Title
A Brief Review of Anthropogenic Sound in the Oceans

Journal
International Journal of Comparative Psychology, 20(2)

ISSN
2168-3344

Authors
Studds, Gerry E
Wright, Andrew J

Publication Date
2007-12-31

Peer reviewed

International Journal of Comparative Psychology, 2007, **20**, 121-133.

A Brief Review of Anthropogenic Sound in the Oceans

Leila T. Hatch
Gerry E. Studds Stellwagen Bank National Marine Sanctuary
U.S. National Oceanic and Atmospheric Administration, U.S.A.

Andrew J. Wright
Leviathan Sciences, U.S.A.

Sound in the oceans is generated by a variety of natural sources, such as breaking waves, rain, and marine animals, as well as a variety of human-produced sources, such as ships, sonars and seismic signals. This overview will begin with a quick review of some basic properties of sound waves with particular reference to differences between the behaviours of these waves underwater versus in air. A basic understanding of the physics of underwater sound is critical to understanding how marine animal acoustic signals have evolved relative to their different functions and how changes in the marine acoustic environment due to increasing anthropogenic sound in the oceans may impact these species. We will then review common sources of anthropogenic sound in the oceans. The frequency contributions of three major sources of underwater anthropogenic sound and their relative intensities will be discussed: naval exercises, seismic surveys and commercial shipping. Finally, a case study examining relative inputs to a regional noise budget, that of the Gerry E. Studds Stellwagen Bank National Marine Sanctuary, will be presented to introduce the audience to methodologies for characterizing and managing sound on an ecosystem level.

A number of reviews of anthropogenic sound in the oceans (and its effects on marine mammals) have described properties of underwater sound, outlined the differences between the transmission of sound underwater versus in air and compared acoustic characteristics associated with different types of anthropogenic sources (e.g., Hildebrand, 2005; MMC, 2007; Nowacek, Thorne, Johnston, & Tyack, 2007; NRC, 1994, 2003; Richardson, Greene, Malme, & Thomson, 1995). This paper will not attempt to provide the same detailed coverage of these topics. Instead, this paper will provide a basic introduction to the sources and physics of underwater sound for the uninitiated audience and provide references for the interested reader to gain additional information.

The reviews noted above also include thorough examination of the current scientific knowledge surrounding the effects of underwater noise on marine mammals; however, Weilgart (this issue) provides a brief overview of this material. Furthermore, natural sources of sound in the oceans will not be detailed here. This is not because these sounds do not affect marine mammals, but because management of underwater noise focuses on human contributions to the marine acoustic environment, in which sound plays important natural roles.

What Is Sound? A Primer

Sound is a compression wave that causes particles of matter to vibrate as it transfers from one to the next. These vibrations produce relatively small changes in

The views expressed in this paper are those of the authors alone and do not represent those of Stellwagen Bank National Marine Sanctuary, the U.S. National Marine Sanctuary Program and/or NOAA. Thanks are due to 2 anonymous reviewers for their helpful comments on an earlier version of this manuscript. Correspondence concerning this article should be addressed to Leila Hatch, Gerry E. StuddsStellwagen Bank National Marine Sanctuary, U.S.A. (leila.hatch@noaa.gov).

pressure (compared to atmospheric pressure) that can be detected by the ear.

Depicted graphically as a sine wave, the wavelength of a sound is equal to the speed of sound divided by its frequency. Thus, high-frequency sounds have shorter wavelengths than low-frequency sounds travelling in the same medium (Figure 1). The perceived "loudness" of a sound is a function of its amplitude (i.e., how much energy it carries) or intensity (the power of the wave transmitted in a particular direction in watts per square meter) and the hearing thresholds of the receiver (i.e., listener). It should be noted that the speed of sound in seawater is the same for all frequencies, but varies with aspects of the local marine environment such as density, temperature and salinity. Due mainly to the greater "stiffness" of seawater relative to air, sound travels approximately 1,500 m/s in seawater while it travels only approximately 340 m/s in air. Boundaries between two mediums with very different sound speeds act somewhat like mirrors to all sound not striking that boundary perpendicularly. Consequently, sound does not travel well between air and the oceans.

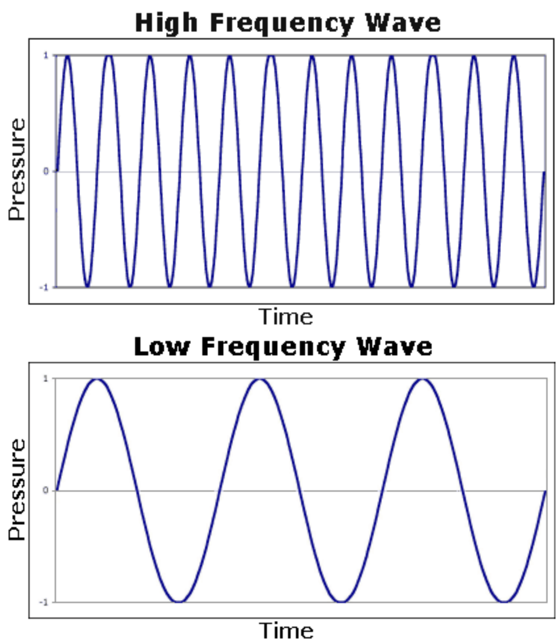

Figure 1. This diagram shows a high frequency wave (above) and a low frequency wave (below), plotted as pressure versus time. The high frequency wave has completed twelve cycles over the time shown. The low frequency wave has completed only three cycles over the same time. Diagram reproduced with permission from *Discovery of Sound in the Sea* http://www.dosits.org/ (a).

