Sources of Anthropogenic Sound in the Marine Environment

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ABSTRACT

Anthropogenic sound is created in the ocean both purposefully and unintentionally. The result is noise pollution that is high-intensity and acute, as well as lower-level and chronic. The locations of noise pollution are along well-traveled paths in the sea and particularly encompass coastal and continental shelf waters. Increased use of the sea for commercial shipping, geophysical exploration, and advanced warfare has resulted in a higher level of noise pollution over the past few decades. Informed estimates suggest that noise levels are at least 10 times higher today than they were a few decades ago.

A long-term monitoring program is needed to track future changes in ocean noise. Acoustic data should be included in global ocean observing systems now being planned by U.S. and international research foundations. Data from these monitoring systems should be openly available, and accessible to decision makers in industry, in the military, and in regulatory agencies. In tandem, a database should be developed to collect, organize and standardize data on ocean noise measurements and related anthropogenic activities. Currently, data regarding shipping, seismic exploration, oil and gas production, and other marine activities are either not collected or are difficult to obtain and analyze because they are maintained by separate organizations. Marine noise measurements and anthropogenic source data should be used to develop a global model of ocean noise. An important component of model development is better understanding of the characteristics for anthropogenic noise sources such as commercial shipping, arigun arrays, and military sonar. Research should be conducted relating the overall levels of anthropogenic activity (such as the types and numbers of vessels) with the resulting noise.

INTRODUCTION

Sources of anthropogenic noise are becoming both more pervasive and more powerful, increasing both oceanic background sound levels and peak intensity levels. Ambient noise in the ocean has increased over the past 50 years at both low frequencies (less than 1000 Hz) and mid-frequencies (1-20 KHz). Contributors to anthropogenic ambient noise are commercial shipping, defense-related activities, hydrocarbon exploration and development, research activities, and recreational activities.

Sound is an extremely efficient way to propagate energy through the ocean, and marine mammals have evolved to exploit its potential. Many marine mammals use sound as a primary means for underwater communication and sensing. The sound environment of the ocean is an important aspect of marine mammal habitat and we can expect marine mammals to choose their locations and modify their behavior based, in part, on natural and anthropogenic sounds.

Human presence at sea is normally on the surface, and the sounds that we produce within the water are rarely given much consideration. The air-sea interface creates a substantial sound barrier. Sounds waves in the water are reduced in intensity by more than a factor of a thousand when crossing the air-sea boundary. This means that we are effectively insulated from the noise produced by rotating propellers that drive our ships or by high-intensity sonars used to measure the depth or probe the interior of the sea. The conflict between human and marine mammal use of the sea is fundamentally a consequence of the fact that we do not inhabit the same sound environment. Marine mammals live with their ears in the water, and we live, even at sea, with our ears in the air.

A notable exception is when the military uses submarines, and stealth is required. Minimization of sound production then becomes crucial to survival. Reduction in noise has been achieved by placing rotating machinery on isolating mounts and by designing efficient propellers that thrust without unnecessary accompanying vibrations and cavitations. Thus, when it has seemed important to keep the sea quiet, the necessary technology has been developed and made available. .

PHYSICS OF SOUND

Sound is a vibration or acoustic wave that travels through some medium, such as air or water. Acoustic waves can be described either by the speed at which a small piece of the medium vibrates, called the particle velocity, or by the corresponding pressure associated with the vibration. Frequency is the rate of vibration, given in Hertz (Hz) or cycles per second; we perceive frequency as the pitch of the sound. A tone is a sound of a constant frequency that continues for a substantial time. A pulse is a sound of short duration, and it may include a broad range of frequencies.

In water, sound waves are typically measured by their pressure using a device called a hydrophone. When discussing ambient noise, the implicit assumption is that sound pressure fluctuations are being described, although it is not clear whether a particular marine organism is able to sense particle velocity or acceleration. Sound pressure is measured in Pascals (Pa) in the international system of units (SI), although it is expressed in bars by the geophysical community (1 Pa = 10^{-5} bar). Since mammalian hearing and sound production cover a large range of pressure values, sound pressure level (SPL) is usually measured on a logarithmic scale called the decibel (dB), and compared against a 1 µPa reference (P_o) for underwater sound as follows:

$$\text{SPL dB re: } 1\ \mu\text{Pa} = 10 \log_{10} (P / P_o)^2$$

$$\text{SPL dB re: } 1\ \mu\text{Pa} = 20 \log_{10} (P / P_o)$$

Pressure is squared in the above expression as a proxy for acoustic intensity, that is, the power flow per unit area in the sound wave, with units of Watts/m^2. Sound intensity is the product of pressure (P) and particle velocity (v). Acousticians working in one medium (water or air) use the fact that for plane waves the pressure and particle velocity are related by the characteristic impedance (Z) of the medium as follows:

$$Z = P / v$$

This allows the acoustic intensity (I) to be related to the pressure squared, divided by the impedance:

$$I = 10 \log_{10} (P^2 /(Z^* I_o))$$

Acoustic power is obtained by integrating intensity over some area, and acoustic energy is obtained by integrating the power over some time period. The same acoustic energy can be obtained from a high-intensity source over a short time (impulse) and a low-intensity source over a long time (continuous wave).

Underwater sounds are classified according to whether they are transient or continuous. Transient sounds are of short duration, often called pulses, and they may occur singly, irregularly, or as part of a repeating pattern. For instance, an explosion represents a single transient, whereas the periodic pulses from a ship's sonar are patterned transients. Underwater sounds also can be classified as continuous, that is, they occur without a pause or hiatus. Continuous sounds are further classified as periodic, such as the sound from rotating machinery or pumps, or aperiodic, such as the sound of a ship breaking ice.

