Where the Decibels Hit the Water: Perspectives on the Application of Science to Real-World Underwater Noise and Marine Protected Species Issues

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It is critical to try to avoid or mitigate potential impacts of man-made sounds on protected marine species.

Understanding the potential impacts of man-made underwater sound on the marine environment is a complicated and often controversial issue. Working as a scientist for over eight years at the National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration (NOAA), a US federal agency, has afforded me a unique perspective on the importance and challenges of applying science to real-world issues associated with underwater noise and marine protected species. This article shares and highlights some of those aspects.

Role of the NMFS in Protecting Marine Species from Human Impacts

The Office of Protected Resources in the NMFS, where I work, is responsible for conserving, protecting, and recovering species and their habitat under two primary US environmental statutes, the Endangered Species Act (ESA) and Marine Mammal Protection Act (MMPA) (NMFS, 2014a,b). We do this with our nationwide five regional offices and six science centers and in partnership with environmental and industry groups, other federal and state agencies, and the academic community.

NMFS has jurisdiction over approximately 212 protected marine species, of which 125 are listed under the ESA as endangered or threatened. These species range from seagrass and invertebrates (e.g., abalones and corals) to fishes, sea turtles, and marine mammals (cetaceans: whales, dolphins, and porpoises; pinnipeds: seals and sea lions). One of our primary responsibilities is to protect marine species and their habitats from threats associated with human activities such as bycatch in fishing gear, habitat destruction, overfishing, and ship strikes. Our responsibilities also include exposure to man-made underwater sounds, which is the focus of this article.

History of NMFS Acoustic Thresholds and US Regulation of Underwater Noise

The underwater marine acoustic environment is inherently noisy as a result of many natural (e.g., wind, earthquakes, and biologics) and man-made sound sources (Wenz, 1962; National Research Council, 2003). These man-made sounds are produced either intentionally for a particular purpose, as in the case of tactical and scientific sonar or air guns used for geophysical or scientific exploration, or

