Reducing Noise from Large Commercial Ships

Progress and partnerships

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Increasing ensonification of our oceans by human sound sources has been identified as an important environmental concern, spurring intensive study by marine scientists during the past few decades. Guidelines and mitigation measures have been developed by regulators, and various sectors have sought ways to reduce noise in the ocean and its effects on marine life. Scientific research and recent national and international efforts continue in their attempts to quiet commercial ships, one of the leading contributors to noise in the ocean.

Radiated Noise from Individual Vessels

Ships generate various noises during normal operations. Modern-powered vessels produce low-frequency sound from hydrodynamic flow noise, onboard machinery, and primarily propeller cavitation. Wenz (1962) provided early characterization of natural and anthropogenic ocean ambient noise, including typical low-frequency noise spectra from differing levels of shipping activity. Many subsequent measurements of different classes of large vessels (e.g., Wales and Heitmeyer, 2002) have informed broad characterizations of vessel noise (e.g., McKenna et al., 2012).

Ship noise is predominately low-frequency—<1000 Hertz [Hz]. Source level and frequency spectrum depend on factors such as vessel size, speed, load, condition, age, and engine type. Larger vessels (exceeding 100m)

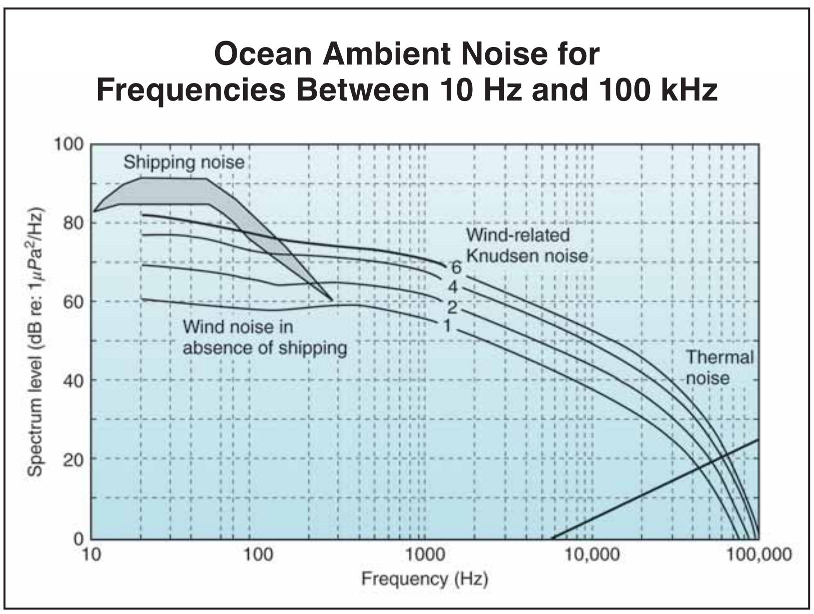

Figure 1. This figure shows typical underwater noise profiles developed by Wenz (1962), but has been modified to reflect modern levels of shipping noise (shaded area), which exceed natural wind noise, even for high sea-states (numbered curves). Figure adapted from Hildebrand (2009), reprinted with permission of J. Hildebrand.

typically produce louder, lower-frequency sounds than smaller boats, and faster vessels are typically louder. Reviews by Hildebrand (2009) and McKenna et al. (2012) discuss typical noise spectra and source level characteristics of different commercial vessel classes.

Commercial Vessels and Low-Frequency Underwater Noise

Vessels add noise to environments filled with natural sounds from waves, wind, animals, and other sources. Broad-scale longitudinal increases in low-frequency ambient noise have been associated with increased shipping traffic in some areas (e.g., Andrew et al., 2002; McDonald et al., 2006).

Low-frequency noise is not increasing throughout the ocean, but changes in low-frequency ambient noise in areas of increased commercial vessel presence (Figure 2) demonstrate that shipping activity can broadly affect low-frequency ambient noise levels on decadal time scales. Such increases may be expected to continue as global trends in commercial shipping suggest the total amount of cargo transported by large commercial ships may double or triple from 2005 to 2025 (USDOT-MARAD, 2006).