Pulsed sounds are measured in terms of their total energy, rather than just their pressure or intensity. Pressure and power measures are difficult to interpret for a brief pulse since they depend on the averaging time. Energy is proportional to the time integral of the squared pressure, described in the units µPa^2-s. For brief pulses, energy in dB re: µPa^2-s is less than peak squared pressure values in dB µPa^2. As others have warned, better standardization of measurement methods for pulsed underwater sounds is urgently needed to permit meaningful comparisons (Greene 1995).

Ambient noise in the ocean is the background sound that incorporates the broad range of individual sources, some identified and others not. Ocean noise may come both from distant sources, such as ships, or from nearby sources, such as the waves breaking directly above the listener. Although ambient noise is always present, the individual sources that contribute to it do not necessarily create sound continuously.

NATURAL SOUND IN THE OCEAN

The ambient acoustic environment of the ocean is highly variable. At a given time and place, a broad range of sources may be combined. In addition, conditions at a particular location may affect how well ambient sounds are received (e.g., sound propagation, water depth, bathymetry, and depth). Natural phenomena known to contribute to oceanic ambient noise include: (a) wind, sea state and swell patterns, (b) bubble distributions, (c) currents and turbulence, (d) seismic activity, (e) precipitation, (f) ice cover and activity, and (g) marine life.

Wind, Waves and Ice

Ocean surface motions due to wind, sea state and swell patterns are the dominant physical mechanisms for natural sound in the ocean. Noise is primarily associated with wind acting on the surface, causing wave activity. In the absence of anthropogenic and biological sound, ambient noise is wind dependent over an extremely broad frequency band from below 1 Hz to at least 100 kHz. At frequencies below 10 Hz, interactions of surface gravity waves are the dominant mechanisms for sound generation. Across the remainder of the band from 10 Hz – 100 kHz, oscillating bubbles in the water column are the primary noise source, both as individual bubbles and as bubble clouds.

In early descriptions, ocean noise was related to sea state (Knudsen et al. 1948). By this theory, noise levels increase with increasing sea state by the same amount across the entire frequency band from 1 kHz to 100 kHz. More recent work has suggested that noise is better correlated with wind speed than with sea state or wave height. The correlation between noise and wind speed allows for more accurate prediction, as sea states are more difficult to estimate than wind speeds. In the open ocean, the noise of breaking waves is correlated with wind speed. Spilling and plunging breakers raise underwater sound levels by more than 20 dB across the band from 10 Hz to 10 kHz (Wilson et al. 1985). Precipitation is another factor that can increase ambient noise levels by up to 35 dB across a broad band of frequencies from 100 Hz to more than 20 kHz (Nystuen and Farmer 1987). Ice cover alters the ocean noise field depending on its type and degree, for instance, whether it is shore-fast pack ice, moving pack ice, or at the marginal ice zone (Milne 1967). Shore-fast pack ice isolates the water column from the effects of wind, and results in a decrease in ambient noise of 10-20 dB. Sounds from ice cracking, however, may increase noise levels by as much as 30 dB. Ice cracking can generate broadband pulses up to 1 kHz lasting for a second or longer. Interaction of ocean waves with the marginal ice zone may raise noise levels by 4-12 dB (Diachok and Winokur 1974).

Earthquakes

Earthquakes and thunder are examples of transient natural sound sources. Underwater recordings of thunder from storms 5 to10 km distant show peak energy between 50 and 250 Hz, up to 15 dB above background levels (Dubrovsky and Kosterin 1993). Seismic energy from undersea earthquakes couples into the ocean and is called T-phase (tertiary) in addition to the usual P-phase (primary) and S-phase (secondary) seismic waves that are observed on land. At ranges of less than 100 km, T-phase energy can have frequencies greater than 100 Hz, with peak energy at 5-20 Hz. It can be as much as 30-40 dB above background noise, with a sharp onset, and can last from a few seconds to several minutes (Schreiner et al. 1995).

ANTHROPOGENIC SOUND IN THE OCEAN

Human activity in the marine environment is an important component of the total oceanic acoustic background. Sound is used both as a tool for probing the ocean and as a byproduct of other activities. Anthropogenic noise sources vary in space and time, but may be grouped into general categories: (a) large commercial ships, (b) airguns and other seismic exploration devices, (c) military sonars, (d) ship-mounted sonars, (e) pingers, (f) acoustic harassment devices (AHDs), (g) polar ice-breakers, (h) offshore drilling implements, (i) research sound sources, and (j) small ships.

Commercial Shipping

At low frequencies (5 to 500 Hz), commercial shipping is the major contributor to noise in the world's oceans. Distant ships contribute to the background noise over large geographic areas. The sounds of individual vessels are often spatially and temporally indistinguishable in distant vessel traffic noise. Noise from vessel traffic at high latitudes is particularly efficient at propagating over large distances because in these regions the oceanic sound channel (zone of most efficient sound propagation) reaches the ocean surface.

Ships generate noise primarily by (a) propeller action, (b) propulsion machinery, and (c) hydraulic flow over the hull. Propeller noise is associated with cavitation (Ross 1987, 1993), the creation of voids from zones of pressure above the ambient. The collapse of these voids generates sound. Cavitation creates both broadband noise and tonal sounds, as it may be modulated by blade-passage frequencies and their harmonics (the blade lines). The broadband and tonal components produced by cavitation account for 80-85 percent of ship-radiated noise power (Ross 1987). Propeller noise may be also generated by unsteady propeller blade-passage forces. Additional ship noise results from propulsion machinery such as diesel engines, gears, and major auxiliaries such as diesel generators.

