure 2. No minke whale calls were detected during this month.

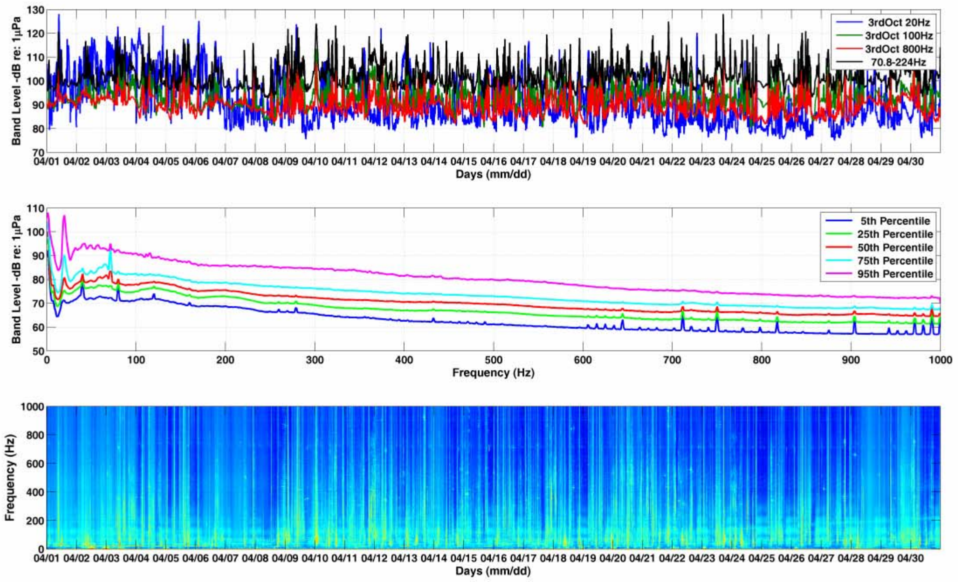

Figure 4. Received sound levels (71-224Hz, 20, 100 and 800 Hz 1/3rd octave bands; dB re 1µPa), percentages of time above several received level thresholds, and spectrogram (frequency vs. time) for the month of April 2008 at a single MARU within the array shown in Figure 2.

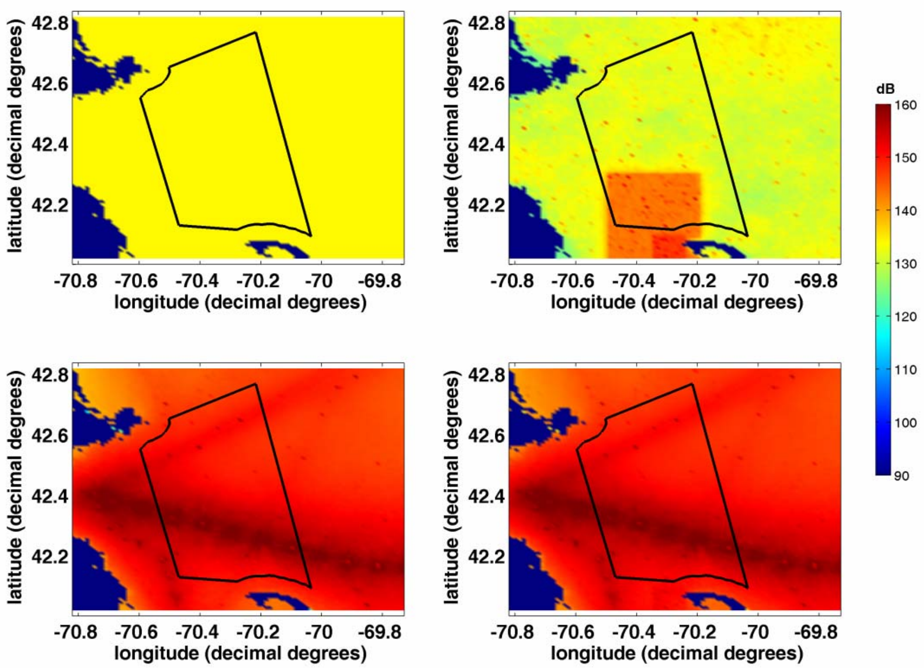

Figure 5. Summation of month-long (April 2008) contributions to total predicted received sound levels (71-224Hz, dB re 1μPa) in the modeling area (bottom right) due to wind-generated noise (top left), calling right whales (top right), and AIS-tracked large commercial ships (bottom left).

