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

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LONG-TERM GOAL

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.

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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 interpret the scientific results.

APPROACH AND WORK PLAN

Well-established passive acoustic technologies and a mixture of existing and newly-developed methodologies are applied to meet the goals of this project. Arrays of Autonomous Recording Units (ARUs), deployed since December 2007[1], are gathering low-frequency acoustic data within the Sanctuary for a continuous 30 month period. ARU 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. Methodologies are developed to combine ARU 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. The locations 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 tools are built as modifications 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). Data from digital tags (Johnson & Tyack 2003) placed on individual humpback whales are analyzed relative to sound fields measured from the ARUs in order to improve parameter values of 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 ARUs, 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. Richard Merrick and Dr. Sofie Van Parijs oversee NEFSC's project responsibilities, including refurbishment of ARUs, 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. Dr. David Wiley and Dr. Leila Hatch oversee the SBNMS's project responsibilities, including hiring of the vessel and staff, scheduling of ARU 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.

In the upcoming year (October 2008-October 2009), 4 consecutive ARU arrays will be deployed, each collecting 3 months of data to address temporally and spatially-specific analytical goals. Analysis methods and tools built in AIM and Matlab/XBAT will continue to be fine-tuned to increase their efficiency and accuracy. Methods to quantify masking impacts and behavioral responses will be further

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[1] Project start dates were delayed until funding was available to Cornell University for hardware (October 2007) and to NOAA for analysis tasks (February 2008).

developed. Data from DTAGs will be integrated to inform parameter settings in these new tools. In addition to ongoing presentations at workshops, meetings and conferences, interfaces with outside databases will be further formalized and publications will be prepared to highlight emerging results.

WORK COMPLETED

Beginning in December 2007, consecutive arrays of ARUs were 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 completed within each array, and analyses-in-progress are compiled and updated via a project-wide, internet-accessible database system.

Two analysis frameworks were developed to merge whale detection/localization results, ship tracking results and ambient noise/wind speed results. The first framework utilizes generalized additive models/GAMs (Hastie & Tibshirani 1998) as implemented in R (R Development Core Team 2008) to assess the relative contributions of several predictor variables to the total noise recorded by the ARUs. Pair-wise relationships between predictor and response variables were explored using JMP (SAS Institute Inc. 2002). The second framework utilized AIM to create predicted received-level (RL) gridded surfaces for an area encompassing Stellwagen based on multiple empirical datasets in order to better understand changes in the communication ranges of marine animal signals. For this work, AIM used the Parabolic Equation propagation model version 5.0 (Zingareli et al. 1999), NOAA's 3 arc-second bathymetry database, Consolidated Bottom Loss Upgrade (CBLUG) with Class 2 setting, and a wind speed of 10 knots to create surface loss curves as per Urick (1983).

Experiments were conducted to empirically measure sound transmission loss (TL) within the array. Average RMS sound pressure levels were measured within the 200-385 Hz frequency band using the software program Raven (Charif et al. 2007), and for the 1/3rd octave bands covering frequencies 200-1000 Hz using a Matlab program called LTspec (Cortopassi 2007). All measurements were corrected for background ambient noise. TL data were used to validate propagation model choice in AIM.

Daily, weekly and monthly received levels (RLs) for two broad frequency bandwidths (10-400 Hz and 10-1000 Hz) and three 1/3rd octave bandwidths (center frequencies at 20, 100, and 800 Hz) were calculated for data from the first ARU array deployment (NOPP1: December 19 2007-February 17 2008). 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. Spectrograms and power curves for each ARU location were generated to display variation in received frequencies and acoustic intensity (dB re 1 μPa) over each of the days, weeks, and months analyzed. Five percent (5%) RL thresholds for 10-minute data samples recorded at the ARU nearest to an oceanographic buoy (GMOOS A01) were regressed against recorded wind speeds (meters/second per 10 minutes). Wind speed data from the oceanographic buoy was also used as a predictor variable in GAMs.