Such data have led noise modelers to predict that continued growth in the number of ships, the quantity of goods carried, and the distances traveled could increase the maximum noise capacity of the global shipping fleet—by as much as a factor of 1.9—by 2030, with major growth in the container and bulk carrier segments (Kaplan & Solomon, 2016). Further, underwater noise from maritime transportation is likely to become an even broader concern as previously inaccessible areas like the Arctic become accessible.

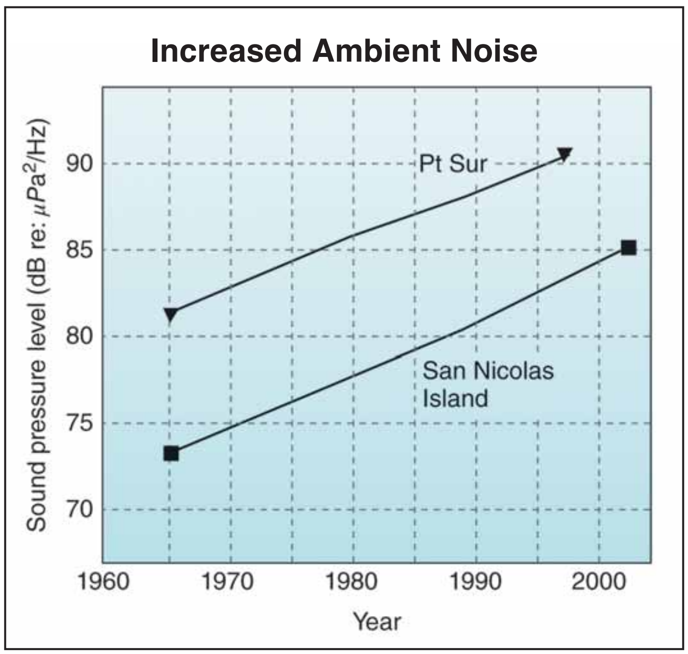

Figure 2. Low-frequency ambient ocean noise increased by about 3 dB/decade at two sites off the coast of California by comparing U.S. Navy data from the 1960s (Wenz, 1969) with more recent measurements below 100 Hz. Graphic created using data from Wenz (1969), Andrews et al. (2002), and McDonald, Hildebrand, and Wiggins (2006).

Consequences of Ship Noise on Marine Life

Sound is centrally important for most marine animals, including all marine mammals. Sound serves key biological functions, including communication, foraging, reproduction, navigation, and predator/hazard avoidance. Some species—dolphins and porpoises—use high-frequency biosonar in feeding and orientation. Others, notably baleen whales, use low-frequency sound for longer-range communication.

Predominately low-frequency sounds associated with large commercial vessels directly overlap these communications, and thus most effectively interfere with low-frequency signals used by baleen whales and some seals and sea lions (Figure 3). Many fishes, and some invertebrates, also rely on low-frequency sound in their natural history and may also be particularly affected.

Acoustic Communication and Hearing

More is known about marine mammal sound production than their hearing, given the relative ease of recording animal sounds compared with the challenges of directly measuring hearing. Direct hearing measurements are available for less than half of the approximately 125 marine mammal species. It should be noted that this includes none of these being low-frequency oriented whales and almost all studies involve only one or a few individual subjects.

Dolphins, porpoises, and other toothed whales use various whistles and other calls ranging from a few hundred hertz (Hz) to tens of kilohertz (kHz), but their high-frequency echolocation clicks can extend above 100 kHz. Potential interference from ship noise is thus relatively limited for these animals and restricted to the lowest frequency signals.