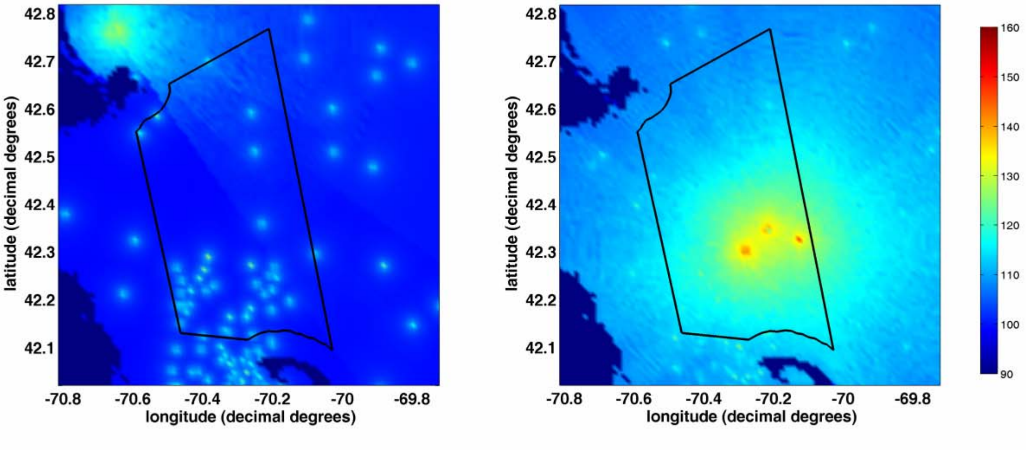

Figure 6. 10-minutes snap shots of received sound levels (71-224 Hz, dB re 1μPa) in the modeling area during a time with one distant (left) versus three central (right) AIS-tracked large commercial ships.

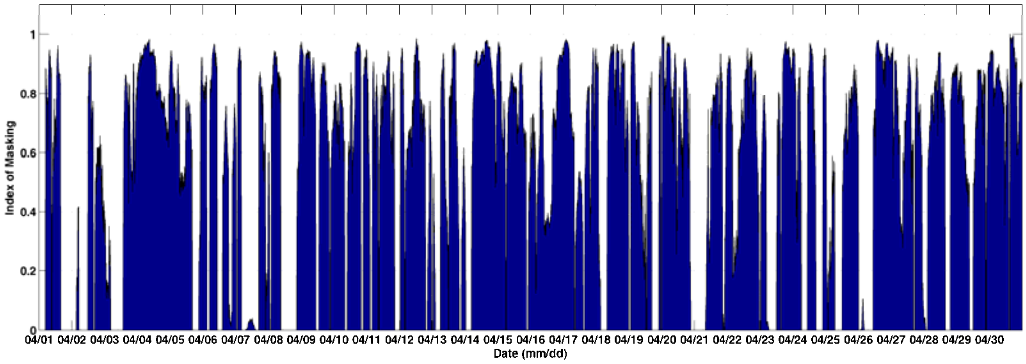

Figure 7. Right whale communication masking index within the modeling area calculated every 10-minutes during the month of April 2008.