A sound's intensity is usually measured in decibels (dB), which is a relative measurement rather than an absolute measurement of wave's directional energy. Measurements in air usually reference 20 micropascals (µPa), or about the sound of a pin drop, while the standard reference in seawater is 1 µPa. Converting between sound intensities in air and water can be confusing and often the source of conflict. This is not only due to the relative nature of the decibel scale, but also the relationship between a sound's intensity and the medium it is travelling through, in addition to the different methods for measuring the level of a sound. Sound waves with the same *intensities* in water and air when measured in watts per square meter have relative *intensities* that differ by 61.5 dB. Thus, for sounds with the same absolute *intensities* in watts per square meter, one must subtract 61.5 dB to obtain the sound's relative intensities in water referenced to 1 µPa. Reference intensities cause 26 dB of this difference, while the differences in densities and sound speeds account for the other 35.5 dB of the difference in *intensities* (Urick, 1983).

As mentioned above, there are different ways to characterize a signal's amplitude. The most common methods are to measure peak-to-peak pressure, peak pressure, and root mean squared (rms). Peak-to-peak amplitude is represented in the waveform by the entire height of the sound wave, peak pressure would be the largest displacement from the central line and rms measures the average of the pressure of the sound signal over a given duration. Due to its direct relationship to the amount of energy carried by the sound wave (i.e., intensity), the rms pressure is the most common metric used to characterize sound waves (Madsen, 2005).

As a result of the physical and measurement differences described above, sounds with equal absolute intensities in seawater and air have higher relative intensity, travel faster and go farther before they loose their energy in seawater than in air. In addition, regardless of the medium the sound is travelling through, low frequency sounds travel farther than high frequency sounds because their energy is absorbed more slowly and louder sounds travel farther than softer sounds because they have more energy to disperse over distance from the source.

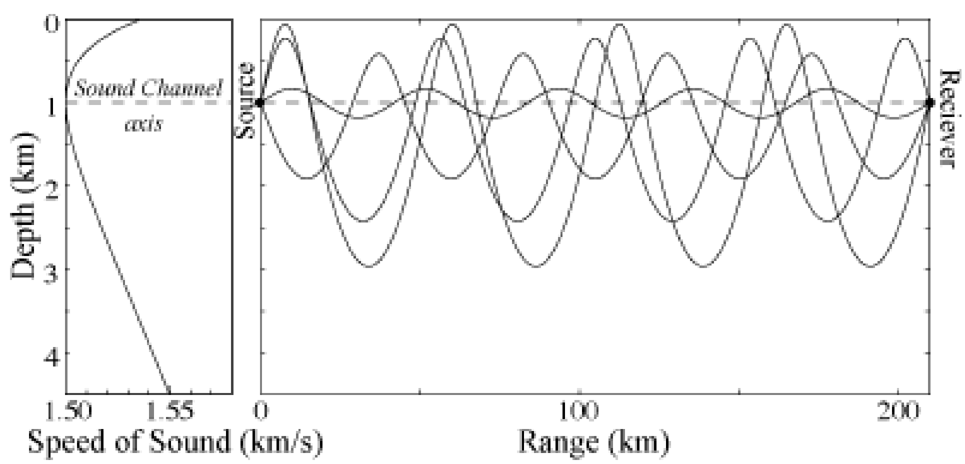

Figure 2. This diagram shows the sound channel axis. Sound speed profile from mid-latitudes is represented on the left. The paths that sound travels from a source at 1000m depth to a receiver at 1000m depth and 210km away from the source are shown on the right. Diagram reproduced with permission from *Discovery of Sound in the Sea* http://www.dosits.org/ (b) and adapted from Figure 1.1 of Munk, Worcester, & Wunsch (1995).