Baleen whales lack specialized high-frequency echolocation, but use sounds for important social and spatial orienting functions. Hearing in baleen whales remains completely untested, but has been estimated by studying a combination of sound production, anatomical characteristics, and behavioral responses to sound. Based on this indirect evidence, some may hear into the tens of kHz range, but most of their signals occur at "very low," "low," and "intermediate" frequency ranges between about 10 Hz and 10 kHz. It is at these low frequencies, where these species' communication signals overlap shipping noise, that they are most susceptible to negative effects from noise interference.

Other marine mammals, including seals and sea lions, also make and listen to sounds for important life functions. Like the large whales, they lack specialized high-frequency echolocation signals, but their communication sounds, produced largely in social contexts, generally occur from about 100 Hz to several tens of kilohertz, thus directly overlapping the predominantly low-frequency energy of vessel propulsion noise.

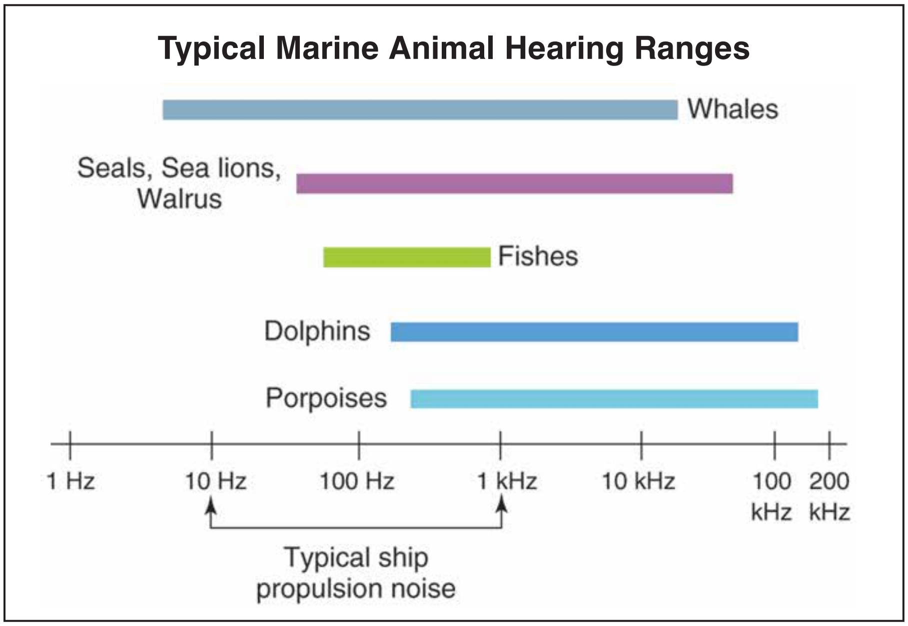

Figure 3. Typical hearing ranges for various groups of marine animals shown relative to the typical predominant frequencies of commercial shipping. Graphic created based on data from Southall et al., 2007.

Effects of Noise on Marine Life

Noise can adversely affect marine life by causing altered behaviors, like reduced communication ranges for social interactions, foraging, and predator avoidance. It also can temporarily or permanently reduce hearing sensitivity and have other physiological consequences (see: Southall et al., 2007; 2017).

Numerous studies have shown that noise from vessels can cause marine mammals to modify or cease sounds used to communicate, forage, avoid predators, or assess their environment. For example, North Atlantic right whales (*Eubalaena glacialis*) and North Pacific blue whales (*Balaenoptera musculus*) adjust vocalizations in the presence of vessel noise (Parks and Clark, 2005). However, such alterations may have biological costs and be constrained by physical and environmental factors.

A key consideration in terms of broad-scale potential impacts is the masking of biologically significant sounds. Such interference with hearing important signals may interfere with key functions, like breeding and navigation. The greatest masking occurs where signals and noise overlap in frequency. These effects have thus been considered explicitly for baleen whales and shipping noise. For example, shipping noise has been found to severely mask communication for North Atlantic right whales more than 70 percent of the time in some conditions (Hatch et al., 2012). Recent laboratory and field experiments have evaluated vessel noise impacts on fishes, examining whether vessel noise is masking detection of the soundscape and/or biologically relevant sounds (e.g., Simpson et al., 2016).