Particular vessels produce unique acoustic signatures associated with noise source levels and frequency bands. Sharp tonal peaks produced by rotating and reciprocating machinery such as diesel engines, diesel generators, pumps, fans, blowers, hydraulic power plants, and other auxiliaries often are seen in these acoustic signatures. Hydrodynamic flow over the ship's hull and hull appendages is an important broadband noise-generating mechanism, especially with increased ship speed. At relatively short ranges and in isolated environments, the spectral characteristics of individual ships can be discerned. At distant ranges in the open ocean, multiple ships contribute to the background, and the sum of many distant sources creates broad spectral peaks of noise in the 5 to 500-Hz band.

Models for representative noise spectra for different classes of ships have been developed by the U.S. Navy. The Research Ambient Noise Directionality (RANDI) model (Wagstaff 1973; Schreiner 1990; Breeding 1993) uses ship length and speed as well as an empirically derived power law to determine the broadband (5-500 Hz) spectral level for various classes of vessels. Peak spectral densities for individual ships range from 195 dB re $\mu Pa^2/Hz$ @ 1 m for fast moving supertankers, to 140 dB re $\mu Pa^2/Hz$ @ 1 m for small fishing vessels. Source-level models have been also developed for the propeller tonal blade lines, occurring at 6-10 Hz for most of the world's large merchant fleet (Gray and Greeley 1980). Small vessels do not contribute significantly to the global ocean acoustic environment, but may be important local sound sources. Examples of noise levels for whale-watching boats are presented by (Au and Green 2000) and (Erbe 2002). A recent study of noise levels from small powerboats suggests peak spectral density levels in the 350-1200 Hz band of 145-150 dB re $1\mu Pa^2/Hz$ @ 1 m (Bartlett and Wilson 2002).

Vessel traffic is not uniformly distributed. The major commercial shipping lanes follow great circle routes, or follow coast lines to minimize the distance traveled. Dozens of major ports and "megaports" handle the majority of the traffic, but in addition hundreds of small harbors and ports host smaller volumes of traffic. The U.S. Navy defines 521 ports and 3,762 traffic lanes in its catalog of commercial and transportation marine traffic (Emery et al. 2001). Vessels found in areas outside major shipping lanes include fishing vessels, military ships, scientific research ships, and recreational craft – the last typically found near shore.

Lloyd's Register of the world's commercial fleet for the year 2001 listed 92,817 vessels (NRC 2003). The principal types (their numbers in parentheses) are cargo/passenger transport (34,704), fishing (23,841), towing/dredging (13,835), oil tankers (10,941), bulk dry transport (6,357), and offshore supply (3,139).

Gross tonnage may be a more important index of noise production than vessel numbers. From that perspective, oil tankers and bulk dry transport vessels represent nearly 50 percent of the total tonnage, but less than 8 percent of the total number of vessels.

The numbers of recreational craft are poorly documented. Some information on the number of U.S. boat registrations, by state and category, is available from the National Marine Manufacturer's Association (2003). The vessel categories are outboard, inboard, sterndrive, personal watercraft, sailboats, and miscellaneous.

Vessel operation statistics indicate steady growth in vessel traffic over the past few decades (Mazzuca 2001). There has been an increase both in the number of vessels and in the tonnage of goods shipped. For example, a 30 percent increase has occurred in the volume of goods shipped by the U.S. fleet (by flag and ownership) over the past 20 years (U.S. Maritime Administration, 2003). Oceanic shipping is an efficient means of transporting large quantities of goods and materials globally. The globalization of economic infrastructure means that more raw materials, as well as finished goods, require long-distance transport. The economic incentives for oceanic shipping are strong, and in the near term, there is no viable alternative for transporting large-tonnage materials to distant global locations.

Seismic Exploration

Seismic reflection profiling uses high-intensity sound to image the earth's crust. It is the primary technique used by the energy industry for finding and monitoring reserves of oil and natural gas. Seismic reflection profiling is used by academic and government groups to gather information on crustal structure, for the purpose of understanding the origin and tectonic history of the earth's crust.

Arrays of airguns are the sound-producing elements in seismic reflection profiling (Dragoset 1984, 2000). Airguns release a specified volume of air under high pressure, creating a sound pressure wave from the expansion and contraction of the released air bubble. To yield high intensities, multiple airguns are fired with precise timing to produce a coherent pulse of sound. Oil industry airgun arrays typically involve 12 to 48 individual guns, operate at pressures of 2000 psi, and are dispersed over a 20 m by 20 m region, typically towed about 200 m behind a vessel. The pressure output of an airgun array is proportional to (1) its operating pressure, (2) the number of airguns, and (3) the cube root of the total gun volume. For consistency with the underwater acoustic literature, airgun-array source levels are back-calculated to an equivalent source concentrated into a one-meter-radius volume, yielding source levels as high as 256 dB re 1μPa @ 1 m for the Root-Mean-Square (RMS) output pressure(Greene and Moore 1995). This source level predicts pressures in the far-field of the array, but in the near-field the maximum pressure levels encountered are limited to 235-240 dB re 1μPa. The far field pressure from an airgun array is focused vertically, being about 6 dB stronger in the vertical direction than in the horizontal direction for typical arrays. The peak pressure levels for industry arrays are in the 5-300 Hz range. The guns are towed at speeds of about 5 knots and are typically fired about every 10 seconds. A seagoing seismic-reflection operation includes a series of parallel passes through an area by a vessel towing an airgun array as well as 6-10 seismic receiving streamers. A recent practice is the use of repeated seismic reflection surveys for "time-lapse" monitoring of producing oil fields.

