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Impacts of Anthropogenic Sound

THERE IS GROWING CONCERN THAT sound introduced into the sea by human activities has detrimental effects on marine mammals. For example, mounting evidence suggests that high-intensity anthropogenic sound from sonar and airguns leads to strandings and subsequent mortality of beaked whales. Although the mechanisms of injury in these events are unclear, the species affected and the implicated sound levels follow a consistent pattern. A more pervasive, yet more subtle, problem may be the effects of increases in background noise levels from commercial shipping. Higher levels of background noise may interfere with marine mammals' ability to detect sounds, whether calls from their own species, echoes from prey, or natural sounds that aid in navigation or foraging. Noise may affect developmental, reproductive, or immune functions and cause more generalized stress. The effects of other pollutants (e.g., chemicals) may be additive or synergistic with those of noise. As Read (this volume) and Plagányi and Butterworth (this volume) suggest, human activities may have both direct and indirect consequences. For instance, noise may have ecosystem-scale effects, including impacts on **AQ1** species that are marine mammal prey.

Sources of anthropogenic sound are becoming both more pervasive and more powerful, increasing both oceanic background noise levels and peak sound intensity levels. Anthropogenic activities in the ocean have increased over the past 50 years, resulting in more low-frequency (<1,000 Hz) and mid-frequency (1–20 kHz) noise. Sources of anthropogenic noise include commercial shipping, defense-related activities, hydrocarbon exploration and development, research, and recreation.

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. Many sources of noise are located along well-traveled paths in the sea, particularly in coastal and continental shelf waters, areas that often include important marine mammal habitats.

There is sufficient evidence to conclude that some high-intensity sounds are harmful and, on occasion, fatal to marine mammals. Given the opportunity, the animals may avoid high-intensity sound, but in some extreme cases there has been documentation of injury from anthropogenic sound exposure. Multiple mass strandings of beaked whales following high-intensity sound exposure demonstrate a repeating pattern of events. Following exposure to high-intensity sonar or airguns, beaked whales have been known to strand on the shore, and if human intervention does not return them to the sea they die. Understanding the causes and consequences of beaked whale mass stranding should be a high research priority. What, then, are the mechanisms for damage or disturbance?

A major impediment to assessing the biological effects of ocean noise is the lack of knowledge concerning marine mammal responses to sound. Behavioral data from the wild are needed to examine those responses so that effects can be assessed. Significant effects may prove to be confined to a few individuals exposed at high sound pressure levels or they may be occurring at a population level as a result of widespread exposure. Discerning population-level effects is challenging as observations must be conducted over long distances and extended time periods.

Sound is an extremely efficient way of propagating 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. Toothed whales have developed sophisticated echolocation systems to sense and track prey and engage in complex exchanges of vocalizations with members of their own species. Baleen whales have developed long-range acoustic communication systems to facilitate mating and social interaction. Some baleen whales produce intricately patterned songs that continue for hours or days. Marine mammals may use sound from natural sources as a guide for navigation, prey detection, and avoidance of predation. 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 constitutes a substantial sound barrier. Sound waves in the water are reduced in intensity by a factor of more than a thousand when they cross the air-sea boundary, which means that we are effectively insulated from the noise produced by the rotating propellers that drive our ships or by the high-intensity sonar used to measure depths or probe the sea bottom. The con-

flict 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, mainly with our ears in the air.

A notable exception is the military use of submarines, where stealth is required, so minimization of sound production then becomes crucial to human survival. Reduction in radiated sound has been achieved by placing rotating machinery on isolating mounts and by designing efficient propellers that thrust without unnecessary vibration and cavitation. Thus, when it has been important to keep the sea quiet, the necessary technology has been developed and made available.

NOISE LEVELS IN THE OCEAN

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 and direction 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 may include a broad range of frequencies.

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

$$\text{SPL dB re } 1 \mu\text{Pa} = 10 \log_{10} (P/P_o)^2 = 20 \log_{10} (P/P_o)$$

Pressure amplitude can be measured either as a root-mean-squared (RMS) or peak value. (Note that in this chapter I use RMS values unless otherwise noted). 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/m². 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 simple plane waves the pressure and particle velocity are related by the characteristic impedance (Z) of the medium:

$$Z = P/v$$

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

$$I = 10 \log_{10} [P^2 / (Z \times I_0)]$$

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

When sound propagates from water into air, there is a 30-dB (1,000×) decrease in acoustic intensity because the characteristic impedance of water (~1,500,000 kg/s-m²) is much greater than that of air (~415 kg/s-m²). This means that sounds made by a high-intensity underwater source (such as a sonar) are not transmitted into the air with the same intensity. In essence, sailors and seafaring passengers are protected from the sounds produced in the sea. Without the air-sea boundary for protection, there would be a strong incentive to protect human hearing from the noise of sonars and cavitating ships' propellers. (Note that for sound in air a different reference level is used, $P_0 = 20 \mu\text{Pa}$, and this may be a source of confusion when comparing sound under water and in air.)

Underwater sounds are classified according to whether they are transient or continuous. Transient sounds are of short duration and 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. Broadband short-duration transients are called pulses and sound like clicks or bangs. Continuous sounds, which occur without pauses, 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 often are measured in terms of their peak-to-peak pressure, whereas continuous sounds are measured in terms of their RMS pressure. The method of converting between RMS and peak-to-peak pressures is well defined for continuous-wave signals (add 9 dB to the RMS pressure to get the peak-to-peak pressure). However, for pulsed sounds, the conversion is problematic because the duration of the signal included dramatically alters the result. For a brief pulse, peak-to-peak pressure is measured from the highest and lowest portions of the waveform, whereas RMS pressure is difficult to interpret because it depends on the duration over which the signal is measured. An alternative for pulsed signals is to estimate the total energy, rather than the peak-to-peak pressure or intensity. Energy is proportional to the time integral of the squared pressure, described in the units $\mu\text{Pa}^2\text{-s}$. For brief pulses, energy in dB re 1 $\mu\text{Pa}^2\text{-s}$ is less than peak-squared pressure values in the same units. As others have warned, better standardization of measurement methods for pulsed underwater sounds is urgently needed to permit meaningful comparisons (Green and Moore 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, 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.

Acoustic pressures are analyzed into their frequency components or spectrum using a Fourier transform (Bracewell 2000). One way to express the result is as a power spectral density with units of $\mu\text{Pa}^2/\text{Hz}$. Note that the bandwidth of the power spectral density is explicitly part of the unit, and by convention noise measurements are presented in 1-Hz-wide frequency bins. Hearing and other auditory measures are often presented in one-octave or one-third-octave frequency bins as an approximation for the filtering characteristics involved in hearing. Source measurements are typically given for varying bandwidths with the following equation allowing for conversion to 1-Hz frequency bins:

$$\Delta\text{dB} = 10 \log_{10} (\text{bandwidth in Hz})$$

The sound level received from a source depends on the distance between the source and receiver, as well as on the propagation characteristics of the environment. Therefore, the distance at which a source measurement was made must be specified, and the convention is to normalize the pressure to an approximation of what would be received at a range of 1 m from the source (dB re μPa at 1 m). When arrays of sources are used, this convention overestimates actual source levels in the near field (e.g., at a 1-m range) but provides a good way to predict source levels in the far field (e.g., at a 1-km range).

NATURAL OCEAN ACOUSTIC ENVIRONMENT

The ambient background noise 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, and bathymetry). Natural phenomena known to contribute to oceanic ambient noise include: (a) wind, waves, and swell patterns, (b) bubbles, (c) currents and turbulence, (d) earthquakes, (e) precipitation, (f) ice cover and activity, and (g) marine life.

Wind, Waves, and Ice

Ocean surface motions that are due to wind, sea state, and swell patterns are the dominant physical mechanisms for natural background noise 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 waves are the dominant mechanisms for sound generation. Across the remainder of the band from 10 Hz to 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 to the same degree across the entire frequency band from 1 to 100 kHz. More recent work suggests 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 1 s or longer. Interaction of ocean waves with the marginal ice zone may raise noise levels by 4–12 dB (Diachok and Winikur 1974).

Earthquakes and Thunder/Lightning

Earthquakes and thunder/lightning are transient natural sound sources. Underwater recordings of thunder/lightning from storms 5–10 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

Human activity in the marine environment is now an important component of oceanic background noise. Sound is used both as a tool for probing the ocean and as a by-product of other activities. Anthropogenic sound sources vary in space and time but may be grouped into general categories: (a) explosions, (b) large commercial ships, (c) airguns and other seismic exploration devices, (d) military sonars, (e) navigation and depth-finding sonars, (f) research sound sources, (g) acoustic harassment devices (AHDs) and pingers, (h) polar icebreakers, (i) offshore drilling and other industrial activity, and (j) small ships, boats, and personal watercraft.

Explosions

Two classes of man-made explosions create high sound levels in the ocean: nuclear and chemical. Nuclear devices have been tested underwater in the ocean, in the atmosphere above the ocean, and on oceanic islands. In 1963 all nuclear states signed the Limited Test Ban Treaty, pledging to stop testing nuclear weapons underwater. The Comprehensive Test Ban Treaty was adopted in 1996, whereby the major nuclear powers pledged to discontinue all nuclear testing. The most recent oceanic tests were 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 the situation could change with geopolitical developments over the coming years or decades.

Nuclear explosions are extremely strong sources of underwater sound. Their source levels are expressed as an equivalent weight of chemical explosives with fission devices yielding the equivalent of tens to hundreds of kilotons and fusion devices yielding the equivalent of tens of megatons. Past tests likely had significant impacts on marine mammals in the vicinity of the test sites, although no marine mammal monitoring or stranding data are available. To ensure compliance with the Comprehensive Test Ban Treaty, an international monitoring system is being implemented, including a series of marine hydrophones and terrestrial (island) seismic sensors to detect high-intensity sounds. This information is transmitted, in real time, to the International Data Centre, where analysts evaluate the data for indications of nuclear explosions. The physical character of the oceans allows 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 currently includes eleven stations, located primarily in the Southern Hemisphere.

Chemical explosions are more portable and more easily conducted in an ocean setting and have been used for oceanic research, for construction, and for military testing. A surprisingly large number (300–4,000 per month) of underwater explosions were reported in the North Pacific during the 1960s (Spiess et al. 1968). At one time chemical explosions were commonly used for marine seismic exploration, but they have been replaced by airgun arrays, which 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 detonations 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 and measurements of hull stress are taken. Other Navy activities that involve underwater explosions include "Sinkex," in which torpedoes or

other chemical explosives are used to sink retired ships; weapons being tested during development; and operational stores being test fired to monitor their military readiness. During the recent war in Iraq, Navy SEALs disposed of a dozen 500-lb sea mines confiscated from the Iraqi navy by detonating them simultaneously in the Persian Gulf, creating 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

$$\text{SPL dB re } 1\mu\text{Pa at } 1\text{ m} = 269\text{ dB} + 7.53 \times \log_{10}(w)$$

where w is the charge weight in pounds (Urick 1975). For instance, 100 lb of TNT produces a shock wave SPL of 284 dB re $1\mu\text{Pa}$ at 1 m with an almost constant frequency content from 10 to 1,000 Hz. The energy from the bubble pulse oscillations contribute approximately an additional 5 dB of source level, yielding a total SPL of 289 dB re $1\mu\text{Pa}$ at 1 m. The signal duration can be obtained from the first few oscillations of the bubble pulse, in this case lasting one-third to one-half a second.