Underwater noise is widely recognized as an important environmental factor for marine species, and the potential effects of noise have been the subject of numerous consultations required under Section 7 of the U.S. Endangered Species Act. For the U.S. Coast Guard, the effects of underwater noise on endangered or threatened marine species have been considered in consultations with the U.S. National Oceanic and Atmospheric Administration (NOAA) and U.S. Fish and Wildlife Service. Impacts from sources including high and ultra-high frequency sonars, liquefied natural gas deep-water port construction and operation, and maintenance of fixed aids to navigation have been addressed.

International Collaborations to Reduce Vessel-Radiated Noise

Scientists, environmental managers, and conservationists are increasingly studying and considering many types of human noise that may impact marine animals. Much of the focus has been on loud, acute point sources, including military sonars and seismic air guns used in oil exploration, but there is increasing appreciation of potentially broader issues associated with chronic noise from, for instance, aggregate commercial vessel operations (e.g., Southall et al., 2007; 2017; Hatch et al., 2012).

A 2004 NOAA-hosted international stakeholder symposium, "Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology," was one of the first events to bring together regulatory and scientific communities with the shipping industry. Uncertainties and complexities regarding the potential effects of ship noise were acknowledged, and large vessels were clearly identified as significant contributors to low-frequency ambient noise levels. Recommended actions included evaluating whether existing vessel-quieting technologies for military and fisheries research vessels could be feasibly and economically applied to large commercial vessels.

A 2007 follow-on NOAA symposium, "Potential Application of Quieting Technology on Large Commercial Vessels," focused specifically on technical aspects, costs, benefits, and potential incentives for various noise reduction options (see Southall and Scholik-Schlomer, 2008). Various technological design and retrofit options, as well as operational measures and the relative costs and benefits associated with these proposed quieting options, were considered.

A recommendation was made to prepare an informative paper on shipping noise and marine mammals for the International Maritime Organization (IMO). Shortly thereafter, the U.S. delegation to the IMO, led by the United States Coast Guard, submitted such a document to the Marine Environment Protection Committee (MEPC) entitled "Shipping noise and marine mammals" (MEPC\57\INF-4). This document, composed by NOAA scientists involved in the 2004 and 2007 symposia, was a broad introduction regarding shipping noise and its potential adverse impact on marine life. This paper opened the door for future collaboration within the IMO, which would be enhanced by new discussions and partnerships among environmental groups, scientists, regulators, and the industry.

Cross-Sector Partnerships Emerge

Building on the collaborative efforts of the NOAA symposia, Okeanos-Stiftung für das Meer [Foundation for the Sea] convened a 2008 workshop in Hamburg, Germany (see Wright, 2008). The workshop sought to expand awareness of the issue, engage different sectors of international maritime transport—particularly ship builders, marine architects, and classification societies—and call for specific action by the IMO. Participants agreed on an ambitious objective, calling for "… initial global action that will reduce the contributions of shipping to ambient noise energy in the 10–300 Hz band by 3 decibels in 10 years and by 10 decibels in 30 years, relative to current levels. This goal [will] be accomplished by reducing noise contributions from individual ships."

Formal consideration of this issue within the IMO began at the 58th session of the MEPC in June 2008, with a U.S. petition to establish a correspondence group to consider potential vessel quieting technologies. The proposal was accepted, and the U.S. chaired a correspondence group within which subject matter experts, ship owners, naval architects, and design model basins began assessing feasibility and developing technical recommendations. The MEPC sent draft guidelines to the IMO's Ship Design and Equipment (DE) Subcommittee (now the Ship Design and Construction Subcommittee) for further consideration and additional technical expertise. A DE correspondence group and later a drafting group, chaired by the United States, were formed.