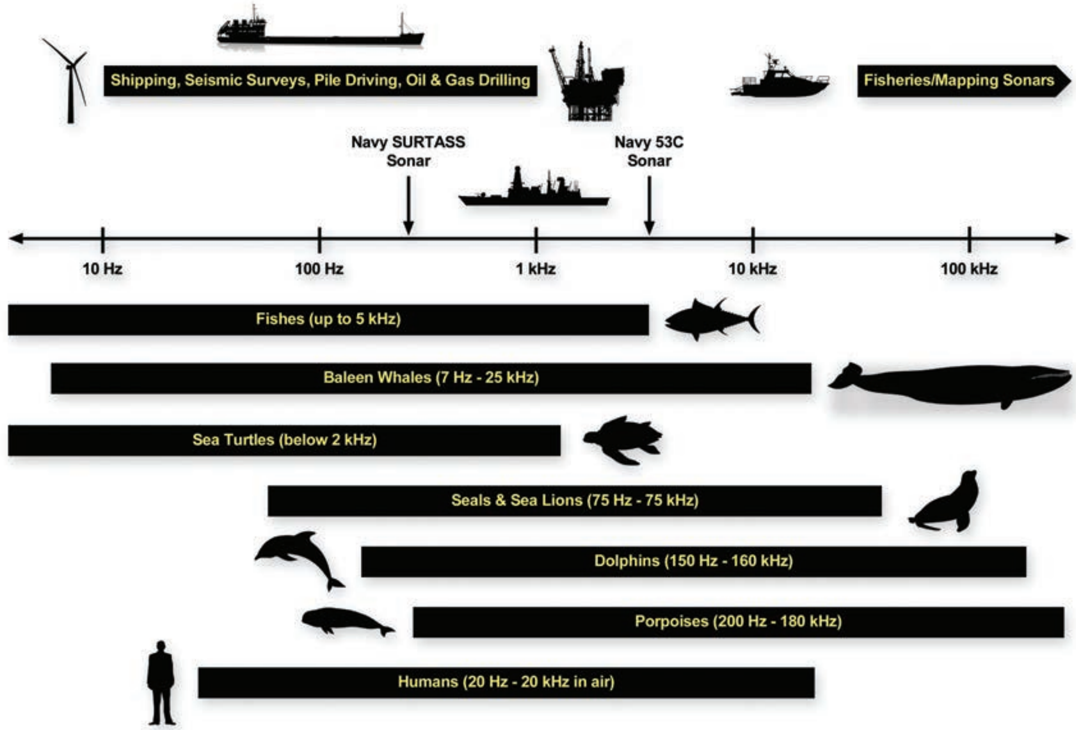

Figure 1. *General overlap between the auditory range of marine species and frequencies produced by man-made underwater sound sources. Human hearing range is provided as a reference. Note: hearing thresholds are not available for all species (e.g., baleen whales), so other data are used to predict hearing ranges (e.g., anatomy, vocalizations, and behavioral responses to sound). SURTASS, Surveillance Towed Array Sensor System.*

incidentally as a by-product of operation, as in the case of sources associated with pile driving, drilling, or shipping.

The ability to accurately detect and interpret the relative importance of sounds in the surrounding environment as well as to communicate, navigate, and detect predators and prey is critical for many species living in the ocean where hearing is often their primary sensory modality (i.e., sound is capable of traveling over much greater distances compared with light in the marine environment). As a result of the diversity of marine life in the ocean, there is a wide range of frequencies at which different animals use and hear sounds. Furthermore, there are numerous man-made sources in the marine environment with varying acoustical and physical characteristics. Many of these sources produce sound that overlap in space, time, and frequency (**Figure 1**) with those used by marine species. Thus there is a need to understand the impacts of man-made sounds on marine life and find and implement measures to avoid or mitigate impacts while still acknowledging the importance of the ocean to our economy and national security.

Concern over the impacts of man-made sound sources on marine species has been an issue for over 40 years (Payne and Webb, 1971). Some of the first activities to receive permits from NMFS in the 1990s were the acoustic thermometry of ocean climate (ATOC) program (Au et al., 1997) and the scientific research program associated with the US Navy Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) program (Croll et al., 2001; Fristrup et al., 2003). Since that time, the mass stranding of beaked whale species associated with the use of tactical midfrequency on multiple occasions (Cox et al., 2006; Ketten, 2014) acted as "focusing events" for the public's interest and awareness of the issue of underwater noise and protected species, in particular marine mammals.

Under both the MMPA and ESA, activities that expose protected species to certain sound levels may result in a "take" of the species and therefore require a permit or, in the case of a federal agency action, consultation with NMFS. "Take" is defined in the two statutes as to harass, hunt, capture, or kill or attempt to harass, hunt, capture, or kill any marine mammal under the MMPA and to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect or to attempt to engage in any such conduct under the ESA. Take is authorized under the MMPA if it is to have no more than a "negligible impact" (i.e., is not reasonably likely to adversely affect the species or stock through effects on annual rates of recruitment or survival on those marine mammal species or stock) or under the ESA if it does not jeopardize the continued existence of a species or destroy or adversely modify critical habitat (NMFS, 2014c,d).

The NMFS first established marine mammal acoustic thresholds in the late 1990s to help members of the public and other federal agencies (hereafter referred to as "applicants") seeking take authorization to determine under what circumstances take is likely to occur. Generic acoustic thresholds were developed for auditory injury based on expert opinion (NOAA, 1998; High Energy Seismic Survey [HESS], 1999) because no direct noise-induced threshold measurements were available for marine mammals at the time. Additionally, existing observations of avoidance from free-ranging individuals, associated with noise exposure, were used to develop behavioral thresholds (e.g., Richardson et al., 1985, 1986, 1990) (**Table 1**).

Table 1: Generic NMFS marine mammal underwater acoustic thresholds.