Commercial Shipping

Commercial shipping is the principal source of low-frequency (5–500 Hz) background noise in the world's oceans. Ships contribute to the noise level over large geographic areas, and the sounds of individual vessels are often spatially and temporally indistinguishable in distant vessel traffic. Noise from vessel traffic at high latitudes propagates particularly well over long distances because the oceanic sound channel (zone of most efficient sound propagation) in those regions reaches the surface.

Ships' noise is generated primarily from (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 below the ambient water pressure. The collapse of these voids generates sound. Cavitation creates both broadband and tonal sounds, as it may be modulated by blade-passage frequencies and their harmonics, which are called the blade lines in a spectrum. The broadband and tonal components produced by cavitation account for 80–85% of ship-radiated noise power (Ross 1987). Propeller noise also may be generated by unsteady propeller blade-passage forces, and there is additional ship noise from propulsion machinery.

Particular vessels produce unique acoustic signatures described by their 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 sound-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 noise, and the sum of many distant sources creates broad spectral peaks of noise in the 5- to 500-Hz band.

Models for representative sound 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 commercial ships range from 195 dB re $\mu\text{Pa}^2/\text{Hz}$ at 1 m for fast-moving (20 knots) supertankers to 140 dB re $\mu\text{Pa}^2/\text{Hz}$ at 1 m for small fishing vessels. Source-level models also have been developed for the propeller tonal blade lines, occurring at 6–10 Hz and their harmonics for most of the world's large merchant fleet (Gray and Greeley 1980).

Shipping vessel traffic is not uniformly distributed. The major commercial shipping lanes follow great circle routes or coastlines to minimize the distance traveled. Dozens of major ports and "megaports" handle the majority of the traffic, but hundreds of small harbors and ports host smaller volumes of traffic. The U.S. Navy lists 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 nearshore.

Lloyd's Register of the world's commercial fleet for the year 2001 listed 92,817 vessels National Research Council 2003b. 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), but gross tonnage may be a more important index of sound production than vessel numbers. From that perspective, oil tankers and bulk dry transport vessels represent nearly 50% of the total tonnage but less than 19% of the total number of vessels.

Vessel operation statistics indicate steady growth in vessel traffic over the past few decades (Mazzuca 2001). There has been an increase in both the number of vessels and in the tonnage of goods shipped. For example, there has been a 30% increase 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 locations.

The bulk of U.S. waterborne trade is conducted through a few ports (Table 7.1). For instance, the combined California ports of Los Angeles and Long Beach carry 37% of the total trade as measured by 20-ft-equivalent container traffic

Table 7.1 U.S. foreign waterborne trade, calendar year 2002

Rank	U.S. port	Total	Export	Import
1	Los Angeles	4,060	866	3,194
2	Long Beach	3,184	717	2,467
3	New York	2,627	747	1,879
4	Charleston	1,197	521	676
5	Savannah	1,014	453	561
6	Norfolk	982	431	551
7	Oakland	979	469	482
8	Houston	851	430	420
9	Seattle	850	338	512
10	Tacoma	769	278	491
Total		19,729	6,814	12,916

Source: U.S. Maritime Administration (2003).

Note: Units are thousands of twenty-foot-equivalent (TEU) containers.

(U.S. Maritime Administration 2003). Within the U.S. Exclusive Economic Zone, this concentrates the noise from shipping into the regions adjacent to these ports and their approaches. Significant concentrations of shipping traffic also occur in New York (13%) and the Puget Sound (Washington) area (8%).

Short sea shipping is commercial waterborne transportation that does not transit an ocean. It is an alternative form of commercial transportation that uses inland and coastal waterways to move commercial freight from major domestic ports to its destination. The U.S. Maritime Administration and the European Commission are playing active roles in the development of short sea shipping to help reduce freight congestion on national rail and highway systems. Short sea shipping already accounts for 41% of the total goods transport market within Europe, compared to 44% by road and 8% by rail (European Commission 2001). Short sea shipping is of particular concern with respect to shipping noise and marine mammals because of its coastal setting.

Seismic Exploration

Seismic reflection profiling uses high-intensity sound to image the Earth's crust. It is the primary technique for finding and monitoring reserves of oil and natural gas and is used extensively by the fossil-fuel extraction industries. It is also used by academic and government researchers to gather information for studies on Earth's origin and tectonic history.

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 twelve to forty-eight individual guns, towed about 200 m be-

hind a vessel, which operate at pressures of 2,000 psi and are distributed over a region that measures 20 × 20 m.

The pressure output of an airgun array is proportional to its operating pressure, the number of airguns, and 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 1-m-radius volume, yielding source levels as high as 259 dB peak re 1 μ Pa at 1 m output pressure (Greene and Moore 1995). This effective source level predicts pressures in the far field of the array, but in the near field the maximum pressure levels encountered are limited to 220–230 dB peak re 1 μ Pa. 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- to 300-Hz range.

Airguns are towed at speeds of about 5 knots and are typically fired every 10 s. A seagoing seismic-reflection operation includes a series of parallel passes through an area by a vessel towing an airgun array as well as six to ten seismic receiving streamers (hydrophone arrays). A recent practice is the use of repeated seismic reflection surveys for "time-lapse" monitoring of producing oil fields, called "4-D" surveys. More than ninety seismic vessels are available worldwide (Schmidt 2004), and about 20% of them are conducting field operations at any given time (Tolstoy et al. 2004).

Offshore oil and gas exploration and construction activities occur along continental margins. Areas of currently activity 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, Indonesia, and the Sea of Okhotsk. New areas of exploration include the deepwater U.S. Gulf of Mexico and deepwater West Africa, both of which have seen increasing activity in the past 5–10 years.

A recent study of ambient noise in the North Atlantic suggests that airgun activity along the continental margins propagates into the deep ocean and is a significant component of low-frequency noise (Nieukirk et al. 2004). Sounds from airguns were recorded almost continuously during the summer, originating at locations over 3,000 km from the receiving hydrophones.

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 is in use for both civilian and military applications. For purposes of discussion, sonar systems can be categorized as low-frequency (<1 kHz), 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 and are operated during both training exercises and combat. Because far more time is spent in training than in combat, training exercises may be the primary context in which military sonar is used. Low-frequency active (LFA) sonars are used for broadscale 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 eighteen projectors operating in the frequency range from 100 to 500 Hz, with a 215 dB re 1 μ Pa at 1 m source level for each projector (Johnson 2002). These systems are designed to project beams of energy in a horizontal direction, and the effective source level of an LFA array, when viewed horizontally, can be 235 dB re 1 μ Pa at 1 m or higher. The signal includes both constant-frequency (CF) and frequency-modulated (FM) components with a bandwidth of approximately 30 Hz. A ping sequence can last from 6 to 100 s, with a time between pings of 6–15 min and a typical duty cycle of 10–15%. Signal transmissions are emitted in patterned sequences that may last for days or weeks.

Mid-frequency tactical antisubmarine 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 (see Table 7.2). There are 117 of these sonars on U.S. Navy ships currently in active service and equivalent systems in foreign navies (e.g., British, Canadian, French) bring the worldwide count to about 300 (Watts 2003). The AN/SQS-53C is the most advanced surface ship ASW sonar in use by the U.S. Navy, and it generates FM pulses of 1–2 s duration in the 1- to 5-kHz band, at source levels of 235 dB re 1 μ Pa at 1 m or higher (Evans and England 2001). This sonar has a nominal 40° vertical beam width (dependent on frequency), directed 3° down from the horizontal. 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 detecting surface ships at greater range than many radar systems.

Table 7.2 U.S. Navy surface ships with mid-frequency antisubmarine warfare sonars

Type of ship	Class	Type of sonar	Number in use
Cruiser	Ticonderoga	SQS-53	27
Destroyer	Spruance	SQS-53	11
	Arleigh Burke	SQS-53	49
Frigate	Oliver Hazard Perry	SQS-56	30
Total			117

Other mid-frequency sonars are used by the Navy for depth sounding, communication between platforms, and device activation. High-frequency sonars are incorporated either into weapons (torpedoes and mines) or weapon countermeasures (mine countermeasures or antitorpedo devices). They are designed to operate over ranges of a few hundred meters to a few kilometers. Mine-hunting sonars operate at tens of kilohertz 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 side-scan 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 now plans to construct shallow-water training ranges on both the West and East coasts of the United States.

Commercial sonars are designed for fish finding, depth sounding, and sub-bottom profiling. They typically generate sound at frequencies of 3–200 kHz, with only a narrow frequency band generated by an individual sonar system. Source levels range from 150–235 dB re 1 μ Pa at 1 m. Commercial depth sounders and fish finders are typically designed to focus sound into a downward beam. Depth sounders and sub-bottom profilers are designed, respectively, to locate the sea bottom and to probe beneath it. They are operated primarily in nearshore and shallow environments. Fish finders are used 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 1 μ Pa at 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 echo-sounding systems (e.g., SeaBEAM or Hydrosweep) form narrow directional beams (e.g., 1° beam width) of sound and are used for precise depth sounding. Using hull-mounted arrays of transducers, these systems can achieve 235 dB re 1 μ Pa at 1 m source levels; they are typically operated at 12–15 kHz in deep water and at higher frequencies (up to 100 kHz) in shallow water. They may ensonify a swath of a few tens of kilometers along the track of the ship.

Sonar is an extremely efficient means for fish finding and depth sounding/sub-bottom profiling. Nearly all of the 80,000 vessels in the world's commercial fleet and many of the 17 million small boats owned in the United States are equipped with some form of commercial sonar, and new applications may lead to even greater proliferation of these systems. It is possible that the impact of the large number of these systems in use may be offset to some degree by their limited range.

Research Sound Sources

Research in underwater acoustic propagation and acoustical oceanography often involves the use of sound. Almost all of the programs in the United States 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 because of 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 (NRC) reports (National Research Council 1994, 2000a). The ATOC source has a 195 dB re 1 μ Pa at 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 at 4-h intervals with a "ramp-up" period of 5 min and a full-power signal duration of 20 min. The long time frame for operation of this experiment was a key aspect that led to questions regarding its potential impact on marine mammals (Potter 1994).

Another basin-scale sonar research project uses drifting sources (Rossby et al. 1986), called SOFAR floats. These devices drift at depth and periodically emit a high-intensity tone (195 dB re 1 μ Pa at 1 m) that is frequency swept at 200–300 Hz or a continuous signal at 185–310 Hz with a duration of 120 s or more. The sounds are detected by 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 and Pingers

Acoustic deterrent devices (ADD) use sound in an effort to repel marine mammals from fishing activities. The idea behind these devices is that they keep the animals away by introducing a local acoustic annoyance or alerting signal. Pingers are used in some fisheries to reduce the bycatch of marine mammals by alerting them to the presence of, or driving them away from, a net or other entangling object. These are typically low-power ADDs with source levels of 130–150 dB re 1 μ Pa at 1 m. Acoustic harassment devices (AHDs) 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 1 μ Pa at 1 m. Both

pingers and AHDs have frequencies in the 5- to 160-kHz band, and generate pulses lasting from 2 to 2,000 ms. To reduce habituation, a single device may transmit with a variety of waveforms and time intervals.

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 the use of AHDs in aquaculture facilities leads to unintended displacement of marine mammals, for example, 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.

Polar Icebreakers

Ice-breaking ships are a source of noise in the polar regions (Erbe and Farmer 2000). Two types of noise have been identified in association with ice breaking: bubbler system noise and propeller cavitation noise. Some ice-breaking ships are equipped with a bubbler system that blows high-pressure air into the water around the ship to push floating ice away. While the bubbler system is operating, the noise is continuous, with a broadband spectrum below 5 kHz. A source level of 192 dB re 1 μ Pa at 1 m in one-twelfth-octave bands has been reported for bubbler system noise. Icebreaker propeller cavitation noise is associated with the ship's ramming the ice with its propeller turning at high speed. The spectrum of propeller cavitation noise is broadband up to at least 20 kHz, and has a source level of 197 dB re 1 μ Pa at 1 m.

