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 GOALS

The 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 were 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

Well-established passive acoustic technologies and a mixture of existing and newly-developed analytical methods were applied to meet the goals of this project. Arrays of Marine Autonomous Recording Units (MARUs), deployed since December 2007, gathered low-frequency acoustic data within the sanctuary for a continuous 30 month period, ending May 2010. MARU data were 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 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 signatures of ships and marine animals were merged in order to investigate the potential for ocean noise to mask animal sounds and/or otherwise impact vocally-active species. These data were input into tools either as modifications to the Acoustic Integration Model/AIM (Frankel et al. 2003) or as Matlab plug-ins that interfaced 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 were used to improve parameter values of whale distribution, 3-D whale movements and behavioral responses.

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). Dr. Christopher Clark’s team at Cornell supplied calibrated MARUs, synchronized acoustic data files, and developed analysis tools for quantifying and mapping ocean noise. Dimitri Ponirakis was a central member of the Cornell analysis team. Dr. William Ellison and Dr. Adam Frankel at Marine Acoustic Inc. collaborated with Cornell to upgrade AIM for vessel noise and total noise spatio-temporal calculations and mapping. Dr. Sofie Van Parijs oversaw NEFSC’s project responsibilities, including refurbishment of MARUs, partial staffing of field work, and whale and fish detection and distribution analyses. Denise Risch was a central member of the NEFSC team, which also included several NOAA-sponsored Hollings Scholars and graduate students. Dr. Leila Hatch oversaw 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 were central members of the SBNMS team.

WORK COMPLETED

Beginning in December 2007 and ending in May 2010, consecutive arrays of MARUs 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, and analyses-in-progress were compiled and updated via a project-wide, internet-accessible database system.

During this reporting year, continued progress was made in developing our understanding of sound propagation and transmission loss (TL) parameters in the SBNMS. Two additional field experiments were conducted (11 November 2009 and 14 May 2010) to gather further empirical data on TL. Refinements to previous experiments included: change in broadcast signal to include 30 individual 1-sec tones, ranging from 250-3676 Hz with logarithmic spacing; a change in broadcast positioning to include 17 stations ranging from 20 m to over 10,000 m from an individual MARU; and a change in bottom type such that one experiment was conducted over muddy bottom in water depth of approximately 83 m, and the other over sandy bottom in approximately 29 m water depth. Root-mean-square (RMS) sound pressure levels (SPL, dB re 1 µPa) were measured from the MARU recordings using LTSpec, a custom-built program written in Matlab (Cortopassi 2007). Data were adjusted to spectrum-level values and were corrected for background ambient noise. Additional modeling was conducted using AIM, including comparison of empirical data with both the Bellhop and the Kraken propagation models. The refinements in field methodology allowed for a more extensive dataset to be used for re-evaluation of the sound propagation modeling in this region.

Modeling efforts in 2009-10 focused on finalizing the analysis framework developed over the three-year project to integrate results from whale detection/localization, ship tracking, MARU RLs and physical environmental variables (wind, sediment type, CTD etc.). AIM was again used to create predicted species-specific RL surfaces throughout greater Mass Bay over the course of a month based on multiple empirical datasets within a 9,576 km^2 (90 km latitude, 106 km longitude) study area gridded into 1 km^2 cells (resulting in 7,538 unique offshore locations). Focus was placed on refining calculations of communication space variance for up-calling North Atlantic right whales (NARW) during the spring of 2008. 10-min 95% RL thresholds (bottom 5th percentiles) were calculated for a bandwidth representing NARW up-calling (71-224 Hz) at MARUs nearest to two oceanographic buoys in Mass Bay (GMOOS A01 and NDBC 44013) and regressed against recorded wind speeds (m/s per 10-min). The resulting relationship was used to estimate present-day ambient noise levels (NLs) throughout the modeling area during the month of April 2008. Per Clark et al. 2009, a reference value for ancient ambient NLs was set at 20 dB less than present-day conditions.