Criterion	Threshold Root-Mean-Square Sound Pressure Level
Permanent threshold shift (auditory injury)	180 dB re 1 μPa (cetaceans) 190 dB re 1 μPa (pinnipeds)
Behavioral harassment associated with impulse sounds (e.g., seismic and impact pile driving)	160 dB re 1 μPa
Behavioral harassment associated with continuous sounds (e.g., drilling and vibratory pile driving)	120 dB re 1 μPa

Acoustic thresholds are used to estimate when animals are likely to be harassed, which results in an estimate of the number of takes on a species-by-species basis, and to inform the development of appropriate mitigation measures (e.g., shut-down procedures) targeted at reducing impacts. Acoustic thresholds are therefore an important tool used in the larger analysis of an activity.

The NMFS current generic acoustic thresholds are extremely simple, which has made them easy to implement for applicants as well as for NMFS analysts and managers. However, as new science becomes available and the understanding of potential impacts of man-made noise on marine species increases, the characteristics of what constitutes meaningful acoustic thresholds become more complicated, and our analyses regarding acoustic impacts should necessarily reflect this added complexity.

Accordingly, the NMFS has been working to reevaluate and update its acoustic thresholds, but various parts of these efforts have evolved at different paces. For example, underwater explosive thresholds for nonacoustic (lung and gastrointestinal tract) injury and mortality have been updated more recently, as have acoustic impact thresholds for tactical sonar (Southall et al., 2007; Finneran and Jenkins, 2012), whereas thresholds for behavioral harassment and airborne sources for pinnipeds are still under different stages of development. The goal is to establish consistent national guidance for all our acoustic thresholds, but we are first focusing on updating those associated with the effects of noise on hearing.

Developing Updated Acoustic Threshold Levels for Impacts on Hearing

The NMFS, on behalf of NOAA, has proposed updated Acoustic Guidance (hereafter referred to as "draft Guidance") for assessing the effects of anthropogenic sound on marine mammal species under our jurisdiction (NOAA, 2013). Specifically, the draft Guidance focuses on the impacts of underwater noise on marine mammal hearing (i.e., updated acoustic threshold levels for the onset of permanent threshold shift [PTS] and temporary threshold shifts [TTS] for all sound sources). The draft Guidance is intended to be used by NOAA managers and other applicants to better predict exposures that have the potential to trigger certain requirements under one or more of NOAA statutes (e.g., MMPA, ESA, and the National Marine Sanctuaries Act, under a sister agency of the NMFS, the National Ocean Service). Although the acoustic thresholds often get a lot of attention because of the overall take numbers they help generate, they are but one tool utilized within a larger impact assessment to help evaluate the effects of a proposed activity on marine mammals and make findings required by our various statutes.

To develop updated threshold levels for auditory impacts, NOAA compiled, interpreted, and synthesized the best available information on the effects of man-made sound on marine mammal hearing. Additionally, because the draft Guidance is classified as a "highly influential scientific assessment" by the President's Office of Management and Budget (OMB), it was also required to undergo an independent peer review (OMB, 2005). The draft Guidance is significant for NOAA because it is the first time the agency has presented this information in a single comprehensive document to establish national guidance. In addition, the draft Guidance is created as a "living" document with a mechanism for updating it as new data become available.

The draft Guidance builds on previous scientific recommendations for acoustic threshold levels by Southall et al. (2007) because more is known about sound sources as well as about marine mammal acoustics and hearing than when our generic thresholds were first derived. However, as with any science field, there are data gaps and associated uncertainty (e.g., TTS data are only available for seven marine mammal species, from few individuals; PTS data are not available for marine mammals and so data for terrestrial mammals are extrapolated and used as surrogates). Nevertheless, NOAA used the best scientific information available in the development of updated Guidance.