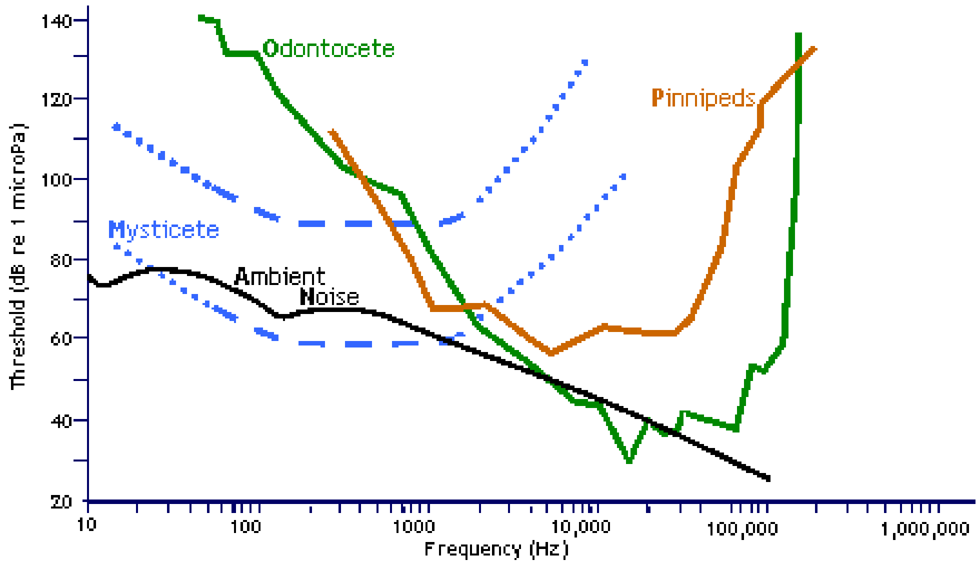

Figure 3. Estimates of the hearing thresholds for mysticetes, odontocetes and pinnipeds with ambient noise profile superimposed. The y-axis is relative intensity in underwater dB. The x-axis is the frequency of a sound on a logarithmic scale. Figure modified with permission from *Discovery of Sound in the Sea* http://www.dosits.org/ (c).

In the majority of the ocean there is often a minimum sound speed due to the predominant effects of heat from the sun and density due to depth on the speed of sound in water (salinity also plays a major role where it varies widely, such as near shore and in estuaries). The increasing sound speeds above and below this minimum tend to focus sounds like a lens at the minimum (Figure 2). Any sound travelling at about 12° or less from the horizontal are unable to escape and are refracted back toward the minimum, allowing sound to propagate much further due to a reduction in spreading and reflection and adsorption by the sea surface and sea floor. This is known as the deep sound channel, or SOFAR channel. In the deep ocean at mid-latitudes, the slowest sound speed occurs at a depth of about 800 to 1000 meters. However, the depth varies from over 1600 m in the warmest waters of the world to100 m in colder waters and can even reach the surface at the ice edge, becoming a surface sound channel.

Finally, sound is often categorized as either signal or noise. However this categorization depends heavily on the receiver (listener), who will define sounds of interest as signals and everything else that might interfere with those signals as noise. For example, Navy sonar operators would consider their sonar to be a signal, while marine mammals are likely to consider it to be noise. Concerns regarding the impacts of noise on signals must also take into account differences in species and/or individuals range of hearing. The quietest sounds, across the range of frequencies that can be heard by an individual receiver define its hearing thresholds (Figure 3).

Anthropogenic Noise

Human use of the sea, such as for shipping, military activities, oil and gas exploration, and recreation (including cruises and pleasure boating), is increasing the amount of sound that is introduced into the oceans (see Table 1). As these sounds are generally not considered to be signals by marine fauna, they will be referred here as noise. The continuing increase in anthropogenic noise in the oceans may be affecting marine life in many ways, since many marine animals have evolved to use sound as their main means to communicate, sense their surroundings, and find food underwater (Berta, Sumich, & Kovacs, 2006). As light does not travel very far in water, auditory capabilities have evolved to supplement and/or replace the use of vision for many marine animals (Bradbury & Vehrencamp, 1998). The same advantages conferred by sound relative to light underwater have led humans to deliberately introduce sound into the ocean for many of the same reasons as marine fauna: communication (e.g., sub-to-sub), feeding (e.g., fish finding sonar) and navigation (e.g., depth-finders).

The sounds produced by the range of sources in Table 1 are also highly variable, some being characterized as impulsive (such as seismic surveys) and tonal (such as sonar), comparatively loud (such as explosives) and relatively quiet (such as most fishing activities), persistent (such as shipping), short (such as winches) and very short (such as a single seismic survey pulse). Some noise sources, such as explosions, naval low frequency active sonars (LFA), some mid-frequency active sonars, high-power seismic surveying systems that are used to explore the ocean floor for oil and natural gas resources and commercial ships can all be heard over large distances, sometimes across oceans (Nieukirk, Stafford, Mellinger, Dziak, & Fox, 2004).

In general, seismic survey airguns represent the most prolific impulsive sounds introduced into the ocean by human activity. Conversely, commercial shipping is collectively making an ever-increasing contribution to the omnipresent background noise over very large spatial scales in the ocean, as well as intermittent local impacts as point sources (see below).

Many of the various sources and their characteristics have been described in previous works (e.g., Hildebrand, 2005; Nowacek et al., 2007; NRC, 1994, 2003; Richardson et al., 1995). Therefore, here we shall focus on three source types that have drawn considerable recent attention: naval exercises, seismic surveys, and commercial shipping.

Naval Exercises and Sonar

Naval activities involve a number of activities that introduce noise into the oceans, including live-ammunition training, vessel noise and explosions. However, the exercises that have been subject to the most scrutiny are those involving mid-frequency sonar operations. Around the world, mid frequency sonars have been correlated with strandings of multiple Cuvier’s beaked whales in the Bahamas and have been coincident in time and space with additional stranding incidents (see Brownell, Yamada, Mead, & van Helden, 2004; Cox et al., 2006; ICES, 2005;

Weilgart, this issue). Mid-frequency naval sonar can produce sound at levels of up to 237 dB re 1uPa @ 1m mainly at frequencies between 2-8 kHz on a 2-second duty cycle repeated as needed for variable periods. The two tactical sonars most frequently used by the US Navy, AN/SQS-53C and AN/SQS-56, are focused in the 2.6 to 3.3 and 6.8 to 8.2 kHz ranges, respectively. Approximately 145 of the US Navy's ~280 ships have mid-frequency sonar capabilities, although not all of these ships utilize these capabilities at any one time. However, the US Navy is not the only military using these or similar sonars and worldwide usage is unknown.