XBAT and the Correlation Sum Estimation (CSE) Tool (Fristrup & Cortopassi unpublished) were used compute locations (x, y) for all up-calling NARWs detected in December 2007-April 2008. Localization was used to identify the spatial and temporal characteristics of vocalizing NARW groups (termed ‘acoustic groups’) present within the array. Calling bouts were tracked by following patterns of calls made by groups across available channels. The end time of a bout was determined when calls ended, when there was an hour of silence, or when acoustic patterns became too confusing to follow. Calling rates, durations, and numbers of calls were estimated for all distinct bouts. SLs for 744 NARW up-calls located in April 2008 were calculated in AIM using their RLs and locations. AIM was used to model the April 2008 acoustic movement of NARWs in the modeling areas as “animats”[1], with distribution, calling intervals and SLs informed by data from MARU-located acoustic groups. The modeling area was again subdivided to create localized regions with perpetual lower and higher NARW densities, however AIM was modified to allow more regular movement between regions, more accurately reflecting visual and acoustic detection information. Finally, AIM was again used to generate a month-long, 10-min series of RLs from up-calling NARWs within the 71-224Hz band over the gridded surface.

SL estimates for AIS-tracked vessels in the modeling area in April 2008 based on RLs at closest points of approach (CPAs) to MARUs were repeated to incorporate more accurate TL modeling

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

and directivity of vessel noise. A preliminary assessment of SL directivity was undertaken using Matlab and focusing on RLs of 5 cargo/container ships, 6 tankers, 6 tug boats, 2 cruise ships, one military/law enforcement vessel and one fishing vessel as they approached and then passed within 10 km of a MARU in April 2008. At each point of RL measurement, relative bearing to the bow (0°) and distance between the vessel and the MARU were recorded and AIM was used to account for TL variation as the vessel passed the MARU. TL was added to RLs, providing estimates of the vessels' SLs relative to their bearings to MARUs. Patterns of directivity in source level that were consistent among sampled vessels of the same type were used to inform subsequent AIM modeling of sound propagation from all vessels of that type within the modeling area. For vessel types that did not show consistent patterns of directivity or for which multiple samples were not examined, sound propagation was modeled as omnidirectional. AIM was then again applied to predict the time-series of RLs from each AIS-tracked vessel within the 71-224Hz band over the gridded surface, and Matlab was used to sum all vessel noise fields and to create a gridded surface representing NLs from present discrete sources/shipping.

Matlab was used to sum 1-sec/10-min gridded RL surfaces for calling NARW, present discrete sources/shipping, present ambient noise, and ancient ambient noise to create month-long, empirically-based, 1 km^2-resolution animations of predicted NL variation. Signal excesses (SEs) for NARWs relative to various noise levels were calculated as presented by Clark et al. (2009). The index of right whale communication masking presented by Clark et al. (2009) was calculated to represent the relative differences between the communication space available to up-calling NARWs under ancient ambient versus present-day ambient, AIS-identified vessel and present-day ambient plus AIS-identified vessel noise conditions.

In addition, progress was made in developing and applying detectors to describe the acoustic behaviors of fin, humpback, and minke whales as well as haddock within the study area. An automated template detector was constructed in XBAT, based on spectrogram cross-correlation and using a single song unit found consistently throughout 2009 humpback whale song. A subset of recordings was co-evaluated by a human operator and the detector, revealing 90% detector efficiency. Recordings from 2009 were then analyzed for the presence of identified humpback song units, and the occurrence of this unit was taken as a proxy of singing. Each hour was scored for song presence or absence and used to calculate an index of mean hour/day with song. Clear song sessions appearing on multiple channels in April 2009 were identified, and the location of each singer was calculated using the CSE Tool. A new location was calculated every 60 seconds, allowing the singer to be acoustically tracked for the duration of the song session. Additionally, seasonal and diel patterns of fin whale 20 Hz pulses in 2008-9 were analyzed using an automated call detection algorithm developed in ISRAT (Urazghildiiev & Clark 2006). Detection data were binned as the number of 10-min bins with detections per month, as well as per day, and per hour. Song measurements were made on the best song bouts available from different periods of the year, using all available channels. Pulse characteristics (start/end frequencies, center/ median frequencies, bandwidth, # pulses in a song bout, pulse duration, inter-pulse-interval, # inter-sequence intervals, # long inter-sequence intervals, and song duration) were measured. Measured parameters were compared within and among seasons. Minke and haddock detectors were also developed using data from 2008 and 2009, and efficiency was evaluated through comparison of detector and hand browsed logs.

