Noise in the Ocean:
A Review of the Issues, Science and Policy
 Relating to the effects of Noise on Marine Life

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PROLOGUE

This report is presented as part of an assignment for the Coastal Resources Management PhD program course CRM6100. The scenario for this review is that the authors are a team of National Oceanic and Atmospheric Administration (NOAA) employees, requested to brief the new, politically appointed, head of NOAA, on the issue of noise in the ocean; to review possible actions for NOAA and to recommend politically feasible actions.
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1.0 SUMMARY

Over the last sixty years our perception of sound in the oceans has gone from silent, to song, to noise, to noise pollution. There is increasing anecdotal and scientific evidence that too much human generated sound is harming marine life. This paper describes the production of sound in the ocean and then reviews scientific investigations that are attempting to determine whether, and how, human generated noise is harmful, and how its effects might be mitigated. The actions of legislators, policy makers, and government agencies, in particular the National Oceanic and Atmospheric Administration (NOAA) to balance the needs and views of various stakeholders are reviewed and recommendations for future actions made.
2.0 INTRODUCTION

In 1953, Jacques Cousteau referred to the oceans as a Silent World (Cousteau 1953). Almost sixty years later his son, Jean-Michel Cousteau is one of the leading campaigners against deafening noise pollution in the ocean, harming entire populations of marine life (Cousteau 2008). What happened? Not only did we start listening but also to make sound in the ocean, to the extent that human generated sound is now frequently referred to as noise pollution.

The 1970 release of the album *Songs of the Humpback Whale*, which has sold over 30 million copies, was key in raising people’s awareness that animals in the oceans make sound, and that the oceans are far from silent. From the 1950s the US navy, while listening for Russian submarines, incidentally recorded whale sounds. Recordings of whales were released in 1967 to biologist Roger Payne. He collaborated on producing an album, in support of the campaign to stop whaling. The campaign against whaling was part of a growing movement of concern about the protection and development of coastal areas generally. The Marine Mammal Protection Act passed by Congress in 1972, included a general moratorium on the importation of marine mammals and their products into the United States, effectively ending whaling in the US. The Act also established the Marine Mammal Commission (MMC) charged with protection and conservation of marine mammals (MMC 2008).

Since the 1950s, humans have increasingly generated sound in the oceans. Some of it deliberately as in the Navy’s use of SONAR to ‘see underwater’ and detect ever quieter enemy submarines (Oceanus 2008), or the use of sound waves in seismic surveys for oil
and gas exploration. Sound is also generated incidentally as a result of other activities, for example engine noise of commercial shipping. One study reports that noise levels in the Pacific, 160 miles west of San Diego, are now 10-12 decibels higher than 40 years ago (Hildebrand et al 2008).

An increase of mass strandings of whales, particularly of the deep diving otherwise rarely seen Cuvier’s beaked whales, since the 1960s in various parts of the world, has drawn attention to the possibility that human made sound in the oceans, particularly the Navy’s use of sonar, could be seriously interfering with its natural inhabitants (Frantzi 1998; Fortescue et al 2005). Whale strandings, are not a new phenomenon; Podesta et al (2006) found reports of over 230 Beaked whale strandings in the Mediterranean Sea over the last 200 years. Although an increase in the last 20 years was found only 1 in 12 could be ‘unequivocally associated with naval activity’ (Podesta et al 2006). In 2007 Rear Admiral Rice (Noel 2007) stated that sonar was implicated in an average 5 strandings per year to over 3,000 from natural causes.

Despite attempts by the Navy and many scientists to keep things in perspective, images of dying whales on beaches inevitably provoke concern, protest and demands for something to be done from the public, media, and Non-Government Organizations (NGOs), in particular the Natural Resources Defense Council (NRDC). All concerned for the environment and all certain of a cause and effect link between sonar and strandings. In response to public pressure through the media and the courts, Navies around the world (including in the US) have conceded and implemented risk mitigation procedures during
exercises (Fortescue 2005). However, these are mostly based on a precautionary approach – rather than on scientific data.