Table 1
Types of anthropogenic noise, with example sources. Note this is not an exhaustive list.

Noise	Example sources
Sonar	Military and commercial
Marine geophysical surveys	Commercial and research
Explosions	Military exercises and testing, dynamite fishing, offshore rig decommissioning
Acoustic deterrent devices (ADDs) and acoustic harassment devices (AHDs)	Fishing activities
Winches, onboard machinery, etc.	Fishing, research, commercial activity
Vessel noise at predominantly lower frequencies	Commercial shipping and other large vessel activity (e.g., tankers, military vessels, cruise liners, etc.)
Vessel noise at predominantly higher frequencies	Smaller commercial vessels (e.g., fishing, ferries, fast ferries, recreational boating, whale-watching and research vessels, etc.) and personal water craft (e.g., jet skis)
Ice breaking and associated engine noise	Icebreakers
Acoustic thermometry of the ocean climate (ATOC) and other sounds used for oceanographical studies	Research vessels and equipment
Noise from offshore development, both during construction and operation	Dredging and other development, (e.g., oil rigs, deep-water ports, wind farms, etc.)
Noise from coastal development (including on-ice activity) both during construction and operation	Ports and harbours, sea walls, piers, bridges, aquaculture facilities, industry and residential buildings
Aircraft (under the circumstances when sound crosses into the ocean)	Helicopters, aeroplanes (especially at supersonic speeds), spacecraft, missiles and other military projectiles
Traffic noise	Traffic on bridges and coastal roads, ice-trucking (through the ice)

Concerns were also raised regarding a surface towed low-frequency active sonar system (SURTASS-LFA) that can include up to 18 projectors in a vertical array, each producing pulses up to 215 dB re 1uPa @ 1m mostly between 100 and 500 Hz. This system utilizes the deep sound channel to propagate over very large distances. Several species of mysticetes use sounds with overlapping frequencies, and also appear to utilise the deep sound channel to increase the range of their sounds (Payne & Webb, 1971). Thus, environmental impact assessments for this sonar type have focused on changes in the feeding behaviors of blue and fin whales (*Balaenoptera musculus* and *B. physalu*; Clark & Altman, 2006; Croll, Clark, Calambokidis, Ellison, & Tershy, 2001), the migratory behaviour of grey whales

(*Eschrichtius robustus*; Tyack & Clark, 1988), and the reproductive behaviour of humpback whales (*Megaptera novaengliae*; Fristrup, Hatch, & Clark, 2003; Miller, Biassoni, Samuels, & Tyack, 2000). Although low-frequency active sonars are utilized much less frequently and by fewer Naval vessels than mid-frequency sonars (i.e., in the US Navy, only 2 ships are currently capable of deploying the SURTASS LFA system), due to the long-distance propagation capabilities of these systems, they may have more subtle impacts due to masking.

Seismic Surveys

Ships undertaking marine geophysical surveys tow seismic (airgun) arrays that emit loud sounds downward to probe under the sea bed for fossil fuels. Point-source intensity estimates for airguns are difficult due to the directional nature of the source, however arrays can produce levels equivalent to 260 dB re 1 μPa @ 1m (peak), with actual in-water pressure levels reaching maximums of approximately 235-240 dB. Although the sound is focused mainly downwards, some sound is emitted horizontally. Similarly, most of the energy is below 1,000 Hz with the predominant frequencies between 10-100 Hz, but there is considerable broadband energy, up to around 15 kHz or more, that is detectible, especially at relatively close range (Goold & Coates, 2006; Goold & Fish, 1998).

Airgun signals last around 40 ms, and are repeated every 7-20 s for several hours or days. Reflection and refraction can lengthen pulse durations (up to several seconds long) at the distance of the receiver. Although seismic surveying activity is concentrated in areas with extractable petroleum or natural gas (i.e., mostly on continental shelves, although this is changing as technology advances) the low frequency nature this source type means that the signal can travel for thousands of kilometers (Nieukirk et al., 2004).

Commercial Shipping

Noise from commercial ships is highly variable, but is generally produced at levels between 160 and 180 dB re 1uPa @ 1m (Richardson et al., 1995). Ships generate noise through their propellers, motors and gears. Noise from propellers comes from the many bubbles formed in the water by the rotating propeller blades. These bubbles quickly collapse or "cavitate" creating a loud acoustic sound. The faster the propeller rotates, the more cavitation noise. The breaking bubbles produce sound over a range of frequencies and, at high speeds, these frequencies can be as high as 40,000 Hz (Bartlett & Wilson, 2002; Wenz, 1962). However, propeller noise from large ships is usually concentrated below 200Hz. Low frequency noise generated by ships contributes significantly to the amount of low-frequency ambient noise in the ocean (Wenz, 1962). Because of the increase in propeller-driven vessels, low-frequency ambient noise has increased 10-15 dB, at an average of approximately 3 dB/decade over the past 50 years (Andrew, Howe, & Mercer, 2002; Cato & McCauley, 2002; Curtis, Howe, & Mercer, 1999; McDonald, Hildebrand, & Wiggins, 2006; Zakarauskas, Chapman, & Staal, 1990).