Finally, progress was also made in developing acoustic fields for non-AIS tracked vessels in the study area. Four different data sources were evaluated to conduct measurements of the sound profiles generated by small vessels (i.e., fishing vessels and whale-watching vessels) operating within the SBNMS. These data sources included: 1) acoustic events recorded when fishing vessels inadvertently trawled individual MARU units; 2) AIS tracks for fishing vessels transmitting AIS data;

3) vessel-monitoring-system (VMS) data for fishing vessels reporting their positions at time-spaced intervals, and 4) GPS data obtained from whale-watching vessels on transits to and from areas of cetacean concentrations. Acoustic and tracking data were compiled and reviewed for instances in which vessels passed within 2km of MARUs. When the signal-to-noise ratio of the closest-point-of-approach (CPA) was sufficient (at least 10dB above background ambient noise levels), received sound levels were calculated for multiple frequency bandwidths.

RESULTS

AIM was used to compare the empirical RL data from the November 2009 TL experiment with the values predicted by the Bellhop and Kraken transmission loss models. The geometry of TL experiments was replicated and propagation was predicted from the initial closest location directly above the MARU, out to a total distance of 11 km. The average difference between empirical and predicted received sound levels at 394Hz over a range of 200-10,900m was Xdb under the Bellhop model (Figure 1) and YdB & Zdb under the Kraken and PE models, respectively. The difference between empirical and predicted data at 929Hz over the same distance ranges was XdB (Bellhop), YdB (Kraken) and ZdB(PE). Based on these experiments, it was determined that the Bellhop model, using the Rayleigh scattering bottom loss model, is the best combination for propagation predictions within the SBNMS (Cholewiak and Frankel submitted).

RL values at the 5% RMS level on the two MARUs closest to the oceanographic buoys averaged 98.5 dB (SD=4.6, MIN=85.6, MAX=123.8 dB). Measured wind speeds were found to correlate significantly with 5th percentile RL values as measured by nearby MARUs (R^2=0.034; ANOVA F=5.7, p=0.02; slope 0.164; intercept 96.1 dB) (Figure 2).

The preliminary assessment of directivity based on a small number of vessel-to-MARU CPAs found that the 5 cargo vessels and the 2 cruise ships sampled showed similar patterns of RLs relative to bearing to the MARU: broadside measures (30-140º) were on average 5 dB higher than stern and bow measures (0-30º and 140-180º) (Figure 3). This pattern was used to model sound propagation for all cargo ships (n=27) and cruise ships (n=2). Directivity patterns among the remaining vessels sampled (tankers, tug boats, military/law enforcement and fishing) were either not consistent or sample sizes were not sufficient to support altering the default omnidirectional modeling pattern.

NARW up-calls were detected every day in April 2008, although not all MARUs detected calls on all days (Figure 4). A total of 22,423 unique up-calls were detected over the course of the month (e.g., calls detected by multiple MARUs were counted only once), averaging 747 calls per day throughout the array (SD=294 calls/day). Multiple NARW acoustic groups were distinguished based on the call times and locations (Van Parijs et al. In prep). Average up-calling rate among MARU-identified NARW acoustic groups in April 2008 was 0.47 calls/minute (SD=0.38, MIN=0.06, MAX=2.7 calls/minute) (Van Parijs et al. In prep). Based on the sample of 100 calls located within 2 km of a MARU, the estimated mean SL of NARW up-calls in the modeling area was 172 dB (SD=6.6 dB) within the 71-224 Hz band.