Industrial Activities, Offshore Drilling, 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 1 μ Pa at 1 m for one-

third-octave bands with peak intensity between 50 and 500 Hz (Greene and Moore 1995).

Oil and gas production activities that generate marine noise include drilling, offshore structure emplacement and removal, and related transportation. Sound pressure levels associated with drilling are the highest with maximum broadband (10 Hz–10 kHz) energy of about 190 dB re 1 μ Pa at 1 m. Drill-ship noise comes from both the drilling machinery and the propellers and thrusters used for station keeping. Jack-up rigs 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, and 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 eight to ten 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 received levels as high as 135 dB re 1 μ Pa at 1 km from the source (Greene and Moore 1995), which suggests source levels as high as 195 dB re 1 μ Pa at 1 m with peak frequencies at 40–100 Hz.

Oil and gas production is moving from shallow-water settings into water depths of up to 3,000 m. Deepwater drilling and production have the potential to generate higher levels of noise than shallow-water production, owing to the use of drill ships and floating production facilities. In addition, noise generated in deep water 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 is a growing number of drill rigs available, with an increase of approximately 10% over the past 5 years.

Small Ships, Boats, and Personal Watercraft

Small vessels do not contribute significantly to the global ocean sound environment, but may be important local sound sources, particularly in coastal settings. Examples of sound levels for whale-watching boats range from 115–127 dB re 1 μ Pa at 1 m for one-third-octave bands (Au and Green 2000) and 145–169 dB re 1 μ Pa at 1 m for one-twelfth-octave bands, with increased sound levels for high-speed operation (Erbe 2002). A recent study of noise levels from small powerboats suggests peak spectral levels in the 350- to 1200-Hz band of 145–150 dB re 1 μ Pa²/Hz at 1 m (Bartlett and Wilson 2002). The total number of recreational craft in operation is poorly documented although about 17 million small boats are owned in the United States (National Marine Manufacturers Association 2003). The vessel categories are outboard (8.4 million), inboard (1.7 million), stern drive (1.8 million), personal watercraft (1.4 million), sailboats (1.6 million), and miscellaneous (2.5 million). In the inshore waters of Florida, there are nearly 1 million registered recreational

boaters (U.S. Fish and Wildlife Service 2001), and the number of boats in operation is raised seasonally by an influx of boats from out of state.

Comparison of Anthropogenic Sound Sources

The anthropogenic sound sources discussed previously are summarized by source level and other parameters in Table 7.3, ordered by their intensity. For sources constructed from arrays of elements (e.g., military sonars and airguns), the individual source elements can be widely distributed. In this case, the source level is given for a range of 1 m to standardize the calculation, but in practice the actual levels experienced near the source never reach the stated levels. Instead, these levels are used to calculate accurately what the source level is at longer ranges, where the distance to the source is much greater than the source dimensions. Table 7.3 is designed to approximate the potential for these sources to impact acutely or injure marine mammals. In practice, the sensitivity of marine mammals to various kinds of sound is another important consideration, as discussed later in the chapter.

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 impact overall. Military SURTASS-LFA sonars and large-volume airgun arrays both have high SPLs. The long ping lengths and high duty cycles of LFA sonars increase their total energy levels; both the SURTASS-LFA and airgun arrays have dominant energy at low frequencies, where long-range propagation is likely. Mid-frequency military sonars (such as the SQS-53C) have shorter ping durations and more moderate duty cycles; because they operate at middle frequencies, propagation effects also limit their range. Concern for the impact of these sonars is for local settings (as discussed later in this chapter).

Commercial supertankers are arguably the most nearly ubiquitous sources of high-intensity, with more than 10,000 vessels operating worldwide. Concern with these noise sources is concentrated near major ports and along the most heavily traveled shipping lanes. The moored research sound source for the ATOC project is a source level equivalent to a supertanker, although it operates on a low duty cycle. AHDs have high source levels, whereas ADDs have relatively moderate source levels. Multibeam hull-mounted echo sounders have high source levels, but their narrow beam widths and medium frequencies limit their range and the area that they ensonify. Research acoustic floats (RAFOS) produce a moderately high source level but are operated at a very low duty cycle. Fishing vessels have moderate source levels and may represent at least local acoustic annoyances.

Anthropogenic Noise Energy Budget per Year

An annual energy budget is one approach to comparing the contribution of each anthropogenic noise source. The approach taken here is to consider the acoustic energy output at the source itself, rather than the sum of many sources af-

Table 7.3 Comparison of anthropogenic underwater sound sources ordered by their short-term (~ 1 s) energy output, approximating their potential for acute or injurious effects

Sound source	SPL (dB re 1 μ Pa at 1m)	Ping energy (dB re 1 μ Pa ² -s)	Ping duration	Duty cycle (%)	Peak frequency (Hz)	Bandwidth (Hz)	Directionality
Underwater nuclear device (30 kiloton)	328	337	8 s	Intermittent	Low	Broad	Omnidirectional
Ship shock trial (10,000 lb TNT)	299	302	2 s	Intermittent	Low	Broad	Omnidirectional
Military sonar (SURTASS/LFA)	235	243	6–100 s	10	250	30	Horizontal
Airgun array (2000 psi, 8000 in. ³)	256	241	30 ms	0.3	50	150	Vertical
Military sonar mid-frequency (SQS-53C)	235	232	0.5–2 s	6	2,600–3,300	Narrow	Horizontal
Supertanker (337 m length, 18 knots)	185	—[AQ4]	Continuous	100	23	5–100	Omnidirectional
Research sonar (ATOC source)	195	226	1200 s	8	75	37.5	Omnidirectional
Acoustic harassment device	185	185	0.5–2 s	50	10,000	600	Omnidirectional
Multibeam echosounder (hull-mounted)	235	218	20 ms	0.4	12,000	Narrow	Vertical
Research sonar (RAFOS float)	195	216	120 s	Small	250	100	Omnidirectional
Fishing Vessel (12 m length, 7 knots)	151	—[AQ5]	Continuous	100	300	250-1000	Omnidirectional
Acoustic deterrent device (AquaMark300)	132	127	300 ms	8	10,000	2000	Omnidirectional

ter propagation within the ocean, as would be experienced by a receiver at a particular location. Ambient noise distributions at a given location result from a complex distribution of worldwide sources and variable acoustic propagation. The question considered here is a simpler 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 a 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. Table 7.3 shows the approximate potential of these sources to produce chronic effects on marine mammal populations. However, many other factors have to be considered before these data can be used to help understand the impacts of sound on marine mammals, including the distribution of sources in space and time and the varying sensitivities of marine mammals to sound.

Starting with the source pressure levels given in Table 7.3, the additional information needed to go from sound pressure to total energy includes the source directionality, dura-

tion, rate of usage, and total number of sources. The first step is to convert sound pressure level (p) to acoustic intensity (I), obtained by dividing the squared pressure by the acoustic impedance (Z):

$$I = |p\vec{v}| = |p|^2/Z \quad [\text{watts/m}^2]$$

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

$$P = AI \quad [\text{joules/sec}]$$

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

$$E_{\text{ping}} = PT_{\text{ping}} \quad [\text{joules}]$$

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

$$E_{\text{total}} = E_{\text{ping}} N_{\text{pings/year}}^N \text{ sources} \quad [\text{joules}]$$

For continuous sources, the energy of 1 s of transmission is used for E_{ping} , and the number of seconds the source is in operation per year is used for $N_{\text{pings/year}}$.

A proposed annual anthropogenic energy budget is presented in Table 7.4, starting with the sources and sound pressure levels from Table 7.3. Underwater nuclear explosions, even assuming a 20-year recurrence rate, top the annual energy budget with 2.1×10^{15} J. This is comparable to a small power plant of 100 MW with an annual energy output of 3.2×10^{15} J. The highest-energy regularly operated sound sources are the airgun arrays from 90 vessels operating for 80 days/year to produce 3.9×10^{13} J. Military sonars for antisubmarine warfare (SSQ-53C) used on 300 vessels for 30 days/year produce 2.6×10^{13} J. The contribution from shipping comes mostly from the largest vessel classes, with 11,000 supertankers, operating 300 days/year, to yield 3.7×10^{12} J. 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 symphony orchestra produces about 10 W of sound energy, and would emit 3.2×10^8 J over the course of a year.

LONG-TERM TRENDS IN OCEAN NOISE

Overall trends for the level of sound in the sea can be broken down into anthropogenic and nonanthropogenic 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 have the effect of increasing background noise levels. Over the past few decades, however, it is likely that increases in anthropogenic noise have been more prominent. In order of im-

portance, 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.

Waters surrounding Australia, which are remote from most commercial shipping, allow the effects of anthropogenic and natural noise to be separated. At low frequency (100 Hz), Australian data suggest that ocean noise levels may be as low as 50 dB re $1 \mu\text{Pa}^2/\text{Hz}$, which is about 30–40 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). see The National Research Council 2003b) pointed to the difficulty of separating wind/wave-generated noise from shipping noise in North American datasets.

Trends in background noise and anthropogenic activity levels suggest that ocean noise levels 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 3–5 dB, and greater average ship speeds, propulsion power, and propeller tip speeds may explain an additional 6 dB.

Other data on long-term noise trends come from a 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 was 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 the number of ships and the gross tonnage. From 1972 to 1999 the total number of ships in the world's fleet in-

Table 7.4 Comparison of anthropogenic underwater sound sources ordered by their total annual energy output

Sound source	Intensity (dB re 1 W/m ²)	Directionality (angle)	Power (dB re 1 W)	Number of sources	Operate (days/year)	Repetition (pings/day)	Total energy (J)
Underwater nuclear explosions	146	4π	157	1	0.05	1	2.1×10^{15}
Airgun arrays	61	π	66	90	80	4320	3.9×10^{13}
Military sonar (mid-frequency)	53	$\pi/2$	55	300	30	4,320	2.6×10^{13}
Supertankers	3.2	2π	11	11,000	300	86,400	3.7×10^{12}
Ship-shock trials	117	4π	128	1	0.5	1	3.3×10^{12}
Military sonar (SURTASS/LFA)	53	π	58	1	30	175	1.7×10^{11}
Merchant vessels	−17	2π	−8.8	40,000	300	86,400	1.4×10^{11}
Navigation sonar	−1.8	π	3.2	100,000	100	86,400	3.6×10^{10}
Fishing vessels	−31	2π	−23	25,000	150	86,400	1.7×10^9
Research sonar	13	4π	24	10	4	86,400	9.1×10^8

Note: Although this table is designed to approximate the potential of these sources to produce chronic effects, many other factors must be considered, including the distribution of sources in space and time and the sensitivities of marine mammals to sound.

creased 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 50 years, equivalent to a 7% 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) (National Research Council 2003b; from McCarthy and Miller 2002).

OCEAN NOISE RESEARCH PRIORITIES

Ocean noise is an important component of the marine environment. Data on ocean noise trends are scarce, despite substantial investments by the U.S. Government in the collection of underwater sound data for military purposes (e.g., SOSUS and other ASW monitoring systems). Expanding use of the sea for commercial shipping, oil and gas development, and advanced warfare has resulted in noise levels that are at least ten times higher today than they were a few decades ago. Without some effort to monitor, reduce, or at least cap them, these noise levels are likely to increase and further degrade the marine acoustic environment. Recommendations for tracking and improving our understanding of ocean noise sources are presented below.