With this in mind, NOAA has made significant advances in updating our acoustic thresholds levels by following similar approaches as those made for marine mammals by Southall et al. (2007) and for fishes and sea turtles by Popper et al. (2014). Specifically, the draft Guidance divides sound sources into two groups (impulsive and nonimpulsive) to reflect the higher potential for auditory injury from impulsive sounds associated with high peak pressures and fast rise times (e.g., explosives, seismic air guns, and impact pile drivers) compared to nonimpulsive sources (e.g., vibratory pile driving, drilling, and most sonars). The draft Guidance provides acoustic thresholds using dual metrics and the applicant uses whichever is most protective (i.e., results in the greatest amount of take). The dual metrics are (1) cumulative sound exposure level, acknowledging the importance of exposure duration, and (2) unweighted peak sound level associated with noise-induced hearing loss.

The draft Guidance also divides marine mammals into five functional hearing groups (low-, mid-, and high-frequency cetaceans and otariid and phocid pinnipeds) and employs auditory weighting functions to recognize that all marine mammals do not hear and use sound in the same manner. Because of these differences, it is difficult to make comparisons between results based on the use of our generic thresholds and results associated with the proposed updated acoustic thresholds. In some situations (e.g., depending on sound source, species, and duration of exposure), updated acoustic thresholds may result in more takes than previously applied thresholds, whereas in others they may result in fewer takes.

Thus the draft Guidance updated acoustic threshold levels are more complex than our previous acoustic thresholds. This added complexity is an important consideration for applicants who have formerly relied on two simple acoustic thresholds. Once the draft Guidance is finalized, along with any changes based on public comments and further consideration, our two thresholds for acoustic injury (i.e., 180/190 dB) will likely be replaced with 10 sets (5 functional hearing groups with different thresholds for impulsive and nonimpulsive sources) of acoustic thresholds, each with 2 new metrics, including one that incorporates duration of exposure (i.e., an applicant needs to incorporate how sources/animals relate to one another over both space and time to determine exposure). Because of the added complexity, the draft Guidance reflects the best available science on the potential for underwater noise to affect marine mammal hearing and will contribute to more meaningful analyses.

Importance of Stakeholder and Public Input and Implementation Challenges and Considerations

A critical component of Guidance development involves soliciting stakeholder input and public comment, which focuses on both the technical and application aspects of the document. This process ensures that NOAA transparently address and consider all aspects of implementing the acoustic thresholds before finalizing the Guidance.

The draft Guidance's initial public comment period occurred in late 2013/early 2014 (www.Regulations.gov:Docket ID:NOAA-NMFS-2013-0177). We received 129 comments (i.e., individual comments as well as letters containing numerous comments) from individuals and groups ranging from members of the public, Congress, and scientists to federal, state, and international government agencies and industry and environmental groups. Many individuals and groups provided substantive comments addressing technical aspects and/or issues relating to the implementation of updated acoustic threshold levels, which we will address via modifications to the Final Guidance as well as in the Federal Register, which will announce the finalization and release of the document. One example of a change based on based on public comment was the addition of a section to the Guidance on data gaps and research recommendations. Before the Guidance is finalized, there will be a second public comment period (July - September 2015) to address more recent updates (e.g., updated implementation methodology based on public comment as well as more recent scientific methodology developed since the draft Guidance was published for public comment).

As mentioned earlier, one of the most difficult challenges NOAA has encountered in finalizing the Guidance is ensuring that applicants can correctly implement the updated acoustic threshold levels given their inherent complexity. The issue of practicality is a fundamental consideration for the regulatory community but is not often encountered or even considered by most scientists in an academic setting. For example, NOAA must recognize that applicants have varying levels of ability (or budgets) to model sound exposure, ranging from sophisticated exposure models that can incorporate source and animal movement and propagation models to less sophisticated models that can only make very simplistic approximations. Often these modeling capabilities scale with the size of an activity (i.e., small construction project versus large multiday military training exercise), resulting in most applicants for large projects having sufficient modeling capabilities. Nevertheless, NOAA must ensure that those with less sophisticated means can use the more complex acoustic thresholds provided in the Guidance. As a result, NOAA is working on a companion "User Guide" to be released with the Final Guidance that will assist applicants to apply updated acoustic threshold levels correctly. Developing simple, alternative approaches that are broad enough to encompass the scope of activities authorized is challenging but essential for the Guidance implementation.