Figure 5 shows summations of RLs from up-calling NARWs and discrete AIS-identified ships within the modeling area during two 10-min frames selected to represent examples of "quieter" (top left, fewer AIS-tracked ships) and "noisier" (top right, more AIS-tracked ships) conditions. Maps of SE relative to PrA2 within these time frames visually depict the loss of communication space for up-calling NARWs during these quieter (bottom left) and noisier (bottom right) periods with less versus more commercial ship traffic, respectively. Average SE over the modeling area during the quieter time period was -1.0 dB (SD=6.8 dB) versus -8.8 dB (SD=10.0 dB) during the noisier time period. This relative difference was quantified by calculating masking (M) for these two time periods: during the noisier time period M=0.90, indicating a loss of 90 % of the communication space for the calling

NARWs in the modeling area relative to what they would have had available under ancient ambient noise conditions. During the quieter time period M=0.74, indicating a loss of 74 % of communication space relative to ancient ambient conditions for the same callers.

Multi-year analyses of seasonal variance in the presence of humpback song found consistent peaks in singing activity in the study area in the spring (March-May) and fall (September-November) (Figure 6). Mean hours of song/day varied among years, however, with more fall hours of fall song in 2008 than in 2009 (mean 2008=13.44 hours/day, SD=7.8; mean 2009=4.80 hours/day, SD=3.85). Analysis of humpback singer tracks to investigate the movement patterns of singing humpback whales within the SBNMS feeding ground is still in progress, as is assessment of SLs for located song units. Although fin whales were detected year-round, their pulses were less frequently detected during the summer months, with consistently high levels of singing activity between September and January (range between60 to 92% of song each hour for these months). There was not a significant diurnal trend in fin whale pulse detections.

Review of small vessel tracklines (Figure 7) determined that acoustic profiles could be generated for 4 whale-watching vessels and over 25 fishing vessels (thought to be unique vessels). The acoustic output of these vessels is considerably lower than that of large vessels (reported previously, Hatch et al. 2008); however, work is currently in process to integrate small vessel acoustic data to estimate overall acoustic contributions to the SBNMS acoustic habitat.

Ongoing research efforts are applying methodologies finalized here for quantifying acoustic communication space variation under different noise conditions within bandwidths utilized by and within time periods critical to fin, humpback, and minke whales and haddock. Progress reported here in characterizing the acoustic behaviors and distributions of these species as well as in mapping noise associated with small and medium vessel types constituted critical first steps in evaluating both signal and noise field conditions for these species during the time periods in which they are acoustically active within the study area.

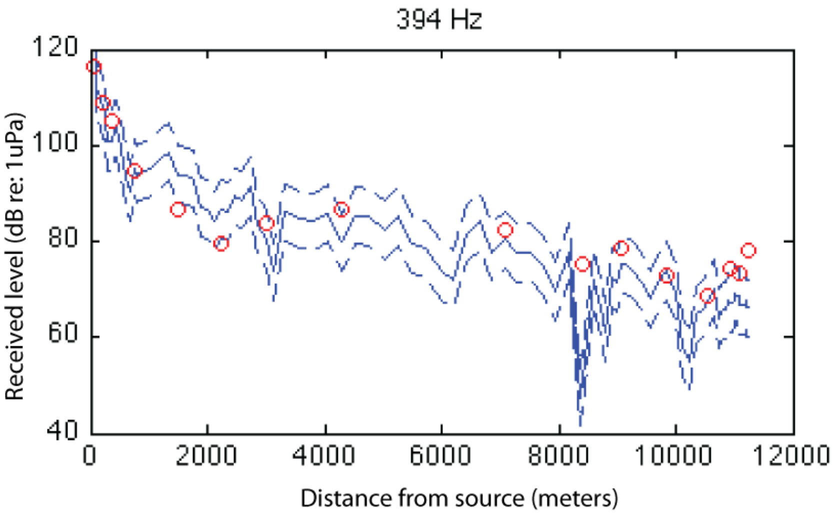

Figure 1 Sound propagation over distance for a transmission at 394Hz. Data represent empirical received levels (red dots) as measured during a sound propagation experiment conducted on 11 November 2009, and received levels as predicted using the Bellhop model (solid blue line). Dashed lines indicate ± 6dB.