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

Priority 2: Analyze historical marine anthropogenic noise data. In tandem with the effort to monitor present-day ocean noise, a program should be developed to collect, organize, and standardize data on ocean noise and related anthropogenic activities (National Research Council 2003b:89). Infrastructure appropriate for maintaining an archive of these data already exists (i.e., 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 source data should be used to de-

velop a global model of ocean noise (National Research Council 2003b:92), that incorporates both transient and continuous noise sources. The development of an accurate global model depends on access to ocean noise data and anthropogenic activity data collected by long-term monitoring, as described previously.

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 sound sources. The description of each source 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 (National Research Council 2003b:90). These correlations will help to extend noise modeling to areas without direct long-term monitoring, but where anthropogenic noise sources are present.

HOW SOUND AFFECTS MARINE MAMMALS

The responses of marine mammals to sound depend on a range of factors, including (a) the sound pressure level and other properties, for example, frequency, duration, novelty, and habituation; (b) the physical and behavioral state of the animals; and (c) the ambient acoustic and ecological features of the environment. Richardson et al. (1995) reviewed marine mammal responses to specific sound sources, but our present understanding of how marine mammals respond to sound is insufficient to allow reliable predictions of behavioral responses either to intense sounds or to long-term increases in ambient background noise.

In humans, the perceived loudness of a sound involves not only hearing sensitivity but also psychological and physiological factors (Beranek and Ver 1992). A loudness-level scale has been developed from detailed testing, where the human subject judges the relative loudness of two sounds; for instance, the phon (in dB) compares the loudness level of tones of varying frequency to a 1-kHz reference tone. In practice, the annoyance level of a sound depends on a range of factors apart from loudness, such as the sound's fluctuation; intermittent sounds are more annoying than continuous ones. The degree to which human and terrestrial animal studies can be reliably extrapolated to marine mammals is uncertain because there are vast differences in the role of sound in sensing the marine and terrestrial environments and the ambient and biologically significant sounds, such as those of predators, differ in each setting.

MARINE MAMMAL SOUND PRODUCTION

The frequency band of sounds that are important to marine mammals matches, or extends beyond, the range of the sounds that they produce. Marine mammal call frequencies generally show an inverse correlation with body size (Watkins and Wartzok 1985), with mysticetes having larger bodies and lower frequency calls than odontocetes.

For mysticetes, most sound production is in the low-frequency range of 10–2,000 Hz (Edds-Walton 1997). Mysticete sounds can be broadly characterized as (a) tonal calls, (b) FM sweeps, (c) pulsed tonals, and (d) broadband grunt-like sounds and are generated either as individual calls or combined into patterned sequences or songs. For odontocetes, most sound production is in the mid-frequency and high-frequency range of 1–200 kHz (Matthews et al. 1999). Odontocetes produce (a) broadband clicks with peak energy between 5 and 150 kHz, varying by species, (b) burst-pulse click trains, and (c) tonal or FM whistles that range from 1 to 25 kHz. Pinnipeds that breed on land produce a limited array of barks and clicks ranging from less than 1–4 kHz. Those that mate in the water produce complex vocalizations during the breeding season. All pinnipeds, the sea otter, and manatees use sound to establish and maintain the mother-young bond, especially when attempting to reunite after separation (Sandegren et al. 1973, Hartman 1979).

The ability to use self-generated sounds to obtain information about objects and features of the environment, called echolocation, has been demonstrated for at least thirteen odontocete species (Richardson et al. 1995). No odontocete has been shown to be incapable of echolocation, and echolocation clicks have been observed in all recorded species. These echolocation sounds are produced in forward-directed beams, using specialized fats in the forehead (melon) as acoustic lenses. Some species of odontocetes produce few or no whistles and very-high-frequency clicks with peak spectra above 100 kHz. Examples include the Amazon river dolphin (*Inia geoffrensis*; Norris et al. 1972), and the harbor porpoise (*Phocoena phocoena*; Kamminga 1988).

Other odontocetes produce clicks with peak spectra below 80 kHz and use whistles regularly. Examples include bottlenose dolphins (*Tursiops* spp.), which are coastal, and the pantropical spotted dolphin (*Stenella attenuata*), which often occurs in offshore waters. Deep-diving odontocetes, such as sperm whales (*Physeter macrocephalus*) and beaked whales (Ziphiidae), are only known to produce clicks (Mohl et al. 2000, Hooker and Whitehead 2002, Johnson et al. 2004). Some odontocete whistles have been described as “signature” calls that identify individuals (Caldwell and Caldwell 1965). Sounds produced by killer whales are known to be group specific (Ford 1991, Tyack 2000), and the patterned “coda” click sequences made by sperm whales show geographic variation (Rendell and Whitehead 2003).

Source levels for odontocete clicks have been reported to be as high as 228 dB re 1 μ Pa at 1 m for false killer whales

(*Pseudorca crassidens*; Thomas and Turl 1990) and for bottlenose dolphins echolocating in the presence of noise (Au 1993), and 232 dB re 1 μ Pa at 1 m for male sperm whales (Mohl et al. 2000). The short duration of such echolocation clicks (50–200 μ s) means that their total energy is low (197 dB re 1 μ Pa²-s) although their source levels are high. Odontocete whistles have lower source levels than their clicks, ranging from less than 110 dB re 1 μ Pa at 1 m for the spinner dolphin (*Stenella longirostris*; Watkins and Schevill 1974) to 169 dB re 1 μ Pa at 1 m for bottlenose dolphins (Janik 2000). The detection range for odontocete clicks and whistles is about 5 km, although greater detection ranges also have been reported (Leaper et al. 1992, Barlow and Taylor 1998, Gordon et al. 2000).

Mysticete calls can be detected over long ranges (Payne and Webb 1971). For instance, blue whales (*Balaenoptera musculus*) produce low-frequency (10–100 Hz) calls with estimated source levels of 185 dB re 1 μ Pa at 1 m (McDonald et al. 2001), which are detectable at ranges of 100 km or more, depending on the acoustic propagation. Most large mysticetes (blue, fin, bowhead, right, humpback, Bryde’s, minke, and gray whales) are known to vocalize at frequencies below 1 kHz, with estimated source levels as high as 185 dB re 1 μ Pa at 1 m (Richardson et al. 1995).

Source levels and frequencies have been estimated for the underwater calls of several species of pinnipeds. Examples are the Weddell seal (*Leptonychotes weddellii*), which produces calls from 148 to 193 dB re 1 μ Pa at 1 m at frequencies of 0.2–12.8 kHz (Thomas and Kuechle 1982), and the Ross seal (*Ommatophoca rossii*), which produces calls at 1–4 kHz (Watkins and Ray 1985). These calls can be detected at ranges of several kilometers both in the open ocean and under ice (Wartzok et al. 1982).

MARINE MAMMAL HEARING

Sound propagates efficiently underwater, and one reflection of its importance to marine mammals is their development of broader hearing frequency ranges than is typical for terrestrial mammals. Audiograms have been produced for eleven species of odontocetes and nine species of pinnipeds, out of a total of approximately 127 marine mammal species (Wartzok and Ketten 1999, Nachtigall et al. 2000). All hearing data are from species that are small enough to be held in captivity. Direct hearing data are not available for species that are not readily tested by conventional audiometric methods. For the latter, audiograms must be estimated from mathematical models based on ear anatomy or inferred from the sounds they produce and field-exposure experiments (Wartzok and Ketten 1999).

Most delphinids are thought to have functional hearing from 200 Hz to 100 kHz, and some smaller species may hear frequencies as high as 200 kHz. Delphinid audiograms measured to date show peak sensitivity between 20 and 80 kHz, along with moderate sensitivity at 1–20 kHz. Since ambient noise decreases at high frequencies, odontocetes

may find it advantageous to hear and echolocate at high frequencies to avoid low-frequency background noise. Another factor favoring high frequencies for some odontocetes is the acoustic background noise of inshore and riverine environments. Higher frequencies also give better spatial resolution, but at the expense of diminished propagation distance.

Based on modeling but with no measured audiograms, mysticete hearing probably ranges between 20 Hz and 20–30 kHz. Several of the larger species, such as blue and fin whales, are thought to hear at infrasonic (down to ~10 Hz) frequencies. Pinniped audiogram data suggest that their best hearing is between 1 and 20 kHz. True seals (phocids) tend to hear higher frequencies underwater than fur seals and sea lions (otariids). Some pinnipeds hear moderately well in both water and air, whereas others are better adapted for underwater than for in-air hearing. Sea lions have the most terrestrially adapted hearing, and elephant seals have the most marine-adapted hearing, with good sensitivity below 1 kHz (Kastak and Schusterman 1998).

Marine mammal hearing is adapted to an aquatic environment, yet their hearing anatomy evolved from terrestrial ancestors. The divergence in hearing physiology between land and marine mammals is most pronounced in the external ears, which are absent in most marine mammal species, and in the middle ears, which are extensively modified in marine mammals. Because levels of ambient noise in the sea can vary by many orders of magnitude as a result of storms and other natural phenomena, marine mammals may have developed resilient mechanisms to guard against hearing loss. Existing studies do not allow for prediction of the impacts of high-intensity sounds on marine mammal hearing except in general terms.

Hearing Losses

Hearing thresholds may be degraded by exposure to high-intensity sound. Hearing losses are classified as either temporary threshold shifts (TTS) or permanent threshold shifts (PTS), where threshold shift refers to the raising of the minimum sound level needed for audibility. Repeated TTS is thought to lead to PTS. The extent of hearing loss is related to the sound power spectrum, the hearing sensitivity, and the duration of exposure. High-intensity, impulsive blasts can damage cetacean ears (Ketten et al. 1993). Hearing losses reduce the range for communication, interfere with foraging capacity, increase vulnerability to predators, and may cause erratic behavior with respect to migration, mating, and stranding. For cetaceans, which are highly dependent on their acoustic sense, both TTS and PTS should be considered serious cause for concern.

Relatively few data are available on hearing loss in marine mammals. Experiments on captive bottlenose dolphins suggest that TTS are observed at levels of 193–196 dB re 1 μ Pa for exposure to 1-s tones at 20 kHz (Ridgway et al. 1997). Work with impulsive sources (seismic waterguns) suggests that exposure to sound pressure levels of 217 dB re 1 μ Pa

and total energy fluxes of 186 dB re 1 μ Pa²-s produces TTS in beluga whales (*Delphinapterus leucas*; Finneran et al. 2002). One hypothesis is that animals are most vulnerable to TTS at or near the frequencies of their greatest hearing sensitivity. For baleen whales, this suggests low-frequency sensitivity and for smaller cetaceans, mid-frequency and high-frequency sensitivity. It also raises the question of why marine mammals (apparently) do not damage their hearing by their own sound production, as both the tonal and impulsive sounds that they produce can be comparable in sound level to those found to induce TTS in the controlled experiments mentioned previously. It is thought that internal mechanisms may protect an animal from its own vocalizations.