The spatial distribution of noise from shipping is non-uniform in the world's oceans. In general, increases are more pronounced in the northern hemisphere because of the higher shipping volumes involved (e.g., Cato, 1976; Cato & McCauley, 2002; McDonald, Hildebrand, & Wiggins, 2006). Also, the concentration of commercial traffic into shipping lanes and around ports tends to amplify vessel noise in these regions, although shallow water propagation on the continental shelf can reduce levels in some high traffic areas. Shipping noise is also directional as it moves away from the source, sometimes strongly so, thus altering the contribution of any single ship to the ambient noise depending on whether the measurement is made at the surface versus on the bottom and/or off the bow versus of the sides or stern (Gray & Greeley, 1980).

Contributions from commercial shipping are similarly variable temporally. For example, the number and size of ships entering the global maritime transport fleet continue to increase dramatically, with implications for noise due to both total input of noise and input per unit vessel. Short-sea shipping (short distance cargo hauling) is becoming more prevalent, with implications again due to additional coastal traffic. As the Arctic Ocean ice melts due to climate change, trans-Arctic paths become the best routes between Europe and both eastern Asia and western North America. Such changes are predicted to change the ambient noise profile of Arctic waters as well as introducing additional point-source noise to this area (Southall, 2005).

A Regional Case Study: The Gerry E. Studds Stellwagen Bank National Marine Sanctuary Passive Acoustic Monitoring Program

Underwater noise from ships can be evaluated at two spatial scales: as transient, relatively high intensity sounds at close range and as omnipresent, relatively low-intensity sound over great distances. The propagation efficiency of low-frequency shipping noise has led to concerns regarding possible “masking” of marine animal signals, particularly low frequency vocalizations, with possible negative effects including diminished abilities to find mates, maintain social structure, forage, navigate and/or evade predation (Erbe, 2002; Erbe & Farmer, 1998, 2000; Morisaka, Shinohara, Nakahara, & Akamatsu, 2005; Nowacek et al., 2007; Payne & Webb, 1971; Southall, Schusterman, & Kastak, 2000). Due to the long-distance propagation of shipping noise, evidence of such effects must be evaluated when animals are closely approached as well as over large spatial scales.

In 2004, the US National Oceanic and Atmospheric Administration (NOAA) Fisheries’ Ocean Acoustics Program further addressed this issue by sponsoring an international symposium on “Shipping Noise and Marine Mammals” (Southall, 2005). Symposium attendees found that prior to developing regulations and/or designing technology to mitigate shipping noise on marine mammals more research was necessary to determine the relative contributions made by identified sound sources to the total noise field. Such descriptive data gathering was also a central recommendation from an NRC (2003) report, which also stated the importance of characterizing temporal variation (e.g., annual, seasonal, monthly, and daily) and spatial variation when measuring sound fields. While the NRC Committee and the NOAA Symposium were focused globally, many of their resultant insights and recommendations can be applied at a smaller “case-study” scale to provide a more local understanding of the noise-marine mammal issue. Insights achieved from case studies can then be used to inform the issue on national and international scales.

Such a case study is being developed within the Gerry E. Studds Stellwagen Bank National Marine Sanctuary (SBNMS or sanctuary), where collaborators are generating methodologies to merge data from passive acoustic monitoring devices with vessel tracking systems and to identify the contributions made by various classes of noise (Hatch et al., in review). The SBNMS is an "urban" marine sanctuary located to the east of Boston, Massachusetts, U.S.A. in close proximity to a densely populated coastal zone (Figure 4).