Whale and fish detection and localization analyses have concentrated on the development of species-specific automatic detector tools. Data collected during the first array deployment (NOPP1) were used to build detectors for fin whale song and haddock spawning sounds. The automatic detector for right whale up-calls, ISRAT (Urazghildiiev & Clark 2006), was run on NOPP1 data. Numbers of detections per ARU per 10 minutes were calculated and used as predictor variables in GAMs. In addition, the acoustic analysis software XBAT and a plug-in locator tool (Fristrup & Cortopassi unpublished) were used to locate individual fin and right whales. Source levels (SLs) for these calls were calculate in AIM from each call's location and RL, and an estimated TL for the site specific conditions. The resultant SL estimates, served as inputs to AIM in order to predict RLs for a hypothetical set of fin whales (20Hz 1/3rd octave) and right whales (100 Hz 1/3rd octave) distributed over the gridded area chosen for modeling.

All AIS data collected between December 2007 and March 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). AIS data for all vessels transiting greater sanctuary waters were used to determine closest points of approach (CPAs) to ARUs, and RLs at these CPAs were calculated for three, low-frequency 1/3rd octave bandwidths (centered at 20, 100 and 800Hz). AIM was applied to calculate vessel SLs within the three 1/3rd octave bands at times and locations of vessel CPAs. AIM was further applied to predict the time-series of RLs in each of the three 1/3rd octave bands over the gridded surface for the AIS-determined track of each transiting vessel. Empirical RL measures from ARUs were compared to AIM-predicted RLs. SLs derived from AIM and distances between each ARU and each vessel (from AIS data) were used to estimate per vessel RL contributions to each ARU for each 1/3rd octave band. Per vessel noise contributions were summed to estimate per ARU and average contributions from AIS-tracked vessels in each bandwidth. These vessel noise metrics were used as predictor variables in the GAMs. Finally, Matlab was applied to these multi-dimensional data to produce an empirically-based, spatio-temporal animation of ambient noise throughout the sanctuary.

RESULTS

Significant progress was made in developing methods to collect and integrate information regarding the relative contributions of human-introduced (shipping) and natural (wind and whales) sources of noise. Results from the two data analyses frameworks, using a single day (27 December 2007) as an example, are presented in Figures 1-4. Initial pair-wise comparisons among metrics designed to quantify contributions from different source types indicated a decrease in fin whale detection rates during the time period when a tanker was transiting the array and contributing high levels of noise to the 20Hz 1/3rd octave band. In addition, there is evidence that right whale detection rates increased during time periods when ambient noise levels in the 100Hz 1/3rd octave band were lower (Figure 3).

Further progress was made in utilizing AIM to predict received noise fields in greater sanctuary waters using ship location information, empirical data on whale calling rates and ambient noise levels, and estimated whale source levels from the NOPP1 array. In both the 20Hz and 100Hz 1/3rd octave bands, contributions from AIS-tracked ships dominated AIM-predicted noise fields. Figure 4 shows an example of the time-varying 100Hz 1/3rd octave receive level during a single, 10-minute sample on 27 December 2007 when two ships were transiting through the sanctuary. As can be seen, wind (Figure 4A) and calling right whales (Figure 4C) do not make a significant contribution to the total predicted noise field in the 100Hz 1/3rd octave band in the presence of large commercial ships (Figure 4D). Methodologies for displaying variation in the signal-to-noise ratio at sampling locations in the sanctuary over the course of the day and for visualizing variation in the communication ranges of located and/or tracked whales within the predicted noise field are now being developed.

Preliminary analysis of data from transmission loss experiments within the 2007 NOPP2 array using RLs measured at five different locations at ranges of 0.16 to 2.99 nautical miles from the source yielded a 17 * log(r) curve to best fit the data. Empirical RLs in the 200-385 Hz band and 1/3rd octave bands are now being compared with simulated RLs in order to validate propagation model choice in AIM.

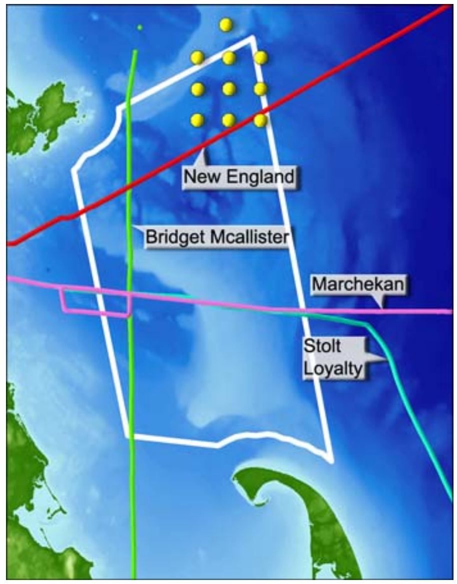


Figure 1. Plot of all AIS-tracked large commercial vessel traffic in the sampling region on 27 December 2007. Empirical data from the ten ARUs (yellow dots) were used to calculate vessels' source levels in AIM.