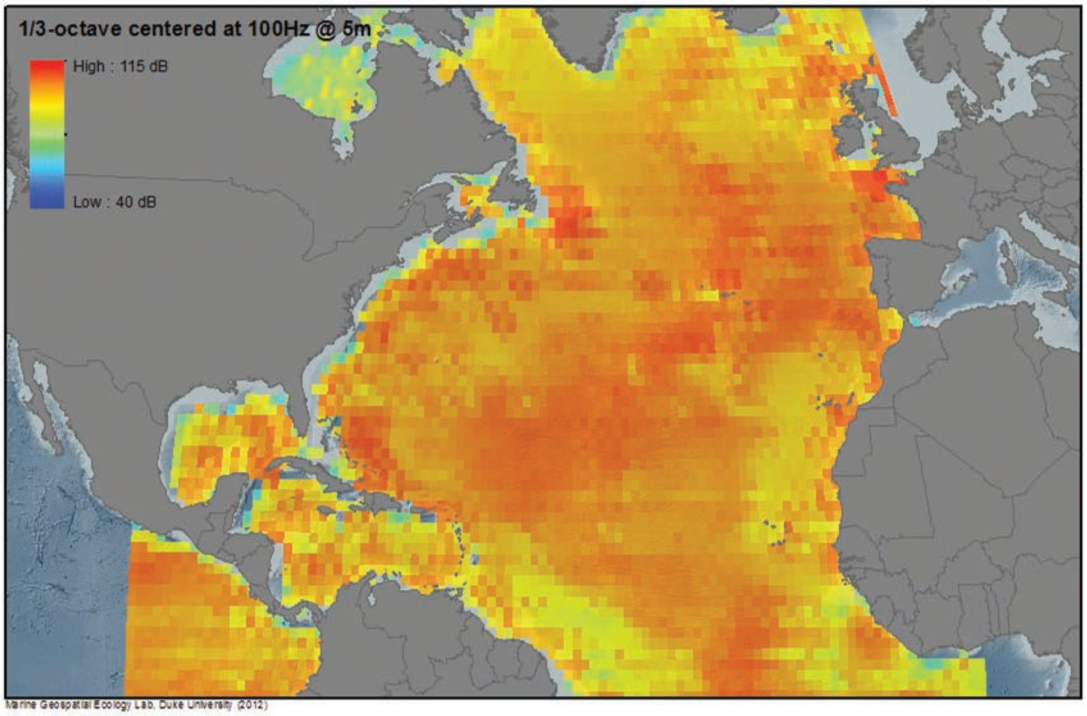

Figure 2. Unweighted annually averaged ambient sound pressure level for the Atlantic (1/3-octave band centered at 100 Hz at a depth of 5 meters) associated with global shipping created for the CetSound project.

Furthermore, NOAA recognizes that when the Guidance becomes finalized, applicants will be in varying stages of the application process. NOAA is considering how best to address applications and actions that are "in the pipeline" and will provide a transition plan when the Guidance is finalized (expected in late 2015).

Impacts Beyond Effects on Hearing

Although the physics associated with sound propagation in the ocean environment can be complex, with access to the proper tools and software, received levels can be estimated and predicted. However, understanding what a particular received level means to a marine species in terms of immediate behavioral responses and impacts to growth, survival, or reproduction as well as long-term consequences to populations is difficult. Due to the inherent complexity and variability of marine mammal behavioral responses, NOAA is starting the challenging process of developing national guidance for better predicting significant behavioral effects.