Offshore oil and gas exploration and construction activities occur along continental margins. Currently active areas include northern Alaska and northwestern Canada, eastern Canada, the U.S. and Mexican Gulf of Mexico, Venezuela, Brazil, West Africa, South Africa, North Sea, Middle East, northwestern Australia, New Zealand, southern China, Vietnam, Malaysia, and Indonesia. New areas of exploration include the deepwater U.S. Gulf of Mexico and deepwater West Africa, both of which have seen activity in the past 5 to10 years. A recent study of ambient noise in the North Atlantic suggests that airguns activity along the continental margins propagates into the deep ocean and is a significant component of low frequency noise (Nieukirk et al. 2004).

Sonar

Sonar systems intentionally create acoustic energy to probe the ocean. They seek information about objects within the water column, at the sea bottom, or within the sediment. Active sonar emits high-intensity acoustic energy and receives reflected and/or scattered energy. A wide range of sonar systems are in use for both civilian and military applications. For purposes of discussion, sonar systems can be categorized as low-frequency (< 1000 Hz), mid-frequency (1 – 20 kHz), and high-frequency (> 20 kHz).

Military sonars are used for target detection, localization, and classification. They generally cover a broader frequency range with higher source levels than civilian sonars. They are operated during both training exercises and combat operations. Because far more time is spent in training than in combat, training exercises may be the primary context in which marine mammals are exposed to military sonar. Low Frequency Active (LFA) sonars are used for broad-scale surveillance; they are designed to allow submarine tracking over scales of many hundreds to thousands of kilometers. Specialized support ships are used to deploy LFA sonars, which consist of arrays of source elements suspended vertically below the ship. The U.S. Navy's Surveillance Towed Array Sensor System (SURTASS) LFA sonar uses an array of 18 projectors operating in the frequency range of 100 to 500 Hz, with 215 dB re 1μPa @ 1 m source level for each projector (Johnson 2002). These systems are designed to project beams of energy in a horizontal direction. The effective source level of an LFA array, when viewed in the horizontal direction, can be 235 dB re 1μPa @ 1 m or higher. The signal includes both continuous-wave (CW) and frequency-modulated (FM) components with a bandwidth of approximately 30 Hz. A ping sequence can last 6 to 100 seconds, with a time between pings of 6 to 15 minutes and a typical duty cycle of 10 to 15 percent. Signal transmissions are emitted in patterned sequences that may last for days or weeks.

Mid-frequency tactical Anti-Submarine Warfare (ASW) sonars are designed to detect submarines over several tens of kilometers. They are incorporated into the hulls of submarine-hunting surface vessels such as destroyers, cruisers, and frigates. There are 117 of these sonars on U.S. Navy ships currently in active service, and equivalent systems in allied navies (e.g., British, Canadian, French). The AN/SQS-53 is the most advanced surface ship ASW sonar used by the U.S. Navy. The AN/SQS-53C sonar generates frequency-modulated pulses of 1-2 second duration in the 1-5 kHz band, at source levels of 235 dB re 1μPa @ 1 m or higher (Evans and England 2001). These sonars emit beams of sound in the horizontal direction. The AN/SQS-53C is designed to perform direct-path ASW search, detection, localization, and tracking from a hull mounted transducer array of 576 elements housed in a bulbous dome located below the waterline of the ship's bow. These systems are used to track both surface and submerged vessels, often picking up surface ships at greater range than most radar systems.

Other mid-frequency military sonars in use by the Navy include depth sounders and communication sonars for interplatform information exchange or device activation. High-frequency sonars are incorporated either into weapons (torpedoes and mines) or weapon countermeasures (mine countermeasures or anti-torpedo devices). They are designed to operate over ranges of a few hundred meters to a few kilometers. Mine-hunting sonars operate at tens of kHz for mine detection and above 100 kHz for mine localization. These sonars are highly directional and use pulsed signals. Other high-frequency military sonars include sidescan sonar for seafloor mapping, generally operated at frequencies near 100 kHz.

Over the past decade, there has been a trend in the U.S. Navy to emphasize training operations in coastal and shallow-water settings. There are currently plans to construct shallow-water training ranges on both the U.S. West and East Coasts. The use of active sonar in these settings means that large numbers of marine mammals may be exposed to high-intensity sonar.

Commercial sonars are designed for fish finding, depth sounding, and sub-bottom profiling. They typically generate sound at frequencies of 3 to 200 kHz, with only a narrow frequency band generated by an individual sonar system. Source levels range from 150-235 dB re 1μPa @ 1 m. Commercial depth sounders and fishfinders are typically designed to focus sound into a downward beam. Depth sounders and sub-bottom profilers are operated primarily in nearshore and shallow environments, however, fish finders are operated in both deep and shallow areas.

The acoustic characteristics of small-scale commercial sonars are unlikely to change significantly in the future since they are limited by several key physical properties. At the low-frequency end (about 3 kHz), they are limited by the physical dimensions of the transducers. At the high-frequency end (200 kHz) they are limited by severe attenuation of sound. Likewise, the maximum power level that can be emitted by a single transducer (200 dB re 1µPa @ 1 m) is limited by cavitation at shallow depths of operation. Higher power levels can be achieved by constructing arrays of sensors on the hull of the vessel. For example, multibeam echosounding systems (e.g., SeaBEAM or Hydrosweep) form narrow directional beams of sound and are used for precise depth sounding. Using hull-mounted arrays of transducers, these systems can achieve 235 dB re 1µPa @ 1 m source levels and are typically operated at 12-15 kHz in deep water, and at higher frequencies (up to 100 kHz) in shallow water.

A significant fraction of the 80,000 vessels in the world's commercial fleet and the 17 million small boats owned in the US are equipped with some form of commercial sonar. Sonar is an extremely efficient means for fish finding and depth sounding/sub-bottom profiling, and new applications may lead to even greater proliferation of these systems.