Although whale strandings draw public attention to the issue of too much human generated sound in the ocean there is increasing evidence that fish are also affected by sound (Luczovich 2008). A number of research groups are endeavoring to provide data so that informed, realistic, decisions on policy and regulation can be made to mitigate the effects of noise on marine life. For example the National Oceanic and Atmospheric Administration (NOAA) is actively involved in this research through its Ocean Acoustics Program (Southall and Gentry 2005) and has just completed collecting data in Hawaii, on deep diving whales and their response to sonar during military exercises (Oceanus 2008). This is a project in partnership with international scientists and the US Navy. Such collaborative efforts are needed to arrive at a win-win situation for all stakeholders.
3.0 SOUND IN THE OCEAN

3.1 The Physics of Sound in the Ocean

Sound waves are a type of wave called a “longitudinal wave” (Madsen, 2004; Sprague, 2008; Southall et.al., 2007). These waves are characterized by alternating pressure sequences as they propagate through different media (Madsen, 2004; Southall et.al., 2007; www.grc.nasa.gov; UNRI OMP, 2008). There are two main components to the sound wave; “...(1)a pressure component and (2) a particle motion component.” (Southall et.al., 2007). Pressure is defined as a force per a unit of area (http://hyperphysics.phy-astr.gsu.edu/hbase/press.html). Particle motion is defined as “...the oscillatory displacement, velocity, or acceleration of the actual ‘particles’ of the medium at a particular location...” (Southall et.al., 2007). Depending on the type of marine organism, either the pressure or particle motion component (or a combination of the two) is perceived and processed (Sprague, 2008; Southall et.al., 2007). Most fishes are able to process particle motion while marine and terrestrial mammals primarily perceive the pressure component (Southall et.al., 2007).

Sound is actually produced as these pressure waves cause vibrations within the different types of matter, such as air or water (Madsen, 2004; Southall et.al., 2007). When graphed, a sound wave looks very similar to an ocean wave (Fig. 1). However instead of highs and lows on the graph representing vertical heights of water level, they represent highs and lows of pressure (Fig. 1) (UNRI OMP, 2008). As these highs and lows in pressure pass through a material they compress and expand the molecules of the material (Fig. 1), creating the vibrations (Madsen, 2004; Southall et.al., 2007). We can describe the resulting
sound in terms of its frequency and intensity (Madsen, 2004; [www.grc.nasa.gov](http://www.grc.nasa.gov); UNRI OMP, 2008).

The frequency is a function of speed of the sound wave and its’ wavelength. Wavelength (Fig. 2) is the distance between two maximums or minimums in wave pressure (Madsen, 2004; [www.grc.nasa.gov](http://www.grc.nasa.gov); UNRI OMP, 2008). Frequency is then the number of wavelengths that pass a point in one second (Madsen, 2004; [www.grc.nasa.gov](http://www.grc.nasa.gov)). When a single wavelength passes over 1 second it is called 1 “cycle” and is reported as a 1 Hertz (Hz) frequency (UNRI OMP, 2008). Sound waves with longer wavelengths are low frequency (fewer cycles per second, Fig. 3A) while shorter wavelengths are higher frequency waves (more cycles per second, Fig. 3B) (Madsen, 2004; UNRI OMP, 2008). This shows us how wavelength and frequency are related.

![Diagram of a sound pressure wave and its’ associated particle motion](image)

Figure 1. Diagram of a sound pressure wave and its’ associated particle motion (UNRI OMP, 2008)
Figure 2. A) Diagram of a sound pressure wave defining wavelength. B) Diagram of a sound pressure wave defining the wave cycle (UNRI OMP, 2008).