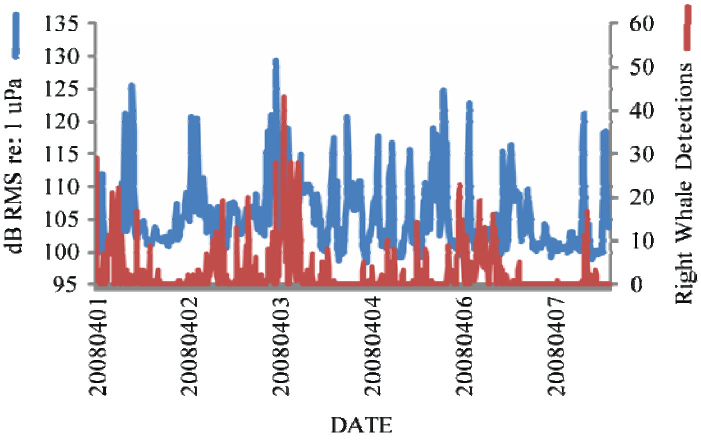

Figure 8. Received sound levels (blue, 30-400Hz dB re 1µPa) and numbers of detected right whale calls (red) for 15-minute time bins recorded on a single MARU in the array (Figure 2) on 1-7 April 2008.

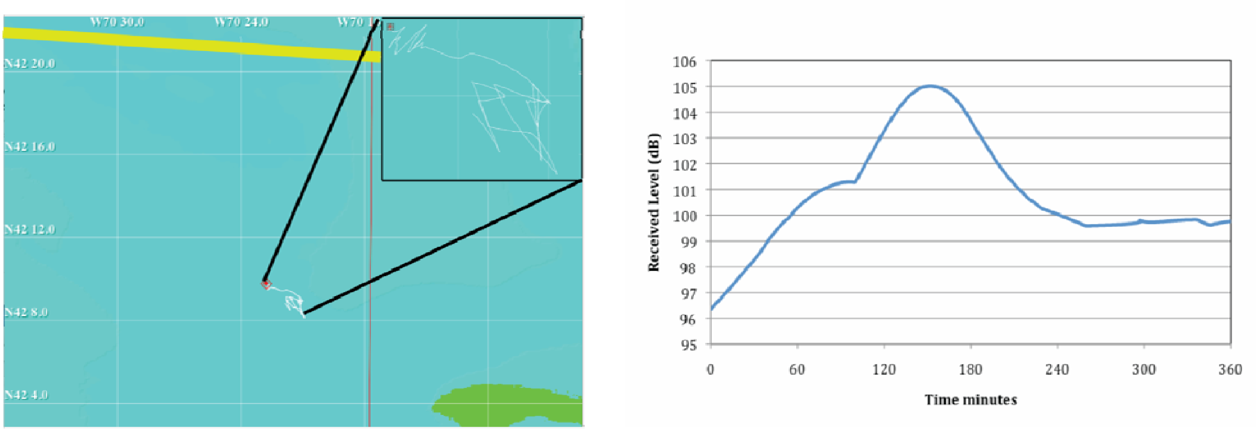

Figure 9. An MARU-tracked right whale acoustic group (left, inset), an AIS-tracked cargo ship M/V Teng He (left, yellow line) and the AIM-predicted received sound levels experienced by the acoustic group during the passage of the ship (right) on 3 April 2008.

IMPACT AND APPLICATIONS

National Security

The Stellwagen NOPP Project is producing a suite of transferable tools for assessing contributions from several sources of noise to the underwater noise budget in an area of interest. These tools are valuable for assessing and contextualizing the place-based environmental impacts of defense-related activities, including training range development, sonar use, and high-density vessel activities.

Quality of Life

By describing changes in the acoustic environment of marine animals over biologically-relevant scales and assessing the impacts of these changes on marine animals this project will better inform managers and the general public on decisions regarding how best to minimize and/or mitigate the costs of human activities in the coastal environment. Tools created as part of the Stellwagen NOPP 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) are included in national, regional and international marine spatial planning initiatives.