Although the focus of the draft Guidance is marine mammals, NOAA also must assess the potential for acoustic take for other species under its jurisdiction. Thus there is a need to establish national acoustic guidance for ESA-listed marine fishes and sea turtles and National Marine Sanctuary resources. Admittedly, NOAA is farther behind in its work addressing nonmarine mammal species (note: NOAA still is able to evaluate the impacts on these species via numerous means, including qualitative assessments or regional guidance). However, there have been numerous recent advances in understanding the impacts of man-made sound on these other important species that should facilitate the development of national guidance documents (Popper et al., 2014).

Chronic Noise Exposure and NOAA Cetacean and Sound Mapping Project

The acoustic thresholds mentioned above focus on discrete, often loud acute acoustic sources and their impact on marine mammals. However, NOAA recognizes that in addition to understanding acute sound sources, there is a need to better incorporate and consider chronic sound to comprehend the complete soundscape these protected species inhabit and the potential impacts of increased background noise on their fitness and habitat (Hatch et al., 2008; Slabbekoorn et al., 2010).

In 2011, NOAA convened two working groups, the Underwater Sound Field Mapping Working Group (SoundMap) and the Cetacean Density and Distribution Mapping Working Group (CetMap), with the overarching effort of both groups referred to as CetSound. These groups consisted of other federal agencies, academia, and industry to develop tools to map the contribution of human sound sources to underwater ocean noise levels and the overlap with cetacean density and distribution. The specific objective of SoundMap was to develop mapping methods to depict temporal, spatial, and spectral characteristics of resulting underwater noise from both acute (i.e., relatively short-term contributions to background ocean noise levels, like those from a discrete sonar exercise) and chronic (i.e., more long-term contributions to background noise levels, like those from commercial shipping) sound sources. These tools used environmental descriptors and the distribution, density, and acoustic characteristics of human activities within US waters to develop first-order estimates of their contribution to ambient noise levels at multiple frequencies, depths and spatial/temporal scales (**Figure 2**).