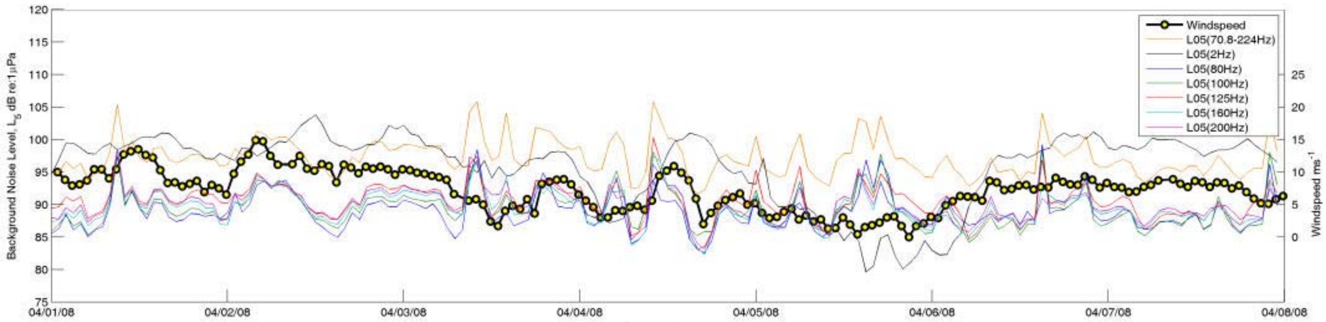

Figure 2. Average hourly wind-speeds (meters/second) recorded on two oceanographic buoys in Massachusetts Bay and 95th (bottom 5%) RL percentiles for six single frequencies and one broad bandwidth recorded on the closest MARU in the NOPP array during first week of April 2008.

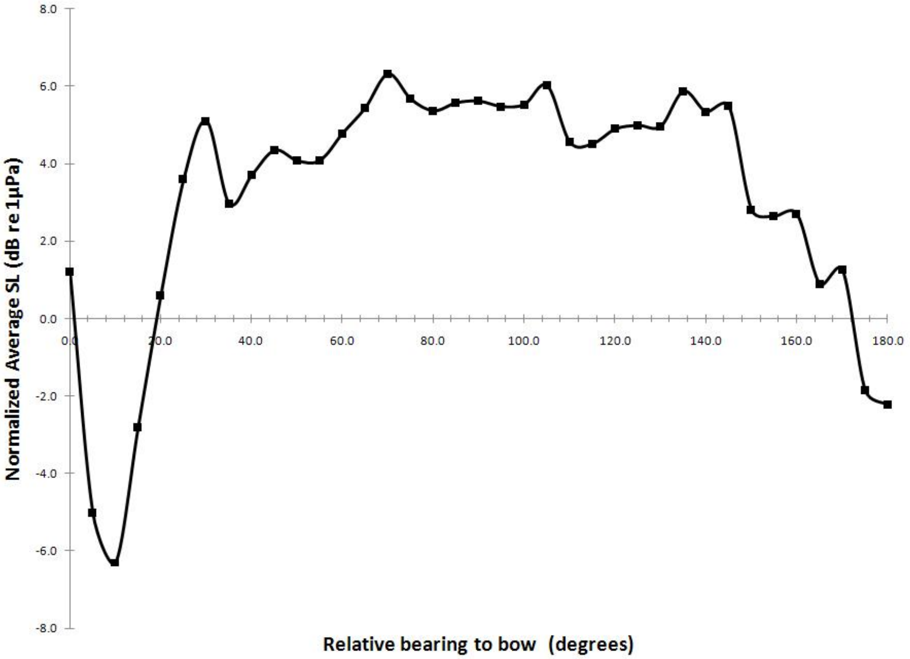

Figure 3. Results from preliminary directivity analysis for the close approaches of five cargo vessels to MARUs, showing normalized average source level (SL) within the 71-224 Hz frequency band versus relative aspect angle of the ship to the MARU (referenced to the bow of the ship, 0º).