Masking

Acoustic signals are detected against the ambient background noise. When background noise increases, it may reduce an animal's ability to detect relevant sound; this is called masking. Noise is effective for masking when it is within a critical band (CB) of frequency around the desired signal. The amount by which a pure tone must exceed the noise spectral level to be audible is called the critical ratio (CR). The CR is related to the bandwidth (CB) within which background noise affects the animal's ability to detect a sound. Estimates of marine mammal CBs and CRs come from captive odontocetes and pinnipeds (Richardson et al. 1995). For all species, the CB expressed as a percentage is broader at low frequencies (25–75% at 100 Hz), and narrower (1–10%) at middle and high frequencies (1–100 kHz). This suggests that band-limited noise is more effective at masking low frequencies than middle and high frequencies. An animal's directional hearing capabilities may help it avoid masking by resolving the different directions of propagation between the signal and the noise. A directivity index of as much as 20 dB has been measured for bottlenose dolphins (Au and Moore 1984). Directional hearing is less acute in pinnipeds.

Erbe and associates have studied masking of beluga whale sounds by icebreaker noise (Erbe and Farmer 1998, 2000, Erbe 2000), including construction of software to model this process (Erbe et al. 1999). Icebreaker noise from ramming, ice cracking, and bubbler systems produced masking at noise-to-signal ratios of 15–29 dB. The predicted zone of masking for beluga calls from ramming noise was 40 km (Erbe and Farmer 2000). Beluga whales' vocal output changes when they are moved to locations with higher background noise (Au et al. 1985). With noise at low frequencies, an animal increases both the sound pressure level and the frequency of its vocalizations, perhaps in an attempt to avoid or overcome masking. Beluga whales also have been observed to increase call rates and shift to higher call frequencies in response to boat noise (Lesage et al. 1999). Likewise, it has been suggested that killer whales shift their call frequencies in response to the presence of whale-watching boats (Foote et al. 2004).

Hearing Development

Does increased noise in the oceans cause developmental problems for young animals? High-noise environments affect auditory development in very young rats (Chang and Merzenich 2003). Brain circuits that receive and interpret sound did not develop at the same rate in animals living in an environment of high continuous background noise as in animals that were raised in a quiet environment. It took three to four times as long for rats raised in a noisy environment to reach the basic benchmarks of auditory development. For marine mammals, comparable data may be difficult to obtain, but the potential for developmental impairment should be an important consideration when assessing the impacts of ocean noise.

NONAUDITORY SOUND IMPACTS

Nonauditory effects involve the interaction of sound with marine mammal physiology. Sound is known to have direct and indirect physiological effects on mammals apart from its effects on hearing discussed previously. The symptoms of these physiological effects range from subtle disturbance, to stress, to injury, and to death.

The physiology of marine mammals is uniquely adapted to life underwater. For example, deep-diving species have specialized cardiovascular and pulmonary systems that allow breath holding and accommodation to changes in pressure. The same physiology that allows marine mammals to spend extended periods underwater and make deep dives may also create vulnerabilities to sound exposure, and their physiological responses to such exposure may differ from those of humans and other terrestrial mammals.

Research on human divers, laboratory terrestrial animals, and captive marine mammals suggests that exposure to underwater sound can produce nonauditory physiological effects. The range of potential impacts may include physiological stress, neurosensory effects, effects on balance (vestibular response), tissue damage from acoustic resonance, gas bubble formation and/or growth in tissues and blood, and blast-trauma injury.

The term stress is used to describe physiological changes that occur in the immune and neuroendocrine systems following exposure to a stressor. Physiological stress responses are not fully understood; however, indicators of stress that is due to noise have been measured in marine mammals. For instance, dolphins experience heart rate changes in response to sound exposure (Miksis et al. 2001). A beluga whale showed increased stress hormone levels (norepinephrine, epinephrine, and dopamine) with increased sound exposure level (Romano et al. 2004). Prolonged noise-induced stress can lead to debilitation such as infertility, pathological changes in digestive and reproductive organs, and reduced growth, as documented for some fish and invertebrates (Banner and Hyatt 1973, Lagardere 1982).

Cases of neurologic disturbance have been described for

human divers exposed to intense underwater sound (160–180 dB re 1 μ Pa for 15 min). Symptoms during exposure included head vibrations, lightheadedness, somnolence, and an inability to concentrate. These divers reported recurrent symptoms days to weeks after exposure, including, in one case, a partial seizure 16 months after the initial exposure (Stevens et al. 1999). Effects of this type have yet to be studied in marine mammals.

Sound exposure in humans may elicit a vestibular response or dizziness (called the Tullio phenomenon) at thresholds as low as 101–136 dB re 1 μ Pa (Erlich and Lawson 1980). When human diver vestibular function was assessed before and after underwater sound exposure, transient effects were detected immediately postexposure to 160 dB re 1 μ Pa for 15 min (Clark et al. 1996). Likewise, rats exposed to 180 dB re 1 μ Pa for 5 min exhibited mild transient impairment in vestibulomotor function (Laurer et al. 2002), and vestibular effects have been detected in guinea pigs immediately following underwater sound exposure of 160 dB re 1 μ Pa for 5 min (Jackson and Kopke 1998).

Acoustic resonance can lead to an amplification of pressure within mammalian air cavities in response to sound. Lung and other air cavity resonance is important for establishing thresholds for injury because at any given level of excitation, the vibration amplitude is greatest at resonance. In vivo and theoretical studies related to tissue damage support a damage threshold of the order of 180–190 dB re 1 μ Pa (Cudahy et al. 1999, Cudahy and Ellison n.d.[AQ2]). These studies also provide a relationship between resonance and body mass, based on underwater measurements of terrestrial mammals, including humans, as well as extrapolation from in-air results. Finneran (2003) measured resonance frequencies for beluga whale and bottlenose dolphin lungs directly and found them to be at low frequencies (30 and 36 Hz, respectively). An important issue for resonance effects is the tuning or amplification effect of the resonance. The degree of tuning (defined as Q , with high Q indicating sharper tuning) that has been measured in vivo in the lungs of pigs and humans is from 3 to 5 (Martin et al. 2000), and for beluga whales and bottlenose dolphins is 2.5 and 3.1, respectively (Finneran 2003). This suggests that a moderate level of amplification (a factor of 3) occurs at resonance frequencies.

Sound can increase gas bubble presence in mammalian tissues, especially when dissolved gases are abundant as a result of repeated dives. Human divers are obliged to decompress slowly following dives to prevent bubble formation, whereas deep-diving marine mammals have evolved a means to avoid decompression sickness during their routine diving activity. Intense sound generates bubbles—in vivo cavitation (ter Harr et al. 1982); it also leads to bubble growth—rectified diffusion (Crum and Mao 1996, Houser et al. 2001). The growth of bubbles increases the potential for blocked arteries.

Intense pressures from sources such as explosions can damage air-filled cavities, such as lungs, sinuses, ears, and intestines (Cudahy et al. 1999). A dramatic pressure drop, such

as occurs from blast waves, may cause air-filled organs to rupture. Research on blast damage in 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). Peak pressures of 222 dB re 1 μ Pa result in perforation and hemorrhage of air-filled intestines in rats (Bauman et al. 1997). Lethal peak pressures of 237 dB re 1 μ Pa cause pulmonary contusion, hemorrhage, barotraumas, and arterial gas embolisms in sheep (Fletcher et al. 1976). Two humpback whales were found dead following a nearby 5,000-kg explosion, and examination of the temporal bones in their ears revealed significant blast trauma (Ketten et al. 1993).

EFFECTS OF NOISE ON MARINE MAMMAL BEHAVIOR

The behavioral responses of marine mammals to noise are complex and poorly understood (Richardson et al. 1995). Responses may depend on hearing sensitivity, behavioral state, habituation or desensitization, age, sex, presence of offspring, location of exposure, and proximity to a shoreline. They may range from subtle changes in surfacing and breathing patterns to cessation of vocalization to active avoidance or escape from the region of highest sound levels. For instance, several studies suggest that bowhead whales follow a pattern of shorter surfacings, shorter dives, fewer blows per surfacing, and longer intervals between blows when exposed to anthropogenic noise (Richardson et al. 1995), even at moderate received levels (114 dB re 1 μ Pa). Another common response pattern is a reduction or cessation of vocalization, such as for right whales in response to boat noise (Watkins 1986), bowheads in response to playback of industrial sounds (Wartzok et al. 1989), sperm whales in response to pulses from acoustic pingers (Watkins and Schevill 1975) and in the presence of military sonar (Watkins et al. 1985), and sperm and pilot whales (*Globicephala* spp.) in response to an acoustic source for oceanographic research (Bowles et al. 1994). Moreover, humpback whales lengthen their song cycles when exposed to the LFA source (Miller et al. 2000), move away from mid-frequency sonar (Maybaum 1993), and tend to cease vocalizations when near boats (Watkins 1986). Beluga whales adjust their echolocation clicks to higher frequencies and higher source levels in the presence of increased background noise (Au et al. 1985). Gray whales (*Eschrichtius robustus*) exhibited an avoidance response when exposed to airgun noise, and their response became stronger as the source level increased from 164 to 180 dB re 1 μ Pa (Malme et al. 1984). They also preferentially avoided LFA transmissions conducted in a landward direction (Tyack and Clark 1998).

Marine mammals have been observed to have little or no reaction to some anthropogenic sounds. For example, sperm whales continued calling when they encountered echosounders (Watkins 1977) and when they were exposed to received sound levels of 180 dB re 1 μ Pa from a detonator

(Madsen and Mohl 2000). A fin whale (*Balaenoptera physalus*) continued to call with no change in rate, level, or frequency in the presence of noise from a container ship (Edds 1988).

Age and sex are important factors in noise sensitivity. For instance, juvenile and pregnant Steller sea lions (*Eumetopias jubatus*) are more likely to leave a haul-out site in response to aircraft overflights than are territory-holding males and females with young (Calkins 1979). Walruses (*Odobenus rosmarus*) may stampede and crush calves (Loughrey 1959) or temporarily abandon them (Fay et al. 1984) when exposed to sounds from aircraft or vessels. In gray whales, cow-calf pairs are considered more sensitive than other age or sex classes to disturbance by whale-watching boats (Tilt 1985), and humpback groups containing at least one calf appear to be more sensitive to vessel traffic than are groups without calves (Bauer et al. 1993).

Marine mammal responses also appear to be affected by the context of the exposure, for example, by the location of the source relative to that of the animal, by the motion of the source, and by the onset of the source and its repetition (random versus periodic and predictable). Fin whales are more tolerant of a stationary than a moving source (Watkins 1986). Humpback whales are less likely to react to a continuous source than to one with a sudden onset (Malme et al. 1985). California sea lions (*Zalophus californianus*) and harbor seals (*Phoca vitulina*) react at greater range from a ship when they are hauled out, and this is also true of walruses (Fay et al. 1984). Bowheads are more responsive to overflights of aircraft when they are in shallow water (Richardson and Malme 1993). In the St. Lawrence River, beluga whales are less likely to change their swimming and diving patterns in the presence of vessels moving at low speed than in the presence of fast-moving boats (Blane and Jackson 1994). In Alaska, beluga whales feeding on river salmon may stop and move downstream in response to noise from small boats, whereas they are relatively unresponsive to noise from fishing boats (Stewart et al. 1982). In Bristol Bay, beluga whales continue to feed when surrounded by fishing vessels, and they may resist dispersal even when deliberately harassed (Fish and Vania 1971). In Sarasota Bay, bottlenose dolphins had longer interbreath intervals during approaches by small boats (Nowacek et al. 2001). In Kings Bay, Florida, manatees' use of boat-free sanctuaries increased as the number of boats in the bay increased (Buckingham et al. 1999).

Only a few studies document long-term marine mammal responses to anthropogenic sound, suggesting abandonment of habitat in some cases. At Guerrero Negro Lagoon in Baja California, shipping and dredging associated with a salt works may have induced gray whales to abandon the area through most of the 1960s (Bryant et al. 1984). After these activities stopped, the lagoon was reoccupied, first by single whales and later by cow-calf pairs. Killer whales (*Orcinus orca*) in the British Columbia region were displaced from Broughton Archipelago in 1993–1999, a period when acoustic harassment devices were in use on salmon farms (Morton and Symonds 2002).