The correspondence groups' combined efforts focused on propeller design and modification to reduce cavitation, but considered hull design, on-board machinery, and operational modifications. In 2014, the MEPC formally adopted the resulting vessel-quieting guidelines (see: MEPC, 2014; and Southall et al., 2017 for more on these processes). Because the guidelines are voluntary and underwater noise is not yet the subject of mandatory code, successful implementation will require commitment from shipping lines, ship classification and green certification societies, port authorities, and member states. Subsequently, the IMO has considered additional proposals that the DE identified to quantify underwater noise output and direct management effort.

Humpback whale tail while diving in Glacier Bay, Alaska. Photo by Andrea Izzotti/Shutterstock.com

Recent Initiatives—North America and Europe

A number of significant international developments regarding shipping noise and marine life have occurred in parallel with the IMO processes.

From 2012–2016, NOAA worked to develop its forward-looking Ocean Noise Strategy to provide long-term direction to NOAA's management and research activities associated with ocean noise impacts to marine life. The final roadmap for this initiative, released in September 2016,[1] highlighted the need for NOAA to broaden its focus to address the need to protect the quality of marine acoustic habitats in addition to minimizing more direct adverse physical and behavioral impacts to specific species. As part of the Ocean Noise Strategy initiative, NOAA has already deployed a Noise Reference Station Network to provide a standardized, calibrated monitoring system with which to characterize status and trends in low-frequency underwater noise and the contributions of various sources, including shipping.

Canadian ocean management and science efforts, with significant investment from Ocean Networks Canada since 2007, have spearheaded the integration of noise monitoring with advancing ocean observation capabilities. Many initiatives have focused on characterizing shipping noise contributions to Canadian waters.[2] The most directed efforts thus far have taken place at the Port of Vancouver, where in 2014 the Vancouver Fraser Port Authority instituted the Establishing Cetacean Habitat and Observation[3] (ECHO) program to better understand and manage the impacts of shipping underwater noise and ship-strike risk on British Columbia's endangered southern resident killer whales in their legally designated critical habitat. Since then, ECHO's mandate has expanded to include other at-risk cetaceans as well as its initiatives on underwater noise.

Establishing Cetacean Habitat and Observation

Researchers on a National Marine Fisheries Service vessel observe a "spy hopping" southern resident killer whale near the San Juan Islands, Washington, in 2006. NOAA photo

ECHO's numerous initiatives on underwater noise include:

- a program to measure and analyze ambient underwater acoustic levels
- acoustically identifying noise contributors to the underwater soundscape
- sharing information with industry on noise reduction technologies
- collecting vessel noise data from a calibrated underwater listening station
- testing an in-water propeller and hull maintenance facility
- an incentive program for vessel quieting compliance (EcoAction)

The Port of Prince Rupert, at the northern end of the British Columbia coast, is anticipating major increases in commercial vessel activity and is following suit with a program modeled on Vancouver's ECHO. Three Canadian federal agencies—Transport Canada, Environment Canada, and the Department of Fisheries and Oceans—are exploring how to manage shipping noise in both the Salish Sea and in the St. Lawrence estuary, where noise presents a recognized threat to a small, endangered population of belugas.

Green Marine, a leading green certification society for the North American shipping industry, has added underwater noise to its voluntary environmental certification program, adopting noise performance indicators for ports, terminals, and shipping companies.[4] Participants include ship owners, ports, terminals, St. Lawrence Seaway corporations, and shipyards based in Canada and the United States. Their compliance with specified noise criteria is voluntary in 2017, and compulsory in 2018.