Research in underwater acoustic propagation and acoustical oceanography often involves use of sound sources. Almost all of these programs are sponsored by the Office of Naval Research, and the information obtained is of value for improving military sonar systems. The sound sources used for these studies are either commercially available transducers or systems specially designed to meet specific research requirements. A wide variety of signals, bandwidths, source levels, and duty cycles are transmitted during these projects. The spatial extent of most experiments is tens of kilometers, but basin-scale projects such as the Acoustic Thermometry of Ocean Climate (ATOC) program have also been undertaken.

The ATOC (later the North Pacific Acoustic Laboratory [NPAL]) project was initiated in the early 1990s to study ocean warming, and received much attention from regulatory agencies, the public, and the scientific community due to concerns regarding the potential impact of its sound source on marine mammals (Baggeroer et al. 1998). This program was extensively discussed in two National Research Council reports (NRC 1994, 2000). The ATOC source has a 195 dB re 1µPa @ 1 m level and is deployed at 939 m, near the axis of the deep sound channel (Howe 1996). It is designed to study the entire North Pacific basin, with the sounds being received by the U.S. Navy's fixed hydrophone arrays. The transmitted signal is centered at 75 Hz with a bandwidth of 37.5 Hz. It broadcasts on 4-hour intervals with a "ramp-up" period of 5 minutes and a full power signal duration of 20 minutes. The long time frame for operation of this experiment was a key aspect that led to questions regarding its potential impacts on marine mammals (Potter 1994).

Another basin-scale sonar research project uses drifting sources (Rossby et al. 1986), called SOFAR or RAFOS floats. These devices drift at depth and periodically emit a high-intensity tone (195 dB re 1µPa @ 1 m) that is frequency swept at 200-300Hz or a CW signal at 185-310 Hz with durations of 120 sec or more. The sounds are detected at distant receivers and their timing is used to determine the float location and therefore its drift, as a proxy for deep currents.

Acoustic Deterrent Devices

Acoustic deterrent devices (ADD) use sound in an effort to repel marine mammals from fisheries activities. The idea behind these devices is that they keep marine mammals away by introducing a local acoustic annoyance. Pingers are used in some fisheries to reduce the bycatch of marine mammals. These are typically low-power ADDs with source levels of 130 – 150 dB re 1µPa @ 1 m. Acoustic harassment devices (AHD) are used to reduce depredation by marine mammals on caught or cultured fish. These are high-powered devices with source levels of 185 – 195 dB re 1µPa @ 1 m. Both pingers and AHDs have frequencies in the 5 – 160 kHz band, and generate pulses lasting from 2 – 2000 msec. To reduce habituation, a single device may transmit a variety of waveforms and have pseudo-random time intervals between transmissions.

Pingers have been shown to be effective in reducing bycatch, at least for some marine mammal species in some settings (Kraus et al. 1997; Culik et al. 2001; Bordino et al. 2002). A trial of pinger use in the California drift gillnet fishery for swordfish and sharks showed that for both cetaceans and pinnipeds, the entanglement rate in nets with pingers was only one third of what it was in nets without these devices (Barlow and Cameron 2003). Likewise, a large-scale trial of pingers in Danish gillnet fisheries showed a reduction in bycatch of harbor porpoises (Larsen 1997; Vinther 1999).

Concerns have arisen that use of AHDs in aquaculture facilities leads to unintended displacement of marine mammals in the cases of killer whales (Morton and Symonds 2002) and harbor porpoises (Olesiuk et al. 2002) in the vicinity of salmon farms off British Columbia. Likewise, there are concerns that widespread use of AHDs may lead to the exclusion of porpoises from important feeding habitat (Johnston 2002). AHDs have sufficiently high source levels that they could result in hearing damage to marine mammals exposed at close range.

Explosions

There are two classes of man-made explosions in or over the ocean: nuclear and chemical. Until the advent of the Comprehensive Test Ban Treaty, nuclear devices were tested regularly in the ocean, in the atmosphere above the ocean, or on oceanic islands. The most recent series of oceanic tests was conducted by France in 1995-1996 on the islands of Fangataufa and Mururoa in the South Pacific. There is currently a low probability of continued ocean testing of nuclear devices although this situation could change with geopolitical developments over the coming years or decades.

Nuclear explosion are extremely strong sources of underwater sound. It is likely that past tests had significant impacts on marine mammals in the vicinity of the test sites. No monitoring data are available, however, to document impacts of nuclear tests on marine mammals. To ensure compliance with the test ban treaty, an international monitoring system is being implemented, including a series of hydrophone- and island-based seismic stations to detect high-intensity sounds (www.ctbto.org). This information is transmitted, in real time, to the International Data Centre where analysts evaluate the data for indications of nuclear explosions. Physical characteristics of the oceans allow the sounds of such explosions to travel for extremely long distances with little energy loss, and monitoring is conducted over a large fraction of the world's oceans with a small number of stations. The network designed for ocean monitoring contains 11 stations located primarily in the Southern Hemisphere.

Clemical explosions are more portable and more easily conducted in an ocean setting. They have been used for oceanic research, for construction, and for military testing. A surprisingly large number (300-4000 per month) of underwater explosions were reported in the North Pacific during the 1960's (Spiess et al. 1968). In the past, chemical explosions were commonly used for marine seismic exploration, but they have been replaced by airgun arrays that provide a more reliable source signature. Chemical explosions continue to be used in the construction and removal of undersea structures, primarily by the oil industry, but the frequency of shot detonation presumably has decreased over the past few decades.