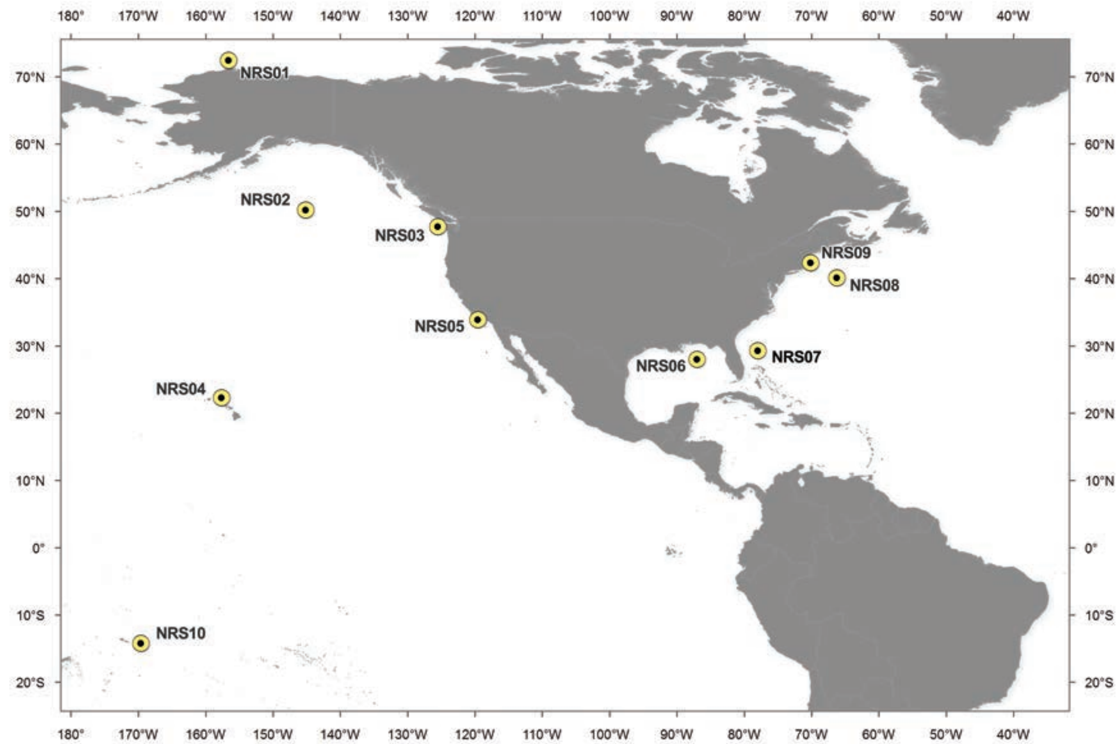

Figure 3. *Ten locations for the Ocean Noise Reference Station Network of the National Oceanic and Atmospheric Administration (NOAA). Map courtesy of Jeffrey Adams, NOAA.*

In conjunction with the mapping methods developed by SoundMap, the CetMap Working Group compiled and created maps to characterize cetacean occurrence, distribution, and density as well as to identify biologically important areas (BIAs; see Van Parijs et al., 2015a). BIAs are valuable because there is growing evidence indicating that contextual factors (i.e., behavioral state: reproducing, feeding, and migrating) play a role in the type and extent of an individual's response to sound beyond a simply received level (Ellison et al., 2012). Together, these tools are an important first step toward better characterization and management of cumulative noise impacts for cetaceans and can serve as a model for other marine species.

NOAA Ocean Noise Strategy and NOAA Ocean Noise Reference Station Network

After the successes of the CetSound project, NOAA began the development of a multifaceted, forward-looking Ocean Noise Strategy (Strategy), with the goal of articulating the agency's vision for addressing the impacts of underwater noise over the next 10 years. NOAA Strategy brings together both the science and management sides of the agency to create a more integrated and comprehensive approach for dealing with ocean noise impacts on protected marine species and their habitats.

One of the first accomplishments associated with NOAA Strategy is the development of an Ocean Noise Reference Station Network (ONRSN). The ONRSN is a NOAA initiative to establish a network of listening stations within US waters to obtain potentially important data on long-term changes and trends in the underwater ambient environment. Each listening station will consist of identical autonomous acoustic low-frequency (10-2,200 Hz) recording systems that will ensure proper calibration and consistency among the collected data sets and allow for more meaningful comparisons among different regions to assess biological and man-made contributions to the overall soundscape (Van Parijs et al., 2015b). The NOAA ONRSN is a collaborative effort between the NOAA Office of Oceanic and Atmospheric Research-Pacific Marine Environmental Laboratory, all NMFS Science Centers, and three of the sites within the National Ocean Service National Marine Sanctuary System as well as Cornell University, Oregon State University, and the National Park Service. There are 10 designated locations for the reference stations, with all being deployed by the end of 2015 (**Figure 3**).

Noise from Commercial Shipping and Working with the International Maritime Organization

With more attention turning from loud acute sources of ocean noise to lower level chronic sources, global commercial shipping has become a focus in terms of understanding its potential impact on the marine environment. This is primarily because of the contributions of these sounds to a rise in ambient noise levels in some regions over the last 50+ years (McDonald et al., 2008; Andrew et al., 2011; Bradley and Nichols, 2015) and its potential to interfere with marine species' acoustic communication and detection of biologically important sounds (Hatch et al., 2012).

One of the advantages of dealing with this source is that ships produces sound as a by-product of operation, making it an easier source to address compared to sources that produce sounds for a particular purpose (e.g., sonar or seismic). As a result, there has been a highly productive and proactive collaboration between federal agencies, academia, environmental groups, and various sectors of the shipping industry to recognize and work together on this issue.