New tools to address cumulative and chronic noise effects over wider spatial scales have continued to emerge in the European Union, including implementation of the Marine Strategy Framework Directive (MSFD).[5] The EU MSFD defines its objective, "Good Environmental Status," to include the requirement that "Introduction of energy (including underwater noise) does not adversely affect the ecosystem." In 2010, the European Commission produced a set of detailed criteria and indicators to help member states implement the MSFD. Two criteria address the noise energy requirement (Van der Graaf et al., 2012):

- the proportion and distribution of days in which anthropogenic sound sources exceed levels that are likely to entail significant impacts on marine animals
- trends in ambient noise levels in specific low-frequency bands (63 and 125 Hz)

The latter criterion considers frequencies dominated by vessel contributions and has led to the development of regional monitoring programs and heightened focus on ship noise characterization and modeling. The European Commission has supported collaborative research programs, like Achieve QUieter Oceans (AQUO),[6] to assess noise impacts and provide practical and achievable noise control measures.

Such initiatives continue to emphasize the need for international standards in noise measurement and monitoring. In 2009, the Acoustical Society of America and American National Standards Institute issued guidelines for measuring underwater noise from ships (ANSI/ASA S12.64-2009). The UK National Physical Laboratory followed in 2014 with a "good practice" guide for underwater ship noise measurement (NPL Good Practice Guide No. 133). In 2016, the International Organization for Standardization (ISO) published its requirements for deep-water measurement of underwater ship noise (ISO 17208-1:2016), with a shallow-water measurement presumably to follow. Three major ship classification societies, Det Norske Veritas (2010), Registro Italiano Navale (2014), and Bureau Veritas (2014), have used these measurement protocols as the basis for new “quiet ship” notations which have been applied by the ports of Vancouver and Prince Rupert to grant substantial reductions in berthing fees for ships bearing one of these notations.

Finally, dialogue surrounding multilateral Arctic marine environmental protection continues to highlight concerns with shipping noise impacts due to the sensitivity of many Arctic species to sound and changing densities and distributions of human activities that produce noise. For example, the January 2017 meeting of the Arctic Council workgroup for Protection of the Arctic Marine Environment (PAME) considered a World Wildlife Fund proposal for “Developing Guidelines for Reducing Underwater Noise from Ship Operations in the Arctic.”

Technical Progress Needed

A Great White shark swims under a ship propeller. Photo by Andrea Izzotti / Shutterstock.com

Additional progress is needed in many areas to better understand the relationship between marine life and shipping and other noise sources.

- better understanding of the relationship between noise and propeller cavitation, including vessel noise signatures for different ship classes and sizes under various operating conditions
- coordinated noise measurements for vessels with means of tracking movement and other operational conditions (e.g., automatic identification system)
- implementation, efficacy testing, and cost/benefit analyses of quieting measures for individual ships, including those recommended by IMO
- quantitative evaluation of ship noise reduction and regional ambient noise levels

Research Needs and New Directions

Scientific and technical progress has and will continue to advance in parallel with action to address the impacts of shipping noise on marine life. Clearly, additional science is needed to better understand the scope and biological significance of disturbance and masking from shipping noise. Efforts are also needed to sustain recent U.S. federal agency initiatives to better understand marine species distribution and density relative to temporal and spatial patterns of shipping and other noise sources.[7]

The scope of potential environmental implications of, and solutions to, shipping noise is substantial and will require concerted and sustained international efforts. Regulatory mechanisms such as nation-specific requirements by port and/or flag states may become part of how the issues are addressed internationally. However, challenges in their implementation and enforcement argue strongly for additional industry engagement. Building on the NOAA ship noise symposia, the Okeanos workshop, and the international progress that has occurred through IMO, proactive involvement of industry can constructively contribute to tangible progress. Moving forward, approaches to motivate this engagement could include government incentives (e.g., incentive-based regulations or tax breaks) and market incentives (e.g., fuel efficiency and “green” company certifications) in addition to regulation. Additionally, coordinated efforts with other environmental issues, like ship-strike mitigation, should be considered, including areas for speed reduction or vessel traffic avoidance that may simultaneously reduce noise *and* reduce the risk of vessel collisions.

Acknowledgments

Portions of this article are adapted from Southall et al. (2017) that include nearly all of the same authors; more recent developments are considered here. We thank J. Hildebrand for his assistance in adapting and updating Figure 1.