HABITUATION AND TOLERANCE OF NOISE

Habituation is the loss of responsiveness to noise over time. A diminution of responsiveness over time may be due to the animals' becoming accustomed to, and no longer threatened by, the signal. Alternatively, animals may return to the noisy area because of its importance, despite the annoying nature of the sound. The best evidence for habituation of marine mammals to intense sound comes from attempts to use acoustic harassment devices (AHDs) to keep marine mammals away from aquaculture facilities or fishing equipment (Jefferson and Curry 1994). For instance, there is evidence that harbor seals habituate to AHDs, partly because they modify their swimming behavior to keep their heads out of the water when they are in high-intensity sound fields (Mate and Harvey 1987). Likewise, harbor porpoises have been shown to habituate to gillnet pingers over a span of 10 or 11 days (Cox et al. 2002).

Observations of responses to whale watching and other vessels also suggest some level of habituation to noise. Near Cape Cod, common minke whales (*Balaenoptera acutorostrata*) changed from being attracted to vessels to appearing generally uninterested, fin whales from flight reactions to disinterest; and humpback whales from mixed, but usually strongly negative, to strongly positive reactions (Watkins 1986). At San Ignacio Lagoon, Baja California, gray whales become less likely to flee from whale-watching boats as the season progresses (Jones and Swartz 1984).

Habituation does not signify that hearing loss or injury from high-intensity sounds has not occurred. Humpback whales in Newfoundland remained in a feeding area near where there was seafloor blasting (Todd et al. 1996). Received sound pressure levels at 1 mi from the explosions were typically 145–150 dB re 1 μ Pa at 240–450 Hz, with presumed source levels of 295–300 dB re 1 μ Pa at 1 m based on the size of the explosive charges. The whales showed no clear reaction to the blasting in terms of behavior, movement, or residence time. However, increased incidental entrapment in nets followed the blast exposure (Todd et al. 1996). In addition, two whales were found dead after a 5,000-kg explosion, and examination of the temporal bones of their inner ears revealed significant blast trauma (Ketten et al. 1993). This incident highlights the difficulty of using overt behavioral reactions to monitor the effects of noise or high-intensity sound on marine mammals.

INCIDENTS OF MASS STRANDING ASSOCIATED WITH HIGH-INTENSITY SOUND

Multiple-animal strandings ("mass strandings") have been associated with the use of high-intensity sonar during naval operations and with the use of airguns during seismic reflection profiling. A key characteristic of these incidents is that they predominantly involved beaked whales, particu-

larly Cuvier's beaked whales (*Ziphius cavirostris*). In many of the areas where such events occurred, Cuvier's beaked whale was not thought to be the most abundant cetacean species present.

Odontocetes are known to mass strand, that is, to come ashore in groups of two or more animals (Walsh et al. 2001). Mass strandings of beaked whales, however, are relatively rare. The National Museum of Natural History, Smithsonian Institution (J. Mead pers. comm.) has compiled a global list of Cuvier's beaked whale strandings involving two or more animals (Table 7.5). Except for a stranding of two individuals in 1914, there are no records of multiple-animal strandings until 1963. Between 1963 and 2004, three to ten mass strandings of Cuvier's beaked whales were reported per decade (Fig. 1) although improved reporting may be a factor in explaining the increasing number of mass-stranding events detected in recent decades.

The first published suggestion of a connection between beaked whale strandings and naval activity was by Simmonds and Lopez-Jurado (1991). They described a set of three multianimal strandings associated with naval activity in the Canary Islands in 1985, 1988, and 1989, and additional incidents of beaked whale mass strandings in the Canary Islands were noted in 1986 and 1987. These authors did not posit a connection between beaked whale mass strandings and the use of ASW sonar, but rather related them to the nearby presence of naval operations.

The increased incidence of multianimal beaked whale stranding events can be correlated with the advent of mid-frequency ASW sonar. Prototypes of hull-mounted ASW sonars (e.g., SQS-23 and 26) were first tested in 1957 (Gerken 1986) and were deployed on a broad range of naval ships (frigates, cruisers, and destroyers) belonging to the United States and other nations beginning in the early 1960s. This timing coincides with increased reports of mass strandings of Cuvier's beaked whales (Fig. 7.1). Eleven out of thirty-two of the documented mass strandings of these whales have been associated with concurrent naval activities. Efforts to record marine mammal strandings worldwide have been intensified during the past few decades, so, again, greater efficiency of reporting may be a factor in the increased numbers recorded.

An examination of the circumstances surrounding these mass strandings may help to define the association with the occurrence of high-intensity sound. Two such strandings have been documented by detailed investigative reports: the Kyparissiakos Gulf, Greece, incident of May 1996 (D'Amico and Verboom 1998) and the Bahamas incident of March 2000 (Evans and England 2001). Examination of other beaked whale mass strandings provides additional perspective on the diversity of sound sources, environment, and conditions associated with these events.

Kyparissiakos Gulf, Greece, May 1996

Frantzis (1998, 2004) first drew attention to a mass stranding of Cuvier's beaked whales in the Ionian Sea that coin-

Table 7.5 Strandings of at least two Cuvier's beaked whales, from Smithsonian records

Year	Location	Species (numbers)	Correlated activity
1914	United States (New York)	Zc (2)	
1963	Italy	Zc (15+)	
1965	Puerto Rico	Zc (5)	
1968	Bahamas	Zc (4)	
1974	Corsica	Zc (3), <i>Stenella coeruleoalba</i> (1)	Naval patrol
1974	Lesser Antilles	Zc (4)	Naval explosion
1975	Lesser Antilles	Zc (3)	
1980	Bahamas	Zc (3)	
1981	Bermuda	Zc (4)	
1981	United States (Alaska)	Zc (2)	
1983	Galapagos	Zc (6)	
1985	Canary Islands	Zc (12+), Me (1)	Naval maneuvers
1986	Canary Islands	Zc (5), Me (1)	
1987	Canary Islands	Zc (group), Me (2)	
1987	Italy	Zc (2)	
1988	Canary Islands	Zc (3), Me (1), <i>Hyperoodon ampullatus</i> (1), <i>Kogia breviceps</i> (2)	Naval maneuvers
1989	Canary Islands	Zc (19+), Me (2), Md (3)	Naval maneuvers
1991	Canary Islands	Zc (2)	Naval maneuvers
1991	Lesser Antilles	Zc (4)	
1993	Taiwan	Zc (2)	
1994	Taiwan	Zc (2)	
1996	Greece	Zc (14)	Navy LFAS trials
1997	Greece	Zc (3)	
1997	Greece	Zc (8)	
1998	Puerto Rico	Zc (5)	
2000	Bahamas	Zc (9), Md (3), unid.[AQ6] ziphiids (2), <i>Balaenoptera acutorostrata</i> (2), <i>Stenella frontalis</i> (1)	Naval maneuvers
2000	Galápagos	Zc (3)	Seismic airgun
2000	Madeira	Zc (3)	Naval maneuvers
2001	Solomon Islands	Zc (2)	
2002	Canary Islands	Zc (7), Me (2), Md (1), unid. ziphiids (9)	Naval maneuvers
2002	Baja California	Zc (2)	Seismic airgun
2004	Canary Islands	Zc (2)	Naval maneuvers

Source: J. Mead (pers. comm.), with updates by the author.

Note: Zc, Cuvier's beaked whale. Other beaked whales that stranded during these events included Gervais' beaked whale, *Mesoplodon europaeus* (Me), and Blainville's beaked whale, *Mesoplodon densirostris* (Md).

cided with tests of ASW sonar by the North Atlantic Treaty Organization (NATO). Twelve of these animals stranded along 38 km of coastline on 12–13 May 1996; another stranded along the same coastline about 20 km to the north on 16 May and was driven back out to sea. Two weeks later, one more animal was found decomposing on a remote beach on the neighboring Zákynthos Island, located northeast of the strandings on the mainland. Twelve of these fourteen animals stranded alive, with no apparent disease or pathogenic cause. These strandings coincided with a 4-day period (12–16 May) when the vessel NRV *Alliance* was towing an acoustic source in the vicinity, primarily at depths between 70 and 85 m. The source generated both low- and mid-frequency sound at source levels of 226 dB re 1 μ Pa at 1m. The transmitted low-frequency signal included a 2-s upsweep at 450–650 Hz, and a 2-s continuous tone at 700 Hz. The mid-frequency signal included a 2-s upsweep at 2.8–3.2 kHz and a 2-s tone at 3.3 kHz. Both frequencies were projected as horizontally directed beams with vertical

beamwidths of about 20°. Three source tows of about 2 h duration were conducted each day, and the beaked whale strandings occurred nearest in time to the first two source runs of 12 May (runs 9 and 10; D'Amico and Verboom 1998) and the last two source runs of 13 May (runs 13 and 14; D'Amico and Verboom 1998). Sound propagation modeling suggests that sound pressure levels only exceeded 190 dB re 1 μ Pa at ranges of less than 100 m. The sound levels present broadly throughout the Kyparissiakos Gulf are thought to have been in the range of 140–160 dB re 1 μ Pa (D'Amico and Verboom 1998).

The association in space and time between stranding locations and acoustic source tracks suggests that the animals were affected by the ASW sonar (D'Amico and Verboom 1998). Figure 7.2 shows the acoustic source tracks and stranding locations for 12 and 13 May. There is a general correlation between the offshore source track locations and the inshore stranding locations. The 13 May source track is shifted northward from the 12 May track, and likewise some

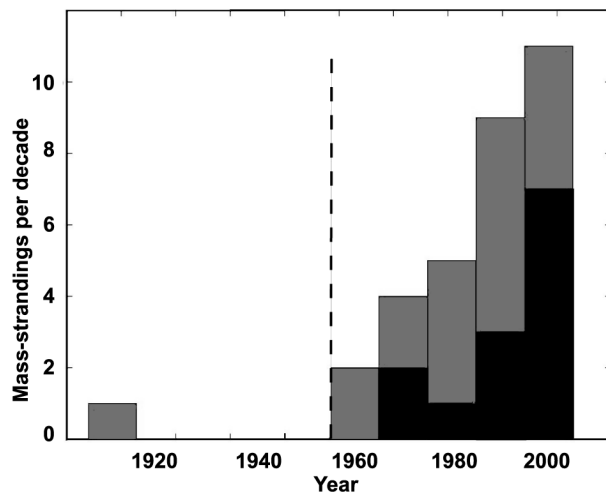


Fig. 7.1. Reported Cuvier's beaked whale mass stranding events tabulated by decade. Total numbers of reported events per decade (gray) are shown, along with the events documented in association with naval activities or airgun usage (black). Incidence of mass-stranding events increased following the deployment of mid-frequency ASW sonar beginning in the 1960s (dashed line), although the level of effort dedicated to reporting has also increased during this period.

of the 13 May stranding locations are located farther north. Correlation of stranding times and source track locations for 12 May suggests that at least three of the six animals with known stranding times were affected by the 0600–0800 h source tow as their stranding times precede the 1100–1300 h source tow. Assuming that they were near the source when they were exposed to the sound (and therefore exposed at levels above 190 dB re 1 μ Pa), their swimming distances to reach the shore would be approximately 30 nmi, covered at speeds of approximately 10 knots. Alternatively, they might have been exposed at locations inshore relative to the source, which would suggest lower sound exposure levels (140–160 dB re 1 μ Pa) but shorter swimming distances and speeds. The two 12 May afternoon stranding locations with known times likewise occurred at swimming distances of 20–30 nmi from the source track locations.