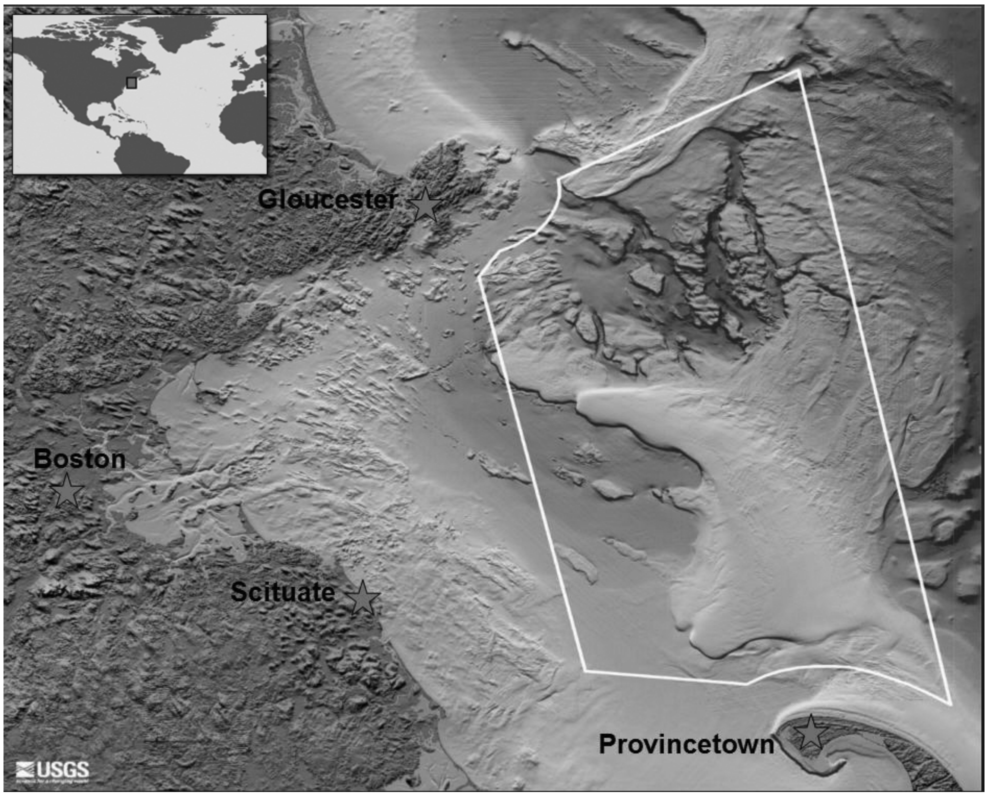

Figure 4. Location, boundaries and bathymetry of the Gerry E. Studds Stellwagen Bank National Marine Sanctuary in Massachusetts Bay off the northeast coast of the United States.

Stellwagen Bank, the central feature of the sanctuary, is home to some of the oldest and highest capacity commercial fisheries in the world and is an important feeding ground for endangered marine mammals such as the North Atlantic right whale (*Eubalaena glacialis*), humpback whale and fin whale. Because the Boston Traffic Separation Scheme (TSS) (the United Nations International Maritime Organization's recommended route for commercial vessels en route to and departing the Port of Boston) transits the sanctuary, these vulnerable marine species are at high risk of collisions with vessels and exposure to shipping noise.

Beginning in January 2005, a collaborative research team comprised of SBNMS, NOAA Fisheries' Northeast Fisheries Science Center, and Cornell

University's Bioacoustics Research Program deployed nine-ten autonomous recording units (ARUs) (Calupca, Fristrup, & Clark, 2000) to monitor the low frequency (10-1000Hz) acoustic environment of the SBNMS. Through additional collaboration with the US Coast Guard's Research and Development Center, data from four Automatic Identification System (AIS) receivers have been used to track all large commercial traffic transiting Massachusetts Bay and surrounding waters. Under the International Maritime Organization (IMO)'s current mandates, all ocean-going commercial traffic over 300 gross tons or carrying over 165 passengers, as well as all tugs and tows, are required to carry Automatic Identification System (AIS) transmitters (Federal Register, 2003; IALA, 2004). Shipboard AIS transponders transmit a vessel's position, identity and other characteristics (including but not limited to length, beam, draught, cargo type, destination and speed) as often as every two seconds.

AIS data are extracted by the SBNMS and the University of New Hampshire's Center for Coastal and Ocean Mapping using custom software written in Python (Python Software Foundation, 2007) added to the NOAA package (Schwehr, 2007). Analyses are then conducted to describe the abundance, behaviour and distribution of different vessel types over various spatial and temporal scales. Analysis of received levels at each ARU are used to compare the low frequency intensities of highly trafficked versus less highly trafficked locations of the sanctuary. Variations in received levels are then correlated with variations in vessel abundance, distribution and/or behaviour. Future research will continue to quantify the relative contribution of noise per vessel type to the sampling region's total "noise budget" (NRC, 2003). These analyses, together with synchronous year-long analyses of vocal behaviours of several endangered whale species in the SBNMS, will be used to inform management of sanctuary resources and initiate sanctuary ocean noise policy. For example, better understanding the large-scale and long-term behaviour of vessels and their acoustic footprints is currently aiding the SBNMS to quantify acoustic benefits to whales due to the recent shifting and narrowing of the Boston Traffic Separation Scheme (IMO, 2006).

Summary

Although descriptive data, including time-series data from longer-term monitoring efforts, continue to be collected and analyzed, it is clear that noise from numerous anthropogenic sources is both extensively and increasingly present within the marine environment. Technological innovation and climate change are allowing human activities to leave both deeper and larger acoustic "footprints" in the world's oceans. In response to increased accessibility and/or the growing use of remote sensing capabilities, new acoustic signals continue to be designed to address commercial, research and defense needs. In addition to purposeful use of acoustic sources, incidental noise from coastal development and vessel traffic are exposing greater proportions of marine life to increasing levels of noise. The vast majority of human-produced sources of underwater noise have intensified over a very short timeframe in evolutionary terms, providing only a few generations (at most) for species to adapt.

Experts agree that a better understanding of the relative contributors to the total ocean noise in areas of concern is needed. With its high concentrations of both acoustically-active endangered species and human activities that produce noise, Stellwagen Bank National Marine Sanctuary represents a perfect test-bed for both characterizing noise inputs and examining their impacts on marine life. Results from this highly collaborative research effort will be used to assist government agencies in fulfilling their responsibilities to identify, implement and monitor means of balancing the protective needs of marine species and ecosystems with the commercial, recreational, research and defensive needs of humans.