Figure 3. A) Example of a low frequency sound wave. B) Example of a high frequency sound wave (UNRI OMP, 2008).
The intensity of a sound wave is a measure of its power. This is seen as the amplitude (Fig. 4) or height of the sound wave (UNRI OMP, 2008). Greater amplitudes represent higher intensity sound waves that are perceived as sounding louder (UNRI OMP, 2008). The power is measured in decibels (dB) as a ratio of the measured sound power to a reference level of sound power (UNRI OMP, 2008; www.phys.unsw.edu/au/jw/dB.html). The ratio is described on a logarithmic scale and the reference level used is based on an agreed upon intensity adjusted by the density of the material the sound is traveling through (UNRI OMP, 2008; www.phys.unsw.edu/au/jw/dB.html). As a decibel is based on a logarithmic scale we need to remember that that increases in decibel levels are not linear. A 10 dB increase in sound power is actually a ten times increase in power and a 20 dB increase is a one hundred times increase in power (UNRI OMP, 2008). However, a 10 dB increase in power is perceived as a two times increase in loudness, not a ten times increase (UNRI OMP, 2008; www.phys.unsw.edu/au/jw/dB.html). So while a measure of decibel level will represent the power of a given sound wave, it only indirectly gives us the perceived loudness of that sound.
As mentioned above, the reference level used to calculate the decibel level for a given sound wave is dependent on the type of material the wave is moving through. The standard reference level for sounds in air is dB re 20µPa while water is dB re 1 µPa (Madsen, 2004; Southall et al., 2007). This complicates comparisons of sound levels between air and water (Madsen, 2004). Table 1 contains some common sound types, their frequency (Hz) and intensity (dB) in both air and water. The same sound in air can appear to have a much lower intensity than the same sound underwater due to the necessary conversion by reference pressure. Therefore, unless you convert the reported decibel level for an underwater sound to its air equivalent, it is hard to determine how loud (in a human frame of reference) the sound actually is.
<table>
<thead>
<tr>
<th>Typical sound in air</th>
<th>Water standard (dB re 1 $\mu$Pa)</th>
<th>Air standard (dB re 20 $\mu$Pa SPL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold of human hearing (1,000 Hz)</td>
<td>[26]</td>
<td>0</td>
</tr>
<tr>
<td>Very quiet living room</td>
<td>[66]</td>
<td>40</td>
</tr>
<tr>
<td>Seal threshold underwater (1,000 Hz)</td>
<td>80</td>
<td>[54]</td>
</tr>
<tr>
<td>Normal speech (1 meter)</td>
<td>[86]</td>
<td>60</td>
</tr>
<tr>
<td>Beluga threshold (1,000 Hz)</td>
<td>100</td>
<td>[74]</td>
</tr>
<tr>
<td>Lion’s roar (10 meters)</td>
<td>[116]</td>
<td>90</td>
</tr>
<tr>
<td>Jet airliner (10 meters)</td>
<td>[130]</td>
<td>104</td>
</tr>
<tr>
<td>Fin whale call (100 meters)</td>
<td>140</td>
<td>[114]</td>
</tr>
<tr>
<td>Human threshold of pain (at ear drum)</td>
<td>[166]</td>
<td>140</td>
</tr>
<tr>
<td>Some military artillery</td>
<td>[186]</td>
<td>160</td>
</tr>
<tr>
<td>Beluga echolocation call (1 meter)</td>
<td>220</td>
<td>[194]</td>
</tr>
</tbody>
</table>

Source: Adapted from Kryter (1985) and Richardson et al. (1991).

NOTE: Bracketed levels are nominal levels after conversion to alternate medium.