Bahamas, 15–16 March 2000

Sixteen cetaceans were found stranded along the Providence Channel in the Bahama Islands during a 2-day period in March 2000, and the episode was correlated with a U.S. Navy training exercise using ASW sonar (Evans and England 2001). The stranded animals were predominantly beaked whales (seven *Ziphius cavirostris*, three *Mesoplodon densirostris*, and two ziphiid sp.), although two minke whales were among the animals that live-stranded. One Atlantic spotted dolphin (*Stenella frontalis*) stranded at a somewhat distant location and is thought to have died of unrelated causes. Eight of the beaked whales died and the remaining animals were refloated, their fates remaining unknown (Balcomb and Claridge 2001). Tissue samples were collected from five of the dead beaked whales. Gross necropsy results suggested that all five were in good body condition; none showed evidence of debilitating disease. Hemorrhages were found in the acoustic fats of the head, the inner ears, and spaces around the brain, with no evidence of external blunt-force trauma. The pattern of injury in the freshest specimens suggested that the ears were structurally intact and that the animals were alive at the time of injury (Ketten et al. 2004).

Five Navy ships were operating hull-mounted ASW sonars in the area, four of which were described in a preliminary report (Evans and England 2001). Of the four ships described, two operated SQS-53C hull-mounted sonars and two used SQS-56 hull-mounted sonars (Watts 2003). The former were operated at 2.6 and 3.3 kHz with a source level of 235 dB re 1 μ Pa at 1 m or higher and ping lengths of 0.5–2 s alternating between tones and FM sweeps. The latter were operated at 6.8, 7.5, and 8.2 kHz at 223 dB re 1 μ Pa at 1 m. Integrated sound exposures of 160–165 dB re 1 μ Pa for 50–150 s would have been experienced in near-surface waters (15 m depth) throughout much of the Providence Channel on 15 March 2000 (Evans and England 2001). Peak sound pressure levels above 185 dB re 1 μ Pa would have been experienced only within a few hundred meters of the ship tracklines along the central portion of the channel.

The association in space and time between the stranding locations and acoustic source tracks shown in Figure 7.3 is

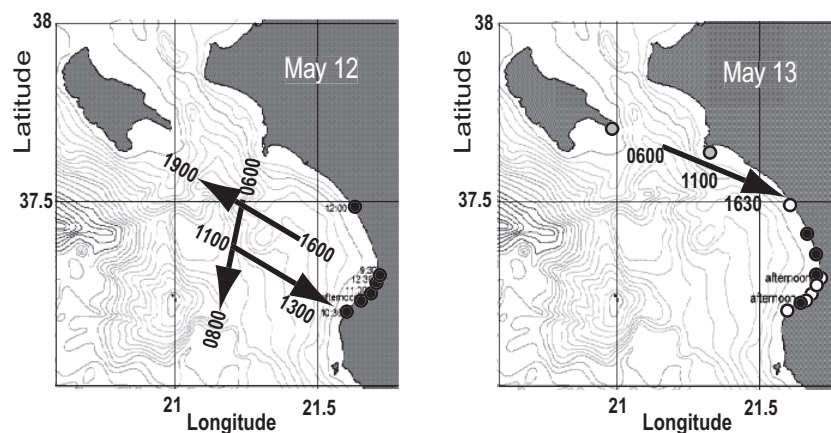


Fig. 7.2. Kyparissiakos Gulf, Greece, Cuvier's beaked whale (*Ziphius cavirostris*) mass stranding locations and acoustic source tracks for 12 May and 13 May 1996. Times for the source tracks and strandings are indicated in GMT. The stranding locations for each day are indicated by black dots on the respective maps. For 13 May, strandings occurring on the previous day are indicated by white dots; strandings occurring after 13 May are shown by gray dots (D'Amico and Verboom 1998, Frantzis 2004).

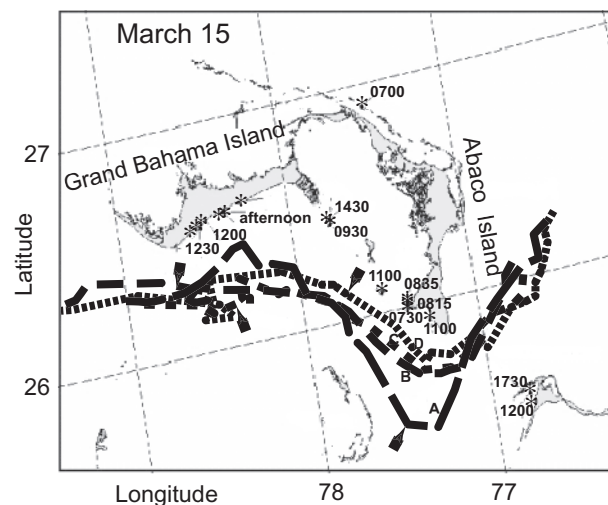


Fig. 7.3. Bahamas stranding locations and acoustic source tracks for 15 March 2000. Stranding locations (asterisks) are shown, along with known stranding times (all times are given as local). Tracks for four U.S. Navy ships are shown moving from east to west through the Providence Channel. Ship tracks are shown as broken lines (ships are given designations A, B, C, and D following Evans and England 2001). Arrows along each ship track designate 0730 h, the time of the first recorded stranding, located at the south end of Abaco Island. Ships B and C entered the channel near Abaco before midnight on 15 March, whereas ships A and D entered the channel at about 0400 h (Evans and England 2001).

compelling evidence that these animals were affected by the high-intensity sound sources (Evans and England 2001). A few hours before midnight on 15 March, two source ships (designated B and C) entered the Providence Channel off the southwest end of Abaco Island and moved through the channel toward the west. Both ships were using active sonar as they entered the channel (ship B 53C sonar, and ship C 56 sonar) with pulse repetition rates of about 24 s. The second pair of source ships (A with 53C sonar, and D with 56 sonar) entered the channel at about 0400 h on 15 March, again from the east and moving west.

A cluster of strandings occurred at the south end of Abaco Island during the morning of 15 March, with the first recorded stranding at 0730 h. These strandings appear to have occurred at the same time or soon after the second pair of source ships passed through the channel south of Abaco, and about 8 h after the first pair of source ships passed this point in the channel. These strandings occurred at minimum ranges of 10–30 nmi from the ships' closest points of approach. During the late morning, the source ships moved northwestward, approaching Grand Bahama Island, and a cluster of noon and afternoon strandings occurred on the south coast of Grand Bahama Island, again with minimum source-to-shore ranges of 20–30 nmi. Balcomb and Claridge (2001) noted that individual Cuvier's beaked whales that had been identified photographically in this region previously have not been sighted subsequent to the stranding event, suggesting that the beaked whale mortality was higher than simply the number of whales that were known to have mass stranded.

The highest sound exposures would have been experienced by animals distributed at locations along the source tracks, suggesting that following exposure they might have swum toward the stranding sites 10–30 nmi distant. However, data on beaked whale distribution (K. Balcomb and D. Claridge pers. comm.) suggest that *Mesoplodon densirostris* is found predominantly along the margins of the channel, in waters about 500 m deep, and that *Z. cavirostris* is also found along the channel margins, but in deeper waters. Combining the source modeling and the animal distribution data suggests that sound at moderate exposure levels (e.g., 150–160 dB re 1 μ Pa for 50–150 s) would have been received at the most likely locations of beaked whales in Providence Channel (Evans and England 2001).

Madeira, May 2000

Three Cuvier's beaked whales stranded in May 2000 on the Madeira Archipelago in the northeastern Atlantic (Freitas 2004). The area south of Madeira Island, specifically the deep channel between Madeira and Porto Santo islands, is a known location for *Ziphius cavirostris* sightings. The animals stranded on 9, 13, and 14 May: two subadults (one male, one female) and a female of unknown age. The two subadults were examined and found to have eye hemorrhages, pleural hemorrhages, and lesions of the lungs (Freitas 2004). It was concluded that they had stranded while still alive. The third animal was found in an advanced state of decomposition and was not examined in detail. A NATO exercise was signaled by the presence of naval vessels and aircraft in the deepwater channel between the islands during the period 9–14 May. The exercise was reported to have involved one aircraft carrier, three submarines, and more than forty surface vessels. Details of the acoustic sources in use during the exercise have not been made available.

Canary Islands, 24 September 2002

A mass stranding of fourteen to nineteen beaked whales occurred on the Canary Islands of Fuerteventura and Lanzarote, associated with naval maneuvers by Spain and other NATO countries on 24–25 September 2002. The stranded animals included seven *Ziphius cavirostris*, two *Mesoplodon europaeus*, and one *M. densirostris*. On 24 September a total of fourteen animals were found stranded; five were dead, three were alive and subsequently died, and six were pushed back to sea. Five more animals were found dead and in a decomposed state between 25 and 28 September. It is possible that these included animals that had been pushed out to sea and then had stranded again. Preliminary necropsy results for six of the beaked whales suggest that they were healthy. The strandings occurred at dawn or in the early morning, and the animals that were found alive all appeared disoriented. Those that were found dead had been feeding shortly prior to stranding (Martín et al. 2004).

Necropsies and dissections (Fernández 2004) revealed no visible signs of traumatic lesions physically caused by ship

strikes, fishing activities, or blunt trauma generally. The stomach contents, and their freshness and digestive status, indicated that there was only a short period between the onset of illness and death.

Examination of these animals' heads and bodies revealed hemorrhages and bubbles (Fernández 2004). Hemorrhages were observed along acoustic paths in the head and in the brain and spinal cord. The hemorrhagic areas observed macroscopically in the acoustic fat were also demonstrated histologically. All of the animals were bleeding profusely from the eyes and there was evidence of multifocal petechial (pinpoint) hemorrhages. Fat embolisms were observed, which could have been responsible for hemorrhages in the macrovascular system. Focal hemorrhages were found in the dura mater membrane, and there was a large quantity of blood in the subarachnoid space around the cranial spinal cord. A generalized congestion of the blood vessels in the brain was seen in all the fresh animals, and multifocal subarachnoid hemorrhages were detected. Additionally, in the tissues that were fresh, empty spaces and bubbles were seen inside the blood vessels. In sections of the brain, multifocal petechial hemorrhages were located mainly in the white matter. All the lungs presented general diffuse congestion, some subpleural hemorrhages, and alveolar edema. The kidneys were enlarged, with marked vascular congestion and hemorrhages in the capsular and interstitial areas. Degeneration (in vivo) of vestibulocochlear portions of the ear was noted. Although the exact physical mechanism for these injuries is not known, several hypotheses currently under investigation are focused on nonauditory acoustic effects (Jepson et al. 2003).

The strandings occurred along the southeastern coast of the islands of Fuerteventura and Lanzarote. At the time of the 24–25 September strandings, ten NATO countries (Germany, Belgium, Canada, France, Greece, Norway, Portugal, Turkey, the United Kingdom, and the United States) were conducting a multinational naval exercise (known as NEOTAPON[AQ3] 2002); however, the acoustic sources employed during the exercise are not known at this time. The participating countries include ASW sonar in their capabilities although the details of their systems vary (Watts 2003). Common features of the sonars that may have been used in this exercise include high-amplitude source levels (SPL > 223 dB RMS re 1 μ Pa at 1 m), periodic (15–60 s) repetition, pulses (up to ~4 s), with significant energy at middle frequencies (3–10 kHz), and formed into horizontally directive beams (Watts 2003). Eight mass strandings of *Z. cavirostris* have been documented in the Canary Islands since 1985, and naval exercises have been recorded as associated with five of them (Table 7.5; Martín et al. 2004).