References

Andrew, R. K., Howe, B. M. & Mercer, J. A. (2002). Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. *Acoustics Research Letters Online*, **3**, 65-70.

Bartlett, M. L. & Wilson, G. R. (2002). Characteristics of small boat signatures (Abstract only). *Journal of the Acoustical Society of America*, **112**(5), 2221.

Berta, A., Sumich, J. L. & Kovacs, K. M. (2006). *Marine Mammals Evolutionary Biology* (2nd ed.). Burlington, MA: Elsevier Inc.

Bradbury, J. W. & Vehrencamp, S. L. (1998). *Principles of Animal Communication*. Sunderland, MA: Sinauer Associates, Inc.

Brownell, Jr., R. L., Yamada, T., Mead, J. G. & van Helden, A. L. (2004). *Mass Strandings of Cuvier's Beaked Whales in Japan: U.S. Naval Acoustic Link?* Paper SC56/E37 presented to the Scientific Committee at the 56th Meeting of the International Whaling Commission, 29 June - 10 July 2004, Sorrento, Italy. (Unpublished. Available from the Office of the Journal of Cetacean Research and Management).

Calupca, T. A., Fristrup, K. M. & Clark, C. W. (2000). A compact digital recording system for autonomous bioacoustic monitoring (Abstract only). *Journal Acoustical Society of America*, **108**(5), 2582.

Cato, D. H. (1976). Ambient sea noise in waters near Australia. *Journal of the Acoustical Society of America*, **60**(2), 320-328.

Clark, C. W. & Altman, N. S. (2006). Acoustic detections of blue whale (*Balaenoptera musculus*) and fin whale (*B. physalus*) sounds during a SURTASS LFA exercise. *IEEE Journal of Oceanic Engineering*, **31**(1), 120-128.

Cato, D. H. & McCauley, R. D. (2002). Australian research in ambient noise. *Acoustic Australia*, **30**, 13-20.

Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K., Barlow, J., Caldwell, J., Cranford, T., Crum, L., D'Amico, A., D'Spain, G., Fernández, A., Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., Hullar, T., Jepson, P. D., Ketten, D., MacLeod, C. D., Miller, P., Moore, S., Mountain, D., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Mead, J. & Benner, L. (2006). Understanding the impacts of anthropogenic sound on beaked whales. *Journal of Cetacean Research and Management*, **7**(3), 177-187

Croll, D. A., Clark, C. W., Calambokidis, J., Ellison, W. T. & Tershy, B. R. (2001). Effect of anthropogenic low-frequency noise on the foraging ecology of *Balaenoptera* whales. *Animal Conservation*, **4**, 13-27.

Curtis, K. R., Howe, B. M. & Mercer, J. A. (1999). Low-frequency ambient sound in the North Pacific: long time series observations. *Journal of the Acoustical Society of America*, **106**, 3189-3200.

Discovery of Sound in the Sea (a). *Science of Sound in the Sea: Sound*. Retrieved 2 August 2007 from http://www.dosits.org/science/whatis/frequency.htm.

Discovery of Sound in the Sea (b). *Science of Sound in the Sea: Sound Movement*. Retrieved 2 August 2007 from http://www.dosits.org/science/sndmoves/4.htm.

Discovery of Sound in the Sea (c). *Animals and Sound in the Sea: Effects of Sound*. Retrieved 2 August 2007 from http://www.dosits.org/animals/effects/e2a.htm.

Erbe, C. (2002). Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. *Marine Mammal Science*, **18**(2), 394-418.

Erbe, C. & Farmer, D. M. (2000). Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea. *Journal Acoustical Society of America*, **108**, 1332-1340.

Erbe, C. & Farmer, D. M. (1998). Masked hearing thresholds of a beluga whale (*Delphinapterus leucas*) in icebreaker noise. *Deep Sea Research*, **45**, 1373-1387.

Federal Register. (2003). Automatic Identification System; Vessel Carriage Requirement. *U.S. Federal Register*. **68**(204), 60559-60570.

Fristrup, K. M., Hatch, L. T. & Clark, C. W. (2003). Variation in humpack whale (*Megaptera novaengliae*) song length in relation to low-frequency sound broadcasts. *Journal of the Acoustical Society of America*, **113**, 3411-3424.

Goold, J. C. & Coates, R. F. W. (2006). *Near Source, High Frequency Air-Gun Signatures*. Paper SC/58/E30 presented to the International Whaling Commission Seismic Workshop, 24-25 May 2006, St. Kitts. (Unpublished. Available from the Office of the Journal of Cetacean Research and Management).

Goold, J. C. & Fish, P. J. (1998). Broadband spectra of seismic survey airgun emissions, with reference to dolphin auditory thresholds. *Journal of the Acoustical Society of America*, **103**(4), 2177-2184.

Gray, L. M. & Greeley, D. S. (1980). Source level model for propeller blade rate radiation for the world's merchant fleet. *Journal Acoustical Society of America*, **67**(2), 516-522.

Hatch, L. T., Clark, C. W., Merrick, R., Van Parijs, S., Ponirakis, D., Schwehr, K., Thompson, M. & Wiley, D. (in review). Characterizing the relative contributions of large vessels to total ocean noise fields: a case study using the Gerry E. Studds Stellwagen Bank National Marine Sanctuary. *Environmental Management*.