Science Education and Communication

Upcoming forums that will showcase the Stellwagen NOPP project include the 18th Biennial Conference on the Biology of Marine Mammals (Quebec City, Quebec; October 12-16 2009) and the Minerals Management Service-sponsored “Workshop on the Status and Applications of Acoustic Mitigation and Monitoring Systems for Marine Mammals” (Boston, MA; November 17-19, 2009). Three invited papers to be included in a theme section of the *Marine Ecology Progress Series* entitled “Applications of Acoustics in Exploring Marine Ecosystems and the Impacts of Anthropogenic Sound” (expected publication late fall-winter 2009-10) will highlight results from this NOPP research.

TRANSITIONS

National Security

Quality of Life

Methodologies being developed for the Stellwagen NOPP Project are also being 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, Cornell is gaining new ways of calculating and communicating the contributions of multiple source types to the sanctuary and surrounding waters as a result of this NOPP-funded research. Additional contracts to provide passive acoustic monitoring in Arctic waters coincident with seismic exploration for oil and gas resources have also been supported by the NOPP setting for tool development.

Science Education and Communication

The sanctuary’s website continues to be supplemented to provide information on the project and on noise in the marine environment (http://stellwagen.noaa.gov/science/passive_acoustics.html). In 2009, materials from the Stellwagen NOPP Project were included in the “Oceans Today Kiosk”, part of the Smithsonian National Museum of Natural History’s new Oceans Hall. Project PIs also hosted a symposium at the International Marine Conservation Congress (Washington, DC; May 2009) entitled “An Ocean Noise Forum: Passive Acoustic Technologies, Impacts and Solutions for The Marine

Environment". This symposium was focused on the use of passive acoustic tools in marine conservation research and management and highlighted examples from the Stellwagen NOPP project. Project PIs and a colleague from the NOAA Ocean Acoustic Program (NMFS S&T) served as panelists. The symposium attracted 60+ attendees from groups as diverse as the U.S. House of Representatives, Resources Committee, NSF, US Navy, the World Shipping Council, CORE, IUCN, NRDC and numerous academic and industry scientists, leading the development of new relationships, partnerships, and recognitions through group discussions and recommendations for ways forward. Additional 2009 domestic and international ocean noise policy forums that highlighted the Stellwagen NOPP Project case study included the International Conference on Marine Mammal Protected Areas (Maui, Hawaii; March 2009), the 157th Meeting of the Acoustical Society of America (Portland, Oregon; May 18-22 2009), the National Meeting of Marine Mammals (Santa Domingo, Dominican Republic; June 29, 2009), Okeanos Workshops on Cumulative Impacts to Marine Mammals from Noise and Alternatives to Airguns for Seismic Exploration (Monterey, CA; August-September 2009), and the 4th International Workshop on the Detection, Classification and Localization of Marine Mammals Using Passive Acoustics (Pavia, Italy; September 10-13, 2009).

RELATED PROJECTS

The Stellwagen NOPP Project is related to two database development projects, one cumulative impact mapping project and one population modeling project. Sofie Van Parijs and Denise Risch provided OBIS-SEAMAP (http://seamap.env.duke.edu/) with an acoustic data set which is going to set the precedent for integrating acoustics into this database. This project will come on line later this year. NOPP acoustic data will be integrated when OBIS-SEAMAP is ready to receive it. Dr. Clark (Cornell) is collaborating with Dr. Andrew Pershing (University of Maine/Gulf of Maine Research Institute) to facilitate the use of passive acoustic data from the Stellwagen NOPP project in the Whale Habitat Informatics Project (WHIP, http://gmri.org/whales/). 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 (200 nm offshore). 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 the input of noise from large commercial shipping in these maps. Finally, following initial discussion at an Okeanos-sponsored workshop in August 2009, Stellwagen NOPP project PIs are engaged in a working group to create a model of the population consequences of noise on feeding North Atlantic right whales using data collected in Massachusetts Bay (including NOPP project data).

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