Gulf of California, 24 September 2002

A stranding of two *Ziphius cavirostris* occurred on 24 September 2002 on Isla San Jose in the Gulf of California, Mexico, coincident with seismic reflection profiling by the R/V *Maurice Ewing* operated by Columbia University, Lamont-

Doherty Earth Observatory (Malakoff 2002, Taylor et al. 2004). On 24 September at about 1400–1600 h local time (2100–2300 h GMT), fishermen discovered two live-stranded whales and unsuccessfully attempted to push them back out to sea (J. Urbán-Ramírez pers. comm.). A group of marine biologists found the whales dead on 25 September (B. Taylor pers. comm.). By 27 September, when one carcass was necropsied, the advanced state of decomposition precluded determination of the cause of death.

On 24 September the R/V *Ewing* had been firing an array of twenty airguns with a total volume of 8,500 in.³. Such an array is expected to have an effective broadband source level of 256 dB peak re 1 μ Pa at 1 m, with maximum energy at frequencies of 40–90 Hz. A later attempt to directly measure the array source level (Tolstoy et al. 2004) was unsuccessful owing to equipment malfunction and ambiguities in converting the pulsed signals into RMS pressure values. Source levels of airgun arrays at middle frequencies (1–5 kHz) are thought to be diminished from levels at low frequencies by 20–40 dB (Goold and Fish 1998, Tolstoy et al. 2004). The *Ewing* airguns were fired with a repetition rate of approximately 20 s (50 m distance between shots). Figure 7.4 shows the *Ewing* track for 24–25 September; the ship was on a transect line directed toward the stranding site and reached the closest point of approach (18 nmi) at 1430 h local time (2130 h GMT). These animals would have received the highest sound pressure levels if they were exposed at locations near the source tracks. Then, following exposure, they might have swum toward the stranding site 20–30 nmi distant. Alternatively, they might have been exposed at lower source levels at locations nearer the stranding site.

Summary of Beaked Whale Stranding Events

The mass strandings of beaked whales following exposure to sound from sonar or airguns present a consistent pattern of events. Cuvier's beaked whales are, by far, the most commonly involved species, making up 81% of the total number of stranded animals. Other beaked whales (including *Mesoplodon europaeus*, *M. densirostris*, and *Hyperoodon ampullatus*) account for 14% of the total, and other cetacean species (*Stenella coeruleoalba*, *Kogia breviceps*, and *Balaenoptera acutorostrata*) are sparsely represented. It is not clear whether: (a) *Ziphius cavirostris* are more prone to injury from high-intensity sound than other species, (b) their behavioral response to sound makes them more likely to strand, or (c) they are substantially more abundant than the other affected species in the areas and times of the exposures leading to the mass strandings. One, two, or three of these possibilities could apply. In any event, *Z. cavirostris* has proven to be the "miner's canary" for high-intensity sound impacts. The deployment of naval ASW sonars in the 1960s and the coincident increase in *Z. cavirostris* mass strandings suggest that lethal impacts of anthropogenic sound on cetaceans have been occurring for at least several decades.

The settings for these strandings are strikingly consistent: an island or archipelago with deep water nearby, appropri-

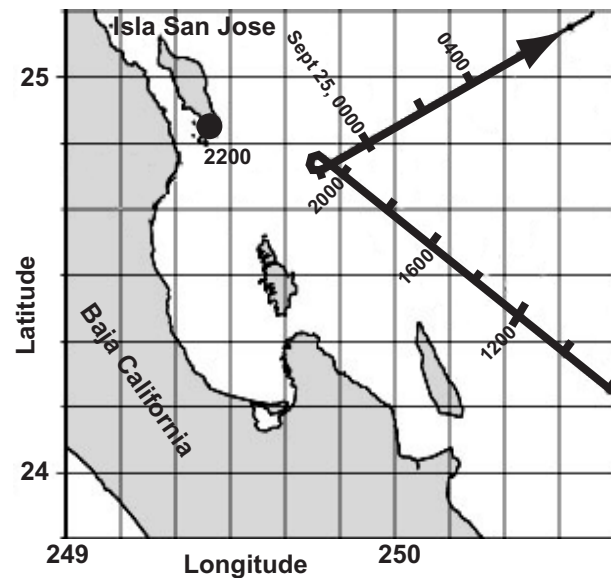


Fig. 7.4. Gulf of California *Ziphius cavirostris* stranding location (black dot) and best estimate for the time of stranding (2200 h GMT), along with the R/V Ewing track for 24–25 September 2002. Times along the ship's track are indicated in GMT. The ship's closest point of approach to the stranding site was 18 nmi.

ate for beaked whale foraging habitat. The conditions for mass stranding may be optimized when the sound source transits a deep channel between two islands, such as in the Bahamas, and apparently in the Madeira incident. When exposed to these sounds, some beaked whales swim to the nearest beach. The animals appear on the beach not as a tight cluster of individuals but rather distributed over miles of coastline. Such scatter in the distribution of stranding locations is an important characteristic, which has resulted in these events being called “atypical” mass strandings (Frantz 1998, 2004, Brownell et al. 2004). The stranded animals die if they are not returned to the sea by human intervention, and the fate of the animals that are returned to the sea is unknown. Necropsies of stranded animals suggest internal bleeding in the eyes, ears, and brain, as well as fat embolisms.

The implicated sounds involve pulses with high-intensity source levels (235 dB re 1 μ Pa at 1 m) from sonar or airgun arrays. Middle frequencies (1–6 kHz) are clearly implicated in the sonar-induced stranding incidents. It is unclear whether low-frequency sound also has the potential of causing injury to beaked whales. Although airguns create predominantly low-frequency energy, they may also have ample mid-frequency energy. The actual sound exposure levels received by animals that later strand are unknown although in the best-documented events these levels may be bounded by careful sound propagation modeling and by knowledge of where the animals are most likely to be found. Source levels high enough to create permanent or temporary hearing loss would be experienced only at ranges close to the source (< 1 km). The sound exposures calculated for sites of most likely animal presence appear to be significantly lower.

For instance, in the Bahamas, the most likely exposure levels appear to have been 150–160 dB re 1 μ Pa for 50–150 s, or less, well below the level expected to create hearing loss in odontocetes. Given that damage to hearing appears unlikely, other mechanisms are needed to explain the connection between sound exposure and stranding in beaked whales.

RESEARCH PRIORITIES FOR SOUND EFFECTS ON MARINE MAMMALS

A decade has passed since the National Research Council (1994) outlined a set of research priorities for understanding the effects of noise on marine mammals. In most of the areas outlined for study, a basic understanding is still lacking. Many of the same research priorities were reiterated by two subsequent National Research Council (2000a, 2003b) reports. The need to study the impacts of noise in the field rather than in captive settings means that a clear understanding may not become available for many years. There is also the need to differentiate the effects that are significant for individual animals from those that are significant on a population level. Addressing population-level impacts requires observations that are distributed in space and time and large numbers of observations to provide statistical power.

Priority 1: Understand, in detail, the causes of mass strandings of beaked whales. When exposed to high-intensity sound, some beaked whales strand and die. Understanding the causes and consequences of beaked whale mass stranding represents the highest research priority for marine mammalogists studying the conservation implications of exposure to sound. The sound levels implicated in these events is probably not sufficient to cause permanent or temporary hearing threshold shifts. What is the mechanism for damage or disturbance? The behavioral reaction is swift and vigorous on an individual level. The lack of close animal clustering on the beach suggests little or no social component to these strandings, yet the potential for large numbers of animals to strand suggests significance at a population level. What are the source characteristics that lead to damage? Is low-frequency sound (the primary energy component of airguns) as damaging as mid-frequency sound (used by SQS-53 ASW tactical sonars)? What sound pressure exposure level creates damage or disturbance? Beaked whale mass stranding events make it clear that high-intensity anthropogenic sound is a threat to at least some marine mammals, yet key parameters about beaked whale strandings must be understood before we can predict the impacts of high-intensity sound on other species in other settings.

Priority 2: Determine behavioral responses to anthropogenic sound. A key impediment to assessing the biological effects of ocean noise is the paucity of knowledge about marine mammal behavior and specifically the lack of understanding of their behavioral responses to anthropogenic sound. Be-

havioral data must be collected in the wild to provide a basis for understanding potential effects. Significant effects of ocean noise may be confined to a few individuals exposed to high sound pressure levels, or they may extend to entire populations as a result of widespread exposure. Controlled exposure experiments might be helpful in defining obvious or short-term effects on individuals but may not reveal long-term impacts. Discerning population-level effects is challenging as the observations must be conducted over long distances and extended periods of time, and there are many confounding influences. Relating migration and movement to noise level is one potential approach. Do marine mammals systematically avoid habitat areas with high noise levels? More subtle behavioral changes may be associated with exposure to high ambient ocean noise. Is natural sound (e.g., snapping shrimp) useful for prey location? A better understanding of how and why marine mammals make and use sound would greatly aid our ability to predict how ocean noise might be disruptive to marine mammal behavior. The sound avoidance response has been exploited to exclude marine mammals from fish pens and fishing operation areas using acoustic harassment devices. However, does their behavioral response take place before some hearing loss occurs? Our ignorance about marine mammal behavioral responses to sound is abysmal, and knowledge of this subject must be improved in the face of rising ocean noise levels.

Priority 3: Improve tools for assessing and measuring the behavior of marine mammals. Better research tools are needed to observe marine mammal behavior in the wild. Such tools are needed both to characterize normal behavior and to detect changes in behavior associated with anthropogenic sound. Acoustic recording tags are important for detailed behavioral studies in the presence of sound. Technical improvements are needed over current tags to increase their duration of attachment, to expand the volume of stored data, and to enhance the suite of available sensors. Improvements to the tag attachment system are particularly needed for large cetaceans, which cannot be captured for tagging. Current noninvasive attachments have limited duration, whereas invasive attachments may involve both disturbance and injury to the animal. Technology for passive acoustic tracking is another important component of behavioral study with the potential for improvement.

Priority 4: Develop tools to study marine mammal physiology in the wild. For many species of marine mammal, large num-

bers of individuals will probably never be maintained in captivity for study of their physiology, so tools are needed to study marine mammal physiology in the wild. For instance, indicators of stress may be used to assess the impact of anthropogenic noise. If stress factors can be measured from blubber or blood samples, perhaps biopsy or other tissue samples collected in the wild could reveal regional or population-wide stress levels associated with noise. Moreover, without a field method that can be rapidly deployed to determine hearing capabilities, it is difficult to collect audiometric data on all marine mammal species and under the full range of conditions where chronic noise may have degraded hearing capabilities. The ability to collect audiometric data on a beached or net-entangled animal is a first step and will be especially useful when high-intensity sound is suspected of having played a role in the animal's stranding.

Priority 5: Characterize and monitor marine mammal populations in areas of high-intensity sound generation. High-intensity anthropogenic ocean sound sources are primarily concentrated in well-defined zones: (a) at major commercial ports and along shipping lanes, (b) within military test and training sites, and (c) within regions of oil exploration and development. The marine mammal populations that inhabit or move through those zones should be characterized and monitored. A combination of visual and acoustic monitoring may be necessary for efficient assessment of marine mammal distributions, ambient noise, and anthropogenic sound. Such monitoring data will help determine whether noise is a factor in discouraging habitat use by marine mammals.

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