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We extend our thanks to the many authors who contributed to this article: Brandon L. Southall (Southall Environmental Associates, Inc.); Leila Hatch, Amy R. Scholik-Schlomer, and Tricia Bergmann (National Oceanic and Atmospheric Administration); Michael Jasny (Natural Resources Defense Council); Kathy Metcalf (Chamber of Shipping of America); Lindy Weilgart (Dalhousie University); Andrew Wright (George Mason University); and M.E. Perera (U.S. Coast Guard).

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Understanding and Addressing the Effects of Shipping Noise in MPAs

Lessons from U.S. National Marine Sanctuaries

The Office of National Marine Sanctuaries, part of the U.S. National Oceanic and Atmospheric Administration (NOAA), manages a system of 14 marine protected areas (MPAs) in U.S. waters.

NOAA's Ocean Noise Strategy Roadmap[1] recently highlighted national marine sanctuaries within the agency's efforts, encouraging enhanced monitoring of ocean noise and development of innovative methods for addressing noise impacts within these sites. Driven by such interests, passive acoustic monitoring capacity within national marine sanctuaries is becoming more systematic and coordinated. Beginning in 2014, NOAA deployed Noise Reference Stations within Olympic Coast, Channel Islands, and Stellwagen Bank National Marine Sanctuaries, adding a fourth to Cordell Bank National Marine Sanctuary in 2016. These are long-term—1- to 2-year sequential deployments—low-frequency and mostly deep-water listening stations that are part of a 12-unit network deployed throughout U.S. waters. Data from this network will inform NOAA's understanding and management of ocean noise impacts (Haver et al., in review).

In 2016, a second program was started to coordinate shallow-water acoustic monitoring in Stellwagen Bank, Gray's Reef, Florida Keys, and Flower Garden Bank National Marine Sanctuaries along the East Coast of the United States and in the Gulf of Mexico. These broadband acoustic recordings are providing standardized and calibrated insights regarding temporal peaks in the spawning activity of fish, feeding and reproductive activity of baleen whales, small and large vessel activity, and offshore energy exploration variability among and within sanctuary soundscapes (J. Stanley, personal communication).

Stellwagen Bank National Marine Sanctuary (SBNMS), off the coast of Massachusetts, has become a hub of research focused on evaluating the potential impacts of noise from high levels of human activity on marine species and habitats co-occurring within its boundaries. The International Maritime Organization-approved Traffic Separation Scheme (TSS) for the Port of Boston routes the daily transits of container ships, tankers carrying oil and liquefied natural gas, and cruise lines directly through the sanctuary in an east-west pattern (Figure 1).

In addition, the sanctuary is a regional hot spot for biological productivity and has supported nationally important commercial fisheries, including those for groundfish like Atlantic cod and haddock. Cod and haddock are among many fish species in the sanctuary that are vocally active, particularly when spawning. Male cod produce low-frequency calls associated with spawning that are overlapped by noise produced by ships (Stanley et al., 2017). The sanctuary is also an important seasonal feeding ground for endangered and threatened marine mammals like North Atlantic right, humpback, and fin whales. These baleen whales also communicate using vocalizations in frequencies that are overlapped by noise produced by ships (Hatch et al., 2012).

For more than a decade, researchers from SBNMS and NOAA's Northeast Fisheries Science Center have been collaborating with a diverse group of academic and industry-based partners to:

- characterize the contribution of shipping noise to sanctuary waters
- document the calling activity of species in the sanctuary
- develop methods to quantify the risk of noise impacts to vulnerable species
- evaluate possible management options to address those risks

Many different types of underwater recording technologies have been used, and acoustic data are integrated with high-resolution ship tracking information available from land-based automatic identification system receivers. This research found that noise generated by commercial shipping contributes significantly to noise levels in the sanctuary, with high-traffic locations experiencing double the acoustic power of less-trafficked locations for the majority of the time period analyzed (Hatch et al., 2008). Methods were developed and applied to quantify the risk that these species' sounds are "masked" by shipping noise, which leads to a decrease in the distance over which calling animals can hear each other in biologically important contexts, like group feeding and mating (Hatch et al., 2012; Stanley et al., 2017).