Hildebrand, J. A. (2005). Impacts of anthropogenic sound. In J. E. Reynolds, III, W. F. Perrin, R. R. Reeves, S. Montgomery, & T. J. Ragen (Eds.), *Marine Mammal Research: Conservation Beyond Crisis* (pp. 101-124). Baltimore: Johns Hopkins University Press.

IALA – International Association of Marine Aids to Navigation and Lighthouse Authorities. (2004). *IALA Guideline No. 1028 On The Automatic Identification (AIS): Part I Operational Issues* (1.3 ed.). Saint Germain en Laye, France: IALA. 131 pp. Available at: http://www.navcen.uscg.gov/enav/ais/IALA_AIS_Guidelines_Vol1_Pt1%20OPS%20(1.3).pdf.

ICES – International Council for the Exploration of the Sea (2005). *Report of the Ad-hoc Group on the Impact of Sonar on Cetaceans and Fish* (AGISC) (2nd ed.). CM 2006/ACE. Denmark: ICES. IMO – International Maritime Organization (2006). *New and Amended Existing Traffic Separation Schemes*. Maritime Safety Committee COLREG.2/Circ.58, Ref. T2-OSS/2.7.1. London: IMO.

Madsen, P. T. (2005). Marine mammals and noise: Problems with root mean square sound pressure levels for transients. *Journal of the Acoustical Society of America*, **117**(6), 3952-3957.

McDonald, M. A., Hildebrand, J. A. & Wiggins, S. M. (2006). Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California. *Journal Acoustical Society of America*, **120**(2), 711-718.

Miller, P. J. O., Biassoni, N., Samuels, A. & Tyack, P. L. (2000). Whale songs lengthen in response to sonar. Nature, **405**, 903.

MMC – U.S. Marine Mammal Commission (2007). *Marine Mammals and Noise: A Sound Approach to Research and Management*. A Report to the US Congress from the Marine Mammal Commission. Bethesda, MD: U.S. Marine Mammal Commission.

Morisaka, T., Shinohara, M., Nakahara, F. & Akamatsu, T. (2005). Effects of ambient noise on the whistles of Indo-Pacific bottlenose dolphin populations. *Journal of Mammalogy*, **86**(3), 541-546.

Munk, W., Worcester, P. & Wunsch, C. (1995). *Ocean Acoustic Tomography*. New York, NY: Cambridge University Press.

Nieukirk, S.L., Stafford, K.M., Mellinger, D.K., Dziak, R.P. & Fox, C.G. (2004). Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. *Journal of Acoustical Society of America*, **115**(4), 1832-1843.

Nowacek, D. P., Thorne, L. H., Johnston, D. W. & Tyack, P. L. (2007). Responses of cetaceans to anthropogenic noise. *Mammalian Review*, **37**(2), 81-115.

NRC – U.S. National Research Council (2003). *Ocean Noise and Marine Mammals*. Washington, DC: National Academy Press.

NRC – U.S. National Research Council (1994). *Low-Frequency Sound and Marine Mammals: Current Knowledge and Research Needs*. Washington, DC: National Academy Press.

Payne, R. & Webb, D. (1971). Orientation by means of long range acoustic signaling in baleen whales. *Annals of the New York Academy of Sciences*, **188**, 110-141.

Python Software Foundation. (2007). Python. v2.5.1.

Richardson, W. J., Greene, Jr., C. R., Malme, C. I. & Thomson, D. H. (1995). *Marine Mammals and Noise*. San Diego, CA: Academic Press, 576 pp.

Schwehr, K. (2007). noaadata - Python software for processing AIS and water level data. v0.29. Durham, NH. Available from:
http://vislab-ccom.unh.edu/~schwehr/software/noaadata.

Southall, B. L. (2005). *Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology*. Final Report of the National Oceanic and Atmospheric Administration (NOAA) International Symposium 18-19 May 2004, Arlington, Virginia, U.S.A. Silver Spring, MD: NOAA Fisheries Acoustics Program.

Southall, B. L., Schusterman, R. J. & Kastak, D. (2000). Masking in three pinnipeds: underwater, low-frequency critical thresholds. *Journal Acoustical Society of America*, **108**(3), 1322-1326.

Tyack, P.L., & C.W. Clark. (1998). *Quick-Look Report: Playback of Low-Frequency Sound to Gray Whales Migrating Past the Central California Coast*. Unpublished. - January, 1998.

Urick, R.J. (1983). *Principles of Underwater Sound* (3rd ed.). New York: McGraw-Hill, Inc.

Weilgart, L. S. (2007). A brief review of known effects of noise on marine mammals. *International Journal of Comparative Psychology*, **this issue**, 159-168.

Wenz, G. M. (1962). Acoustic ambient noise in the ocean: Spectra and sources. *Journal of the Acoustical Society of America*, **34**, 1936-1956.

Zakarauskas, P., Chapman, D.M.F. & Staal, P.R. (1990). Underwater acoustic ambient noise levels on the eastern Canadian continental shelf. *Journal of the Acoustical Society of America*, **87**(5), 2064-2071.