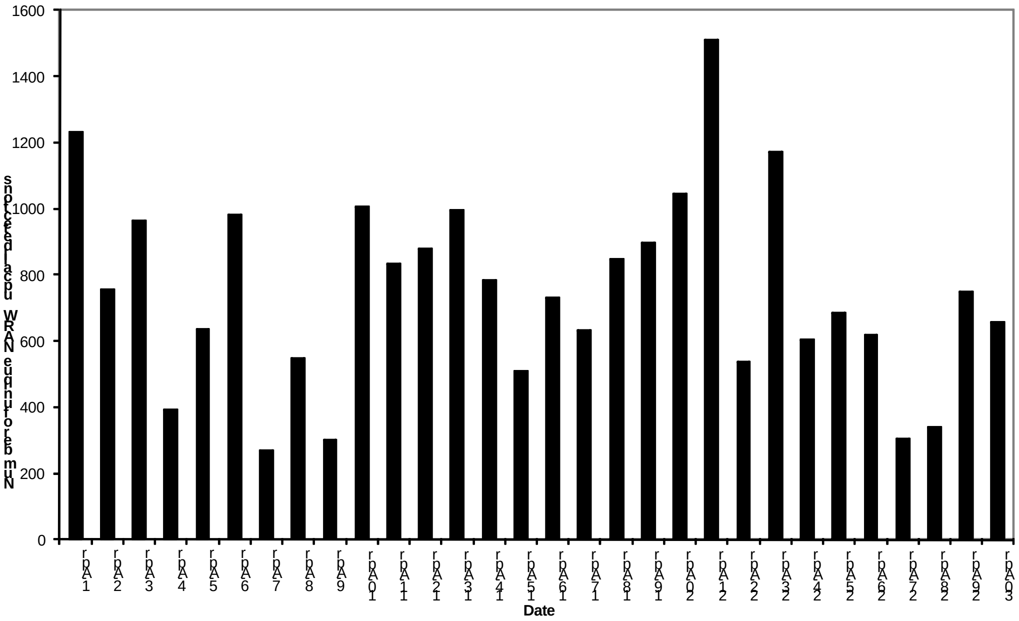

Figure 4. Number of unique North Atlantic right whale up-call detections within the NOPP MARU array during April 2008.