New classes of military vessels undergo tests, called ship-shock trials, to determine their ability to withstand explosions (Commander_Naval_Air_Warfare_Center 1994). During a ship-shock trial, a large chemical explosion (e.g. 10,000 lb) is detonated near the vessel's hull, while measurements of hull stress are conducted. Ocean explosions are also conducted by other Navy programs, such as the "Sinkex" program that sinks retired ships using torpedos or other chemical explosions. Weapons are tested during development, and operational stores are test-fired to monitor their military readiness. During the recent Iraq war, Navy SEALS disposed of a dozen 500 pound sea mines confiscated from the Iraqi Navy by simultaneously detonating them in the Persian Gulf, a blast that could be heard 50 miles away in Kuwait (Dao 2003).

The spectral and amplitude characteristics of chemical explosions vary with the weight of the charge and the depth of the detonation. The RMS source level of the initial shock wave, a large component of the energy, is given by

$$\text{SL (dB re } 1\mu\text{Pa @ 1 m)} = 269 \text{ dB} + 7.53 * \log(w),$$

where w is the charge weight in pounds (Urick 1975). For instance, 100 lb of TNT would produce a shockwave SL of 284 dB re 1μPa @ 1 m with almost constant frequency content from 10 to 1000 Hz. The energy from the bubble pulse oscillations will contribute approximately 5 additional dB of source level, yielding a total SL of 274 dB re 1μPa @ 1 m. Research on blast damage to animals suggests that the mechanical impact of a short duration pressure pulse (positive acoustic impulse) is best correlated with organ damage (Greene and Moore 1995).

Industrial Activities and Construction

Industrial activities and construction both in the ocean and along the shoreline can contribute to underwater noise. Examples include coastal power plants, pile driving, dredging, tunnel boring, power-generating wind mills, and canal lock operations (Greene and Moore 1995). The coupling of these sounds into the marine environment is poorly understood, but it is generally more efficient at low frequencies.

Marine dredging is commonly conducted in coastal waters to deepen channels and harbors, reclaim land, and mine seabed resources. Reported source levels for dredging operations range from 160 to 180 dB re 1μPa @ 1 m for 1/3 octave bands with peak intensity between 50 and 500 Hz (Greene and Moore 1995).

Oil and gas activities that generate marine noise include drilling, offshore structure emplacement and removal, and production. The associated noise levels from drilling, structures, and production are typically lower than those from seismic surveying. Sound pressure levels associated with drilling are the highest with maximum broadband (10 Hz to 10 kHz) energy of about 190 dB re 1μPa @ 1 m. Drill-ship noise comes from both the drilling machinery and the propellers and thrusters for station-keeping. Jack-ups are the most commonly used offshore drilling devices, followed by platform drill rigs. Drilling generates ancillary noise from the movements of supply boats and support helicopters. Emplacement of offshore structures creates localized noise for brief time periods. Powerful support vessels are used to transport these large structures from the point of fabrication to the point of emplacement. This activity may last for a few weeks and may occur 8 to 10 times a year worldwide. Additional noise is generated during oil production activities, which include borehole casing, cementing, perforating, pumping, pipe laying, pile driving, and ship and helicopter support. Production activities can generate source levels as high as 135 dB re 1μPa at 1 km from the source (Greene and Moore 1995) which suggests as much as 195 dB re 1μPa @ 1 m with peak levels at 40 to 100 Hz.

Oil and gas production is moving from shallow-water settings into water depths of up to 3000 m. Deep-water drilling and production have the potential to generate greater noise than shallow-water production, owing to the use of drill ships and floating production facilities. This noise may be more easily coupled into the deep sound channel for long-range propagation. The worldwide count of offshore mobile drill rigs in use fluctuates with business conditions, but there are an increasing number of drill rigs available, with an approximate 10 percent increase over the past five years.

Comparison of anthropogenic sound sources

The anthropogenic sound sources discussed above are summarized by source level and other parameters in Table 3, ordered by their relative potential for large-scale exposure of marine mammals to high-intensity sound. For high intensity sources which are constructed from arrays of elements (e.g. high intensity sonars and airguns) which can be widely distributed, the 1 m source range is a device for calculation, but in practice the actual source levels experienced near the source never reach the stated levels. Instead, these levels are used to give an accurate way to calculate what the source will be at greater ranges, where the distance to the source is much greater than the source dimensions.

Underwater nuclear tests and ship-shock trials produce the highest overall sound pressure levels, yet these are rare events and so may be assumed to have limited impacts. Military SURTASS-LFA sonars and large-volume airgun arrays both have high SPLs. The long ping lengths and nearly continuous duty cycle of LFA sonars increase their likelihood of exposing marine mammal populations on a basin-scale. Both the SURTASS-LFA and airgun arrays have dominant energy at low frequencies, where long-range propagation is likely. Tactical military sonars (such as the 53C) have shorter ping durations and more moderate duty cycles than LFA sonars; they also operate at mid-frequencies, where propagation effects limit their range. Concern for the impact of these sonars is for local settings, particularly where deep-diving animals may be present. Commercial supertankers are arguably the most ubiquitous high-intensity sound source, with more than 10,000 vessels operating worldwide. Concern with these noise sources will be concentrated near major ports and along the most heavily utilized shipping lanes.

TABLE 1. Comparison of anthropogenic underwater sound sources ordered by their potential for sound exposure.