Table 1. Comparison of sound pressure levels between air and water.
Another characteristic we are concerned about is the speed and velocity of a sound wave. The speed of the wave reflects the amount of energy it has and the type of medium it is moving through, while velocity is a combination of speed and directionality of movement (Madsen, 2004). As sound waves move through different types of matter, the density of that material will affect the wave’s speed. Higher density materials such as liquids will cause sound waves to move faster and require less energy to propagate. Lower density mediums such as air cause sound waves to move more slowly and require more energy to travel long distances (Madsen, 2004). Also, as sound waves propagate through different materials their intensity can change with distance. So the intensity of a sound measured at its source (usually measured 1 m from source) and the received level (intensity of the sound wave at its reception by an organism or recording instrument) can be different (Southall et al., 2007). This is important because depending on the properties of the medium and the distance the sound travels through it, the intensity of the sound when it is heard by say a whale, is different than when it was first produced (Southall et al., 2007). So measurements of source level may not help in determining the end result of the sound wave when it reaches a point of interest.

Another factor we need to look at is if the sound is a “(1) pulse or (2) nonpulse” (Table 2) (Southall et al., 2007). Pulses of sound can have very different affects on marine organisms then nonpulse or more constant sounds (Southall et al., 2007). Pulsed sounds include explosions, single air guns, piling strikes, some sonars and depth sounders. Multiple pulsed sounds are primarily air gun arrays, some active sonars, piling strikes and explosions. Finally, nonpulse sounds include vehicle vibrations, drilling and construction, and the two
main types of Navy sonar, low frequency active and mid-frequency, as well as depth sounders (Southall, *et al.*, 2007).

Table 1. Sound types, acoustic characteristics, and selected examples of anthropogenic sound sources; note sound types are based on characteristics measured at the source. In certain conditions, sounds classified as pulses at the source may lack these characteristics for distant receivers.

<table>
<thead>
<tr>
<th>Sound type</th>
<th>Acoustic characteristics (at source)</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single pulse</td>
<td>Single acoustic event: &gt; 3-dB difference between received level using impulse vs equivalent continuous time constant</td>
<td>Single explosion; sonic boom; single airgun, watergun, pile strike, or sparker pulse; single ping of certain sonars, depth sounders, and pingers</td>
</tr>
<tr>
<td>Multiple pulses</td>
<td>Multiple discrete acoustic events within 24 h; &gt; 3-dB difference between received level using impulse vs equivalent continuous time constant</td>
<td>Serial explosions; sequential airgun, watergun, pile strikes, or sparker pulses; certain active sonar (IMAPS); some depth sounder signals</td>
</tr>
<tr>
<td>Nonpulses</td>
<td>Single or multiple discrete acoustic events within 24 h; &lt; 3-dB difference between received level using impulse vs equivalent continuous time constant</td>
<td>Vessel/aircraft passes; drilling; many construction or other industrial operations; certain sonar systems (LFA, tactical mid-frequency); acoustic harassment/deterrent devices; acoustic tomography sources (ATOCS); some depth sounder signals</td>
</tr>
</tbody>
</table>

Table 2. Sound types (Southall, *et al.*, 2007)

3.2 Sources of Sound in the Ocean

Marine mammals utilize sound for social interaction, echolocation, orientation, and predator-prey interactions (Southall *et al.*, 2007). Soniferous fishes also create sound for mating purposes (Luzckovich, 2008). Table 3 illustrates some of the ranges of hearing for groups of marine mammals. When this is compared to Table 4, we can begin to see where different sources of anthropogenically produced sound in the ocean could affect marine mammals.
Table 2. Functional marine mammal hearing groups, auditory bandwidth (estimated lower to upper frequency hearing cut-off), genera represented in each group, and group specific (M) frequency-weightings