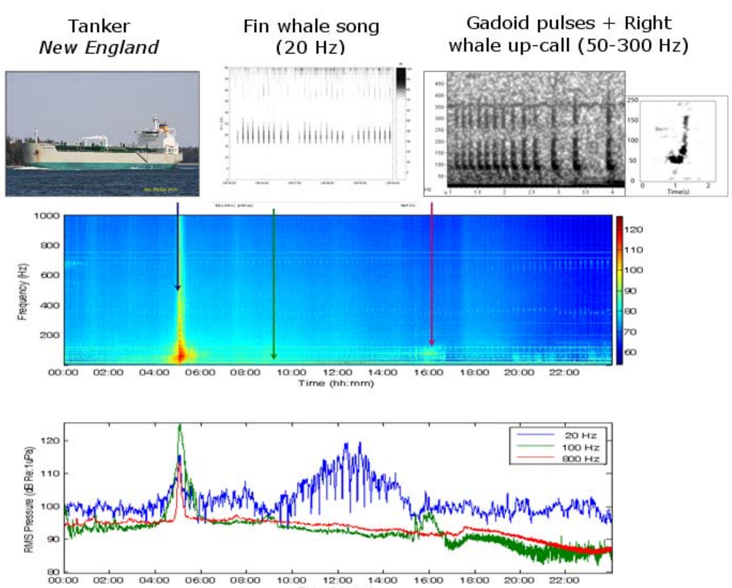
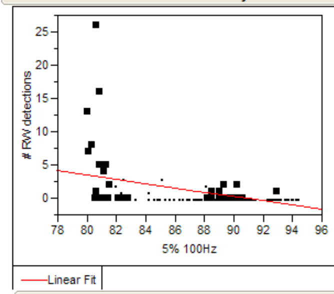


Figure 2. Long-term spectrogram and received levels over time for select 1/3rd octave frequency bandwidths from a single ARU location on 27 December 2007. Note peaks in received levels associated with a transiting commercial vessel and vocalizing whales and fish.

Bivariate Fit of # RW detections By 5% 100Hz



Linear Fit

RW detections = 29.445994 - 0.3232344 5% 100Hz

Summary of Fit

RSquare	0.202998
RSquare Adj	0.197385
Root Mean Square Error	2.662947
Mean of Response	0.770833
Observations (or Sum Wgts)	144

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	256.4751	256.475	36.1676
Error	142	1006.9624	7.091	Prob > F
C. Total	143	1263.4375		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	29.445994	4.773265	6.17	<.0001
5% 100Hz	-0.323234	0.053747	-6.01	<.0001

Figure 3. Results from preliminary bivariate logistic regression analysis indicating pattern of higher rates of right whale up-calling on 27 December 2007 during times with lower ambient noise in the 100Hz 1/3rd octave bandwidth.