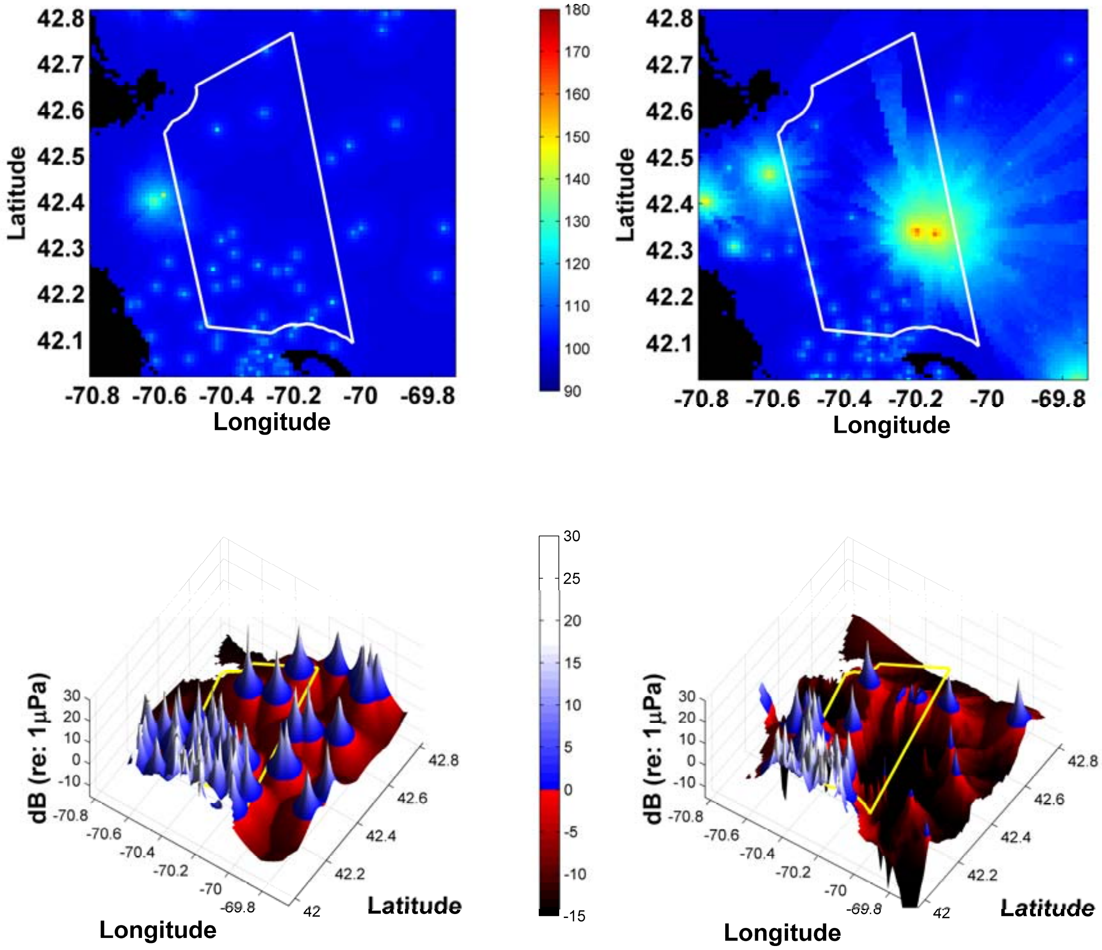

Figure 5. Spatial distributions of summed received levels (top) and signal excess (bottom) for up-calling North Atlantic right whales relative to noise from discrete AIS-identified ships (71-224 Hz, RMS re 1 µPa) during two 10-minute samples selected to represent quieter (left) and noisier (right) samples.

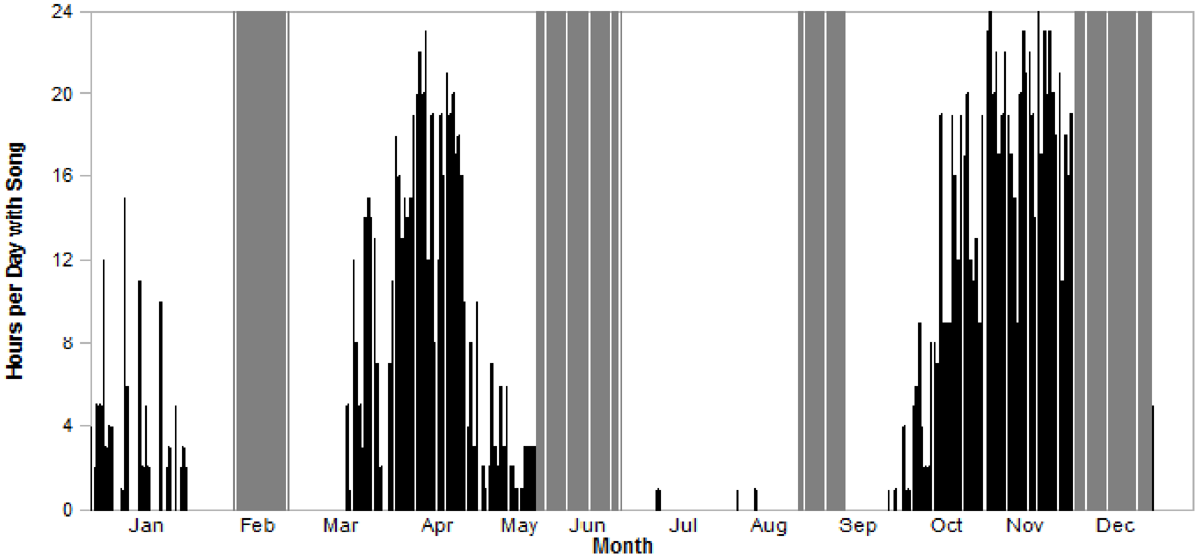

Figure 6. Humpback whale song occurrence (mean hours/day in which identified song units were detected) in 2008 with shaded areas representing data gaps.