Sound Source	SPL dBre 1µPa @1m	Ping Energy (dB re $1\mu Pa^2*s$)	Ping Duration	Duty Cycle (%)	Peak Frequency (Hz)	Band Width (Hz)	Direct-ionality
Underwater Nuclear Device (30 kilo-ton)	328	338	10 s	Inter-mittant	Low	Broad	Omni
Ship Shock Trial (10,000 lb TNT)	299	299	1 s	Inter-mittent	Low	Broad	Omni
Military Sonar (SURTASS/LFA)	235	243	6 – 100 s	10	250	30	Horizontal
Airgun Array 2000 psi and 8000 in^3	256	241	30 ms	0.3	50	150	Vertical
Military Sonar (53C)	235	232	0.5 – 2 s	6	2,600-3,300	Narrow	Horizontal
Super Tanker 270 m long	198		CW	100	23	5-100	Omni
Research Sonar (ATOC Source)	195		20 minutes	8	75	37.5	Omni
Acoustic Harrassment Device	185	185	0.5 - 2 s	50	10,000	600	Omni
Multibeam (Echosounder Hull-mounted)	235	218	20 ms	0.4	12,000	Narrow	Vertical
Research Sonar (RAFOS float)	195		120 s	small	250	100	Omni
Fishing Vessel 12 m long (7 knots)	150		CW	100	300	250-1000	Omni
Acoustic Deterrent Device (AquaMark300)	132	127	300 ms	8	10,000	2000	Omni

The moored research sound source for the ATOC project is an equivalent source level to a supertanker although it operates on a much lower duty cycle. Acoustic harassment devices have source levels of concern for long-term hearing damage, and may displace marine mammals from important habitat. Multibeam hull-mounted echo-sounders have a high source level, but their narrow beam widths and mid-frequency character limit their range and the ensonified area. Research acoustic floats (RAFOS) produce a moderately high source level but are operated at a very low duty cycle. Fishing vessels and acoustic deterrent devices have moderate source levels but may represent at least local acoustic annoyances, although in the case of ADDs there is a significant benefit from the reduction of marine mammal bycatch.

Anthropogenic noise energy budget per year

An annual energy budget is one approach to comparing the contribution of each anthropogenic noise source. The approach take here is to consider the acoustic energy output at the source itself, rather than as the sum of many sources after propagation within the ocean, as would be experienced by a receiver at a particular location. Ambient noise distributions at a given location will result from a complex distribution of worldwide sources and variable acoustic propagation. The question considered here is a simplier one: what is the total energy output from each source type at the location of the source. That is, all sources are assumed to be at a compact location, at range of 1 m, and the total annual energy output of each source type is estimated. This is clearly not the most desirable form of energy budget, but is amenable to a manageable tabulation.

Starting with the source pressure levels given in Table 1, the additional information needed to go from sound pressure to the total energy includes: the source directionality, duration, rate of usage, and total number of sources. The first step is to convert sound pressure level (p) to acoustic intensity (I), obtained from dividing the squared pressure by the acoustic impedance (ρc) as follows:

$$\mathrm{I} = |\mathrm{p}\vec{\mathrm{v}}| = \frac{|\mathrm{p}|^2}{\rho \mathrm{c}} \qquad \text{Watts/m}^2$$

This next step is to account for the directionality of the source. For omni-directional sources the acoustic power (P) is given by the solid angle (A) emitted by the source (for an omni-directional source this is 4π , the area of a sphere of 1 m radius) multiplied by the acoustic intensity (I).

$$P = A * I \qquad \text{Watts} = \text{Joules/sec}$$

The energy per source transmission or ping (E_{ping}) is given by the acoustic power, multiplied by the duration of the transmission:

$$E_{\text{per ping}} = P * T_{ping} \qquad \text{Joules}$$

The number of source pings per year per source and the total number of sources in operation yield the annual energy budget for each source type:

$$E_{total} = E_{\text{per ping}} * N_{PINGS/YEAR} * N_{SOURCES} \qquad \text{Joules}$$

For continuous sources, the energy of one second of transmission is used for E_{ping}, and the number of seconds the source is in operation per year is used for $N_{pings/year}$.

TABLE 2. Comparison of anthropogenic underwater sound sources ordered by their total annual energy output							
Sound Source	**Inten** (dB re:W/m^2)	**Direct-ional**	**Power** (dBre Watts)	**Sources**	**Ops** (Days/yr)	**Reps** (Pings/ Day)	**Total Energy** (Joules)
Underwater Nuclear Explosions	146	4π	157	1	0.05	1	2.6E+15
Airgun Arrays	61	π	66	90	80	4320	3.9E+13
Military Sonar (53C)	53	π/2	55	100	30	4320	8.5E+12
Super Tankers	3.2	2π	11	11000	300	86400	3.7E+12
Ship Shock Trials	117	4π	128	1	0.5	1	3.3E+12
Military Sonar (SURTASS/LFA)	53	π	58	1	30	175	1.7E+11
Merchant Vessels	-17	2π	-8.8	40000	300	86400	1.4E+11
Navigation Sonar	-1.8	π	3.2	100000	100	86400	3.6E+010
Research Sonar	13	4π	24	10	4	86400	9.1E+08
Fishing Vessel 12 m long (7 knots)	-42	2π	-34	25000	150	86400	1.3E+08

A proposed annual energy budget is presented in Table 2, starting with the sources and pressure levels from Table 1. Underwater nuclear explosions, assuming a 20 year recurrence rate, top the annual anthropogenic energy budget with 2.6E+15 Joules. This is comparable to a small power plant of 100 Mwatts which has an annual energy output of 3.2E+15 Joules. The most energetic regularly operated sound sources are the airgun arrays from 90 vessels operating for 80 days/year to produce 3.9E+13 Joules. Military sonars for anti-submarine warfare (SSQ-53C) operated on 100 vessels for 30 day/year produce 8.5E+12 Joules. Shipping contributes mostly from the largest vessels classes, with 11000 supertankers, operating 300 days/year to yield 3.7E+12 Joules. Lesser contributions are made by other vessel classes (e.g. merchant and fishing) and by navigation and research sonars. For comparison at the low energy end, a 100 W light bulb (common for household use) consumes 3.2E+09 Joules if operated for a year.