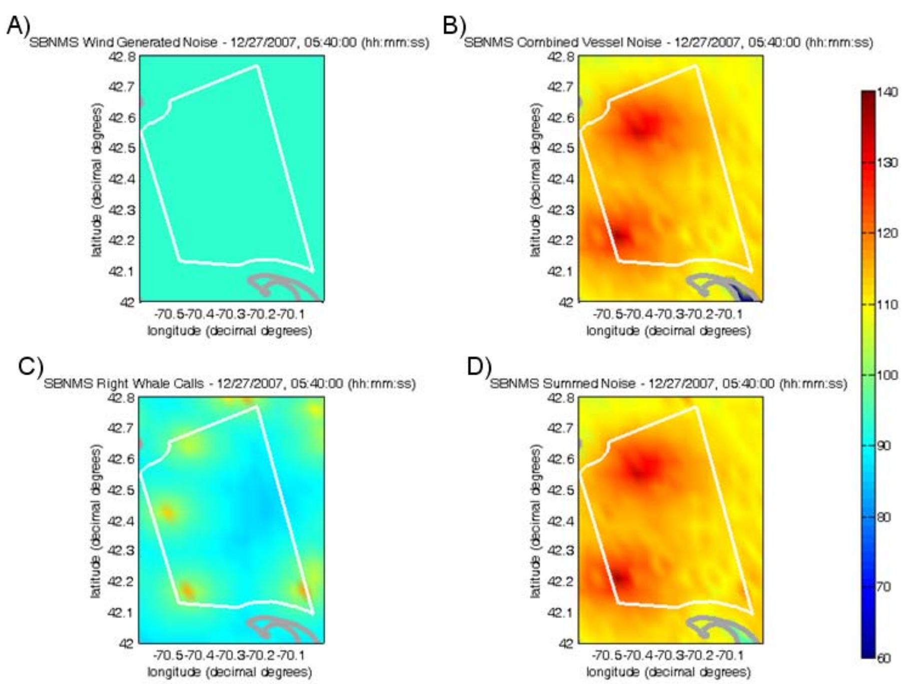


Figure 4. Spatial distributions of noise levels as contributed by A) wind, B) large commercial vessels, and C) up-calling right whale, and D) a summation of wind, vessels and whales. Noise levels were predicted by AIM for the 100Hz 1/3rd octave frequency band using empirical data from a 10-minute sample (05:40 - 05:50L) on 27 December 200. Noise level intensities (dB re 1µPa) are scaled according to the legend on the right.

Movement data from DTAGs deployed on humpback whales in 2006 were imported into AIM to inform NOPP animats[2]. RLs obtained from DTAG efforts in sanctuary waters[3] in July 2008 focused on a few tagging whales located within the NOPP acoustic array. In addition, movement data from 2008 tags will be used to assess responses of animals to vessel tracks and vessel noise (as modeled by AIM).

IMPACT AND APPLICATIONS

National Security

The Stellwagen NOPP Project will produce 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 will be 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.

Science Education and Communication

In 2009, materials from the Stellwagen NOPP Project will be included in the “Oceans Today Kiosk”, part of the Smithsonian National Museum of Natural History’s new Oceans Hall. Our work will also be highlighted on the History Channel as part of a series on the Evolution of Communication and Hearing (scheduled to air in 2009). Project PIs have submitted a proposal to host 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. Finally, three invited papers submitted for inclusion in a theme section of the *Marine Ecology Progress Series* entitled “Applications of Acoustics in Exploring Marine Ecosystems and the Impacts of Anthropogenic Sound” highlight results from this NOPP research.

TRANSITIONS

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.

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[2] An animat is the AIM term for an artificial animal with positional and movement data governed by AIM parameters.
[3] The collection of data using DTags in FY 2008-10 is not funded by this NOPP award; however these projects were planned to support one another and allow for data exchange when possible.

Science Education and Communication

Following a press release (http://www.nefsc.noaa.gov/press_release/2008/SciSpot/ss0804/) on the Stellwagen NOPP project, this work was highlighted in several newspapers, a television news segment (http://www.thebostonchannel.com/environmental/17428686/detail.html), and a radio segment (http://streams.wgbh.org/online/play.php?xml=cape2/science/oceannoise.xml&template=cape_audio). In addition, the sanctuary's website has been supplemented to provide information on the project and on noise in the marine environment (http://stellwagen.noaa.gov/science/passive_acoustics.html). Finally, the Stellwagen NOPP Project has been highlighted as a case study within several domestic and international ocean noise policy forums in 2008, including the Okeanos Workshop on Shipping Noise and Marine Mammals (Hamburg, Germany; April 2008), the NOAA Workshop to Identify and Assess Technologies to Reduce Ship Strikes of Large Whales (Providence, RI; July 2008), and the North Atlantic Right Whale Consortium Meeting (New Bedford, MA; November 2008).

RELATED PROJECTS

The Stellwagen NOPP Project is related to two ongoing database development projects: OBIS-SEAMAP http://seamap.env.duke.edu/ and the Whale Habitat Informatics Project (WHIP) http://gmri.org/whales/. On April 16-18, 2008 Sofie Van Parijs (NEFSC), Denise Risch (NEFSC) and Chris Clark (Cornell) attended a workshop on integration of passive acoustic monitoring data sets into the OBIS-SEAMAP data archive at the Duke University Marine Laboratory in Beaufort, NC. The 2008 workshop focused on how to integrate passive acoustic data from numerous platforms into OBIS-SEAMAP. 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).

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