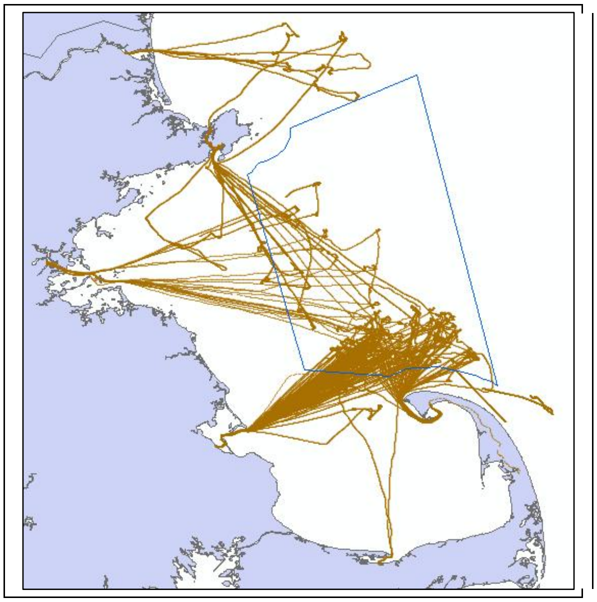

Figure 7. Sample tracks of whale-watching vessels operating within the SBNMS region in 2009, generated using GPS data.

IMPACT/APPLICATIONS

National Security

The Stellwagen NOPP Project produced 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 that introduce noise into 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 noise-generating activities (i.e. shipping noise) are included in national, regional and international marine spatial planning initiatives.

Science Education and Communication

Results from this project will be portrayed in an article on ocean noise produced for *Scientific American* in fall 2010. Three scientific papers associated with this research, one focused on sound propagation modeling, one on communication masking of North Atlantic right whales and one on seasonal and diel presence of humpback whale song have been submitted for publication and are currently under review. One paper on communication masking for four species of baleen whales in preparation, as well as one on right whale calling behavior, and several on Minke whale acoustic behavior. . Project PIs will highlight this work in presentations at a Cumulative Effects Workshop [Arlington, VA, Oct 2010, CW Clark], the American Cetacean Society Annual Meeting [Monterey, CA, Nov 2010, CW Clark, keynote address], a workshop on Offshore Energy Development (Cornell University, Dec 2010 CW Clark, the 3rd Conference on Animal Acoustic Communication Conference [ASA, Cornell University, Aug 2011, CW Clark] and We are currently working on a Ocean sound exhibit which will integrate some of this projects work, for the NEFSC aquarium in Woods Hole. This exhibit will be designed to inform and educate the public visiting the aquarium about the sounds of marine mammals and human made noise interactions.

TRANSITIONS

Quality of Life

Methodologies being developed for the Stellwagen NOPP 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 sanctuary and surrounding waters. 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 sanctuary's website was supplemented to provide information on the project and on noise in the marine environment (http://stellwagen.noaa.gov/science/passive_acoustics.html). Between October 2009 and September 2010, the Stellwagen NOPP project was highlighted in several public media pieces, the *Washington Post* (March 2010, "30 years of the MMPA and ESA"), *Science* magazine ("Changing Oceans" Special Issue, June 2010, including an on-line podcast interview Dr. Hatch). In July 2010, the SBNMS installed two new kiosks at the Cape Cod National Seashore and a state park on the tip of Cape Ann to provide information on tracking ships in the sanctuary via AIS and noise impacts. Project PIs highlighted this project's results in presentations within a diversity of forums, including a AAAS symposium invited paper (San Diego, CA, 11 Feb 2010), the 18th Biennial Conference on the Biology of Marine Mammals (Quebec City, Quebec; October 12-16 2009), 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), 159th Meeting of the Acoustical Society of America (Baltimore, MD; 19-23 April 2010), 62nd meeting of the International Whaling Commission's Scientific Committee (Agadir, Monaco; June 2010**),** the World Ocean Council (Belfast, Ireland; 16 June 2010), a Navy-NOAA sponsored workshop on Marine Mammals and Sound (Washington, DC; July 14-15 2010), and an ONR-sponsored workshop on Population Consequences of Acoustic Disturbance (Woods Hole, MA; 7-9 September 2010). Three invited papers 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" (December 2009) highlighted results from this NOPP research (see publications list below).

RELATED PROJECTS

The Stellwagen NOPP Project is related to two database development projects, a cumulative impact mapping project and a 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 is 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 Pershing's 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 working groups 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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