LONG TERM TRENDS IN OCEAN NOISE

What is the long-term trend for ocean noise? Overall trends of the level of sounds in the sea can be broken down into anthropogenic and non-anthropogenic components. For instance, there is evidence that global climate change may have resulted in higher sea states (Bacon and Carter 1993; Graham and Diaz 2001), which would increase ambient noise levels. Over the past few decades, however, it is likely that increases in anthropogenic noise have been more prominent. In order of importance, the anthropogenic sources most likely to have contributed to increased noise are: commercial shipping, offshore oil and gas exploration and drilling, and naval and other uses of sonar.

To isolate the effects of anthropogenic and non-anthropogenic noise, waters surrounding Australia, which are remote from commercial shipping, have been examined. At low frequency (100 Hz), Australian data suggest that ocean noise levels may be as low as 50 dB re 1μPa^2/Hz, which is about 30 to 40 dB below levels in North American and European waters ((Cato and McCauley 2002)). These data further suggest that wind/wave noise increases at low frequencies, in contrast to the predictions of the deepwater curves developed from northern hemisphere data (Wenz 1962). Cato (2001, from NRC2003) points to the difficulty of separating wind/wave-generated noise from shipping noise in North American datasets.

Trends in ambient noise over the past few decades suggest that sound levels have increased by 10 dB or more between 1950 and 1975 (Ross 1987, 1993). These trends are most apparent in the eastern Pacific and eastern and western Atlantic, where they are attributed to increases in commercial shipping. A doubling of the number of ships explains 3 to 5 dB, and greater average ship speeds, propulsion power, and propeller tip speeds explain an additional 6 dB.

Other data on long-term noise trends come from comparison of historical U.S. Navy acoustic array data (Wenz 1969) with modern recordings along the west coast of North America (Andrew et al. 2002). A low-frequency noise increase of 10 dB over 33 years is observed at a site off the central California coast. The explanation for a noise increase in this band is the growth in commercial shipping, in terms of both number of ships and gross tonnage. From 1972 to 1999 the total number of ships in the world's fleet increased from approximately 57,000 to 87,000, and the total gross tonnage increased from 268 to 543 million gross tons.

Mazzuca (2001) compared the results of Wenz (1969), Ross (1987), and (Andrew et al. 2002) to derive an overall increase of 16 dB in low-frequency noise from 1950 to 2000. This corresponds to a doubling of noise power (3 dB) every decade for the past five decades, equivalent to a 7 percent annual increase in noise. During this period the number of ships in the world fleet tripled (from 30,000 to 87,000) and the gross tonnage increased by a factor of 6.5 (from 85 to 550 million gross tons) (NRC 2003; from (McCarthy and Miller 2002).

OCEAN NOISE RESEARCH PRIORITIES

Ocean noise is an important component of the marine habitat. Data on ocean noise trends are scarce, however, despite substantial investment by the U.S. government in underwater sound data collection for military purposes (e.g. SOSUS and other ASW monitoring systems). Informed estimates suggest noise has increased significantly during the past few decades. Expanding use of the sea for commercial shipping and advanced warfare has resulted in noise levels are at least 10 times higher today than they were a few decades ago. Without some effort to monitor, reduce or at least cap these noise levels, they are likely to increase and further degrade the acoustic environment of marine mammals. A summary of recommendations for tracking and improving our understanding of ocean noise sources are presented in Table 4.

Table 4. Research Priorities for Understanding and Tracking Ocean Noise.	
Priority	**Research Topic**
1	Initiate long-term ocean noise monitoring programs
2	Collect, organize, and analyze historic marine anthropogenic noise data
3	Develop global models for ocean noise
4	Report signal characteristics for anthropogenic noise sources
5	Determine the relationship between anthropogenic activity level and noise level

Priority 1: Initiate long-term ocean noise monitoring
A long-term monitoring program is needed to track future changes in ocean noise (NRC 2003:90). Acoustic data should be included in global ocean observing systems now being developed by U.S. and international research foundations. Data from these monitoring systems should be openly available, and presented in a manner accessible to decision makers in industry, in the military, and in regulatory agencies.

Priority 2: analyze historic marine anthropogenic noise data
In tandem with the effort to collect and monitor present-day ocean noise, a database should be developed to collect, organize and standardize data on ocean noise measurements and related anthropogenic activities (NRC 2003:89). Infrastructure already is in place that is appropriate for maintaining an archive of these data (e.g. the National Oceanographic Data Center, www.nodc.noaa.gov). Currently, data regarding shipping, seismic exploration, oil and gas production, and other marine activities are either not collected or are difficult to obtain and analyze because they are maintained by separate organizations. International cooperation in this effort should be encouraged.

Priority 3: Develop global models for ocean noise
Marine noise measurements and anthropogenic source data should be used to develop a global model of ocean noise (NRC 2003:92). This model should incorporate both transient events, and continuous noise sources. The development an accurate global model depends on access to ocean noise data and anthropogenic activity data, as described for the database research priority above.

Priority 4: Report signal characteristics for anthropogenic noise sources
An important component of model development is better understanding of the signal characteristics for representative anthropogenic noise sources. The description of these signals should include enough information to allow reconstruction of its character (e.g. frequency content, pressure and/or particle-velocity time series, duration, repetition rate).

Priority 5: Determine the relationship between anthropogenic activity level and noise level
Research should be conducted relating the overall levels of anthropogenic activity (such as the types and numbers of vessels) with the resulting noise (NRC 2003:90). These relations will help to extend noise modeling to areas without direct long-term monitoring, but where anthropogenic noise sources are present.

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