NOAA first brought experts together to examine the issue of shipping noise in two symposia in 2004 and 2007 (Southall, 2005; Southall and Scholik-Schlomer, 2008). As a result of these symposia, it was recommended that the issue of shipping noise be introduced in the International Maritime Organization (IMO), a specialized agency within the United Nations that is responsible for the safety and security of shipping as well as the prevention of marine pollution by ships. Thus, with commercial shipping's broad impact spatially and temporally as well as its global nature (e.g., 90% of international trade occurs via commercial shipping; most vessels are flagged and built outside the United States; Maritime Knowledge Centre [MKC], 2012; United Nations Conference on Trade and Development [UNCTAD], 2014), it was logical that shipping noise could best be addressed via an international forum such as the IMO rather than strictly within NOAA.

In addition to work at the IMO, there have been other notable efforts (Southall et al., in press). For example, concrete targets to significantly reduce commercial shipping's contribution to ambient noise within 30 years have been established (Wright et al., 2008) as well as national and international measurement standards for measuring underwater sound from ships (American National Standards Institute [ANSI], 2009; ISO, 2015). Furthermore, the European Union, via the Marine Strategy Framework Directive, has set targets for achieving "Good Environmental Status," which specifically includes targets relating ambient noise in two low-frequency noise bands (centered at 63 and 125 Hz) directly to sounds associated with commercial shipping (Dekeling et al., 2014). Last, with sea ice reductions in the Arctic, there is heightened interest in understanding the potential impacts, including those from noise, from increased shipping in the region (Arctic Council, 2009; Moore et al., 2012; NOAA, 2014).

In April 2014, the IMO Marine Environment Protection Committee approved voluntary guidelines that provide advice to shipbuilders and operators on to how to reduce underwater noise from ships (IMO, 2014). The guidelines primarily focus on propeller design and modification to reduce cavitation but also consider hull design, onboard machinery, and operational modifications. Although establishing these guidelines is a big step forward, there is still much that needs to be done to keep momentum on this issue (e.g., better quantify how individual ship noise reduction corresponds with background region levels and the relationship between ship efficiency and noise production).

Final Thoughts

The role of NMFS is to translate available science into applied solutions for safeguarding marine protected species from the potential impacts of man-made underwater noise. Fortunately, significant recent scientific developments in understanding and predicting the impacts of underwater noise on marine species using various perspectives, forums, and techniques have provided additional tools needed to hone my craft of science-management translation. And, as we learn more about the effects of sound on marine species, our understanding becomes inherently more complex, reflecting the true diversity of the real world where these species live. Thus an essential responsibility for NOAA will always be to balance the cost/benefits of management solutions that are overly complicated and capable of implementation by a few with solutions that may be overly simplistic and unable to capture key components necessary for consideration as well as consider the potential consequences of being overly protective or not protective enough. Ultimately, effectively dealing with underwater noise and marine species takes both scientists and managers working together to set research priorities and ensure that the data being collected can be used to the greatest extent possible for the good of the marine environment. Although, I consider myself someone who bridges both worlds, I hope my perspective from a policy point of view has been useful. Finally, I urge managers to interact with scientists and use the best available science to support their analyses and scientists to reach out to managers to understand better their scientific and practical needs because the work they do is important and is the realm where the decibels really do hit the water!

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For more information about NOAA, see the following Web sites: NOAA Fisheries Office of Protected Resources at
http://www.nmfs.noaa.gov/pr/,
Acoustic Guidance at
http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm,
and CetSound Project and Ocean Noise Strategy at
http://cetsound.noaa.gov/.

Biosketch

Amy Scholik-Schlomer works for NOAA Fisheries, serving as the technical lead for acoustic issues within the Office of Protected Resources. She has a BS degree in Fisheries Management from The Ohio State University and a PhD in Biology from the University of Kentucky, where her dissertation focused on the effects of noise on fish hearing. She has been active in the field of bioacoustics for over 17 years and has been an author of several publications and reports as well as a presenter at numerous national and international conferences on the issue of underwater noise and marine protected species.

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