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Such methods can also examine the possible gains in listening capacity resulting from changes in the quantity, distribution, or operation of ships. For example, NOAA and the USCG have worked to reduce the risk of lethal collisions between large ships and North Atlantic right whales, including within the sanctuary. This resulted in shifting and narrowing the Boston TSS and reducing ship speed within the TSS during time periods of high risk.

These mitigations have been evaluated for their indirect effects on reducing peak exposures of large whales and spawning fish groups to noise from ships transiting the sanctuary. However, because of the long-distance propagation of ship noise, efforts to design and implement quieter designs, as discussed in this article, will be necessary to reduce the contributions of both nearby and distant shipping to chronic background noise conditions within the boundaries of national marine sanctuaries and other protected areas (Hatch et al., 2016).

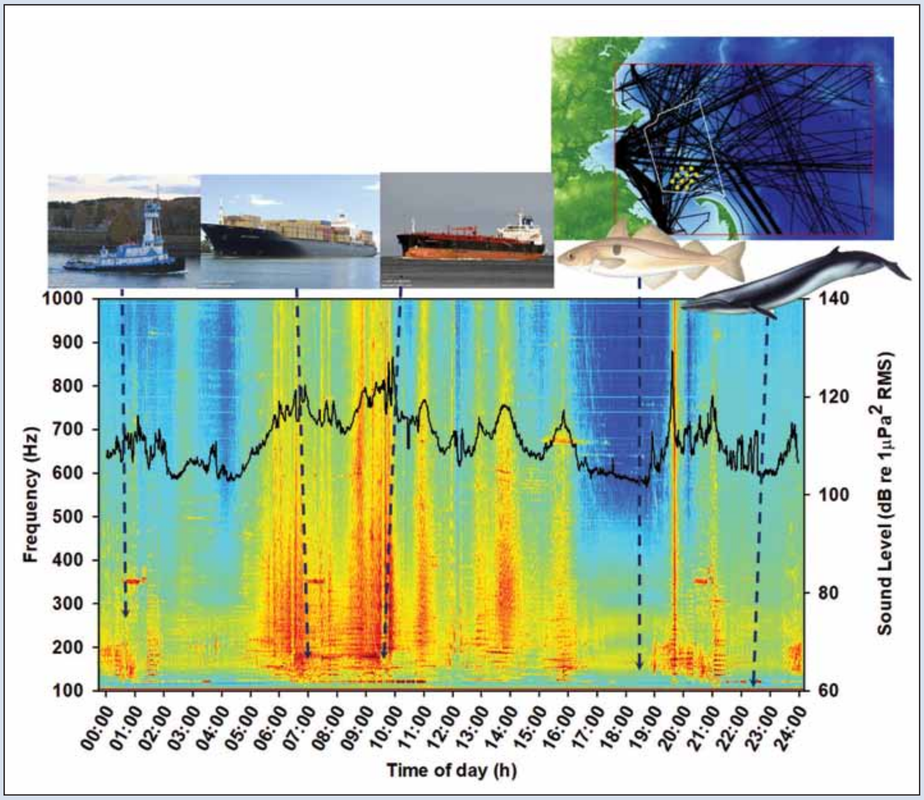

Figure 1. Map of coastal Massachusetts off the U.S. East Coast (upper right) showing one month of shipping traffic (black lines) in areas surrounding the Stellwagen Bank National Marine Sanctuary (white boundaries) and example placement of underwater recording equipment (yellow dots). 24-hour spectrogram showing example of contributions to low-frequency recordings from multiple vessel types as well as fish and baleen whales (dashed arrows). Sound intensity is indicated as both redder color and broadband levels (right axis) in the spectrogram. NOAA Stellwagen Bank National Marine Sanctuary image

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