<table>
<thead>
<tr>
<th>Functional hearing group</th>
<th>Estimated auditory bandwidth</th>
<th>Genera represented</th>
<th>Frequency-weighting network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frequency cetaceans</td>
<td>7 Hz to 22 kHz</td>
<td>Delphinus, Peponocephala</td>
<td>(Mf: low-frequency cetaceans)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(13 species/subspecies)</td>
<td></td>
</tr>
<tr>
<td>Mid-frequency cetaceans</td>
<td>150 Hz to 160 kHz</td>
<td>Steno, Sousa, Scylla, Tursiops, Stenella, Delphinus, Lagophthalmus, Lagenorhynchus, Lissodelphis, Grampus, Pinnipedia, Gerbillus, Delphinapterus, Monodon, Ziphius, Berardiidae, Tyulina, Hyperoodon, Megaptera (57 species/subspecies)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Mf: mid-frequency cetaceans)</td>
<td></td>
</tr>
<tr>
<td>High-frequency cetaceans</td>
<td>200 Hz to 180 kHz</td>
<td>Phocoena, Neophocaena, Phocoenidae, Platanista, Inia, Kopi, Lipotes, Pontoporia, Cephalorhynchus (20 species/subspecies)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Mf: high-frequency cetaceans)</td>
<td></td>
</tr>
<tr>
<td>Pinnipeds in water</td>
<td>75 Hz to 75 kHz</td>
<td>Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarctos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histrionicus, Pagophilus, Cetopsetta, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga, and Odobenus (41 species/subspecies)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Mf: pinnipeds in water)</td>
<td></td>
</tr>
<tr>
<td>Pinnipeds in air</td>
<td>75 Hz to 30 kHz</td>
<td>Same species as pinnipeds in water (41 species/subspecies)</td>
<td>(pa: pinnipeds in air)</td>
</tr>
</tbody>
</table>

Table 3. Functional marine mammal hearing groups, auditory bandwidth (estimated lower to upper frequency hearing cut-off), genera represented in each group, and group specific (M) frequency-weightings (Southall et al., 2007).

Table 1. Source levels for human-generated sound sources of potential significance to fishes. Data listed in dB re 1 µPa at 1 meter from the source. Data taken from Richardson et al. (1995) presented in 1/3 octave bands unless otherwise noted. ? = Noise was not quantified, though known to be present.

<table>
<thead>
<tr>
<th>Source</th>
<th>&lt; 20 Hz</th>
<th>20 – 500 Hz</th>
<th>1 – 3 kHz</th>
<th>&gt; 20 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship Noise</td>
<td>?</td>
<td>170 – 178</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drill ships (two vessels)</td>
<td>?</td>
<td>161 – 177</td>
<td>148 – 168</td>
<td></td>
</tr>
<tr>
<td>Large tanker</td>
<td>?</td>
<td>177</td>
<td>169</td>
<td></td>
</tr>
<tr>
<td>Tug and barge (18 km/h)</td>
<td>?</td>
<td>161</td>
<td>157</td>
<td></td>
</tr>
<tr>
<td>Seismic survey air gun (32)</td>
<td>?</td>
<td>210</td>
<td>191</td>
<td></td>
</tr>
<tr>
<td>Greene (1985)</td>
<td></td>
<td>250 – 255</td>
<td>223</td>
<td></td>
</tr>
<tr>
<td>Pearson et al. (1992)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Echosounders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slott et al. (2004) (38 kHz)</td>
<td>?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schwartz and Greer (1984) (50 Hz – 2 kHz)</td>
<td>?</td>
<td>?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Military sonars</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SURATSS LFA¹</td>
<td>240 (215)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid frequency (AN/SQS-53C)</td>
<td>~235</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bell 212 helicopter</td>
<td>159</td>
<td>155</td>
<td>142</td>
<td>none noted</td>
</tr>
</tbody>
</table>

¹ Fairfield source level is 240 dB re 1 µPa; however, the received level within the nearfield does not exceed 219 dB re 1 µPa (the source level of a single projector in the array).

Table 4. Source levels for anthropogenic sound in the ocean.
Two large contributors to anthropogenic sound in the ocean are the use of SONAR and air gun arrays. SONAR stands for “sound navigation and ranging” and is used for acoustic locating in the ocean by both ships and marine mammals. There are two main types of SONAR, active and passive (UNRI OMP, 2008). With active SONAR, a sound is generated and then the time between that sound creation and when an echo (or return) of the sound is received is measured (UNRI OMP, 2008). The time tells us the distance the sound travel before it was reflected back, allow us to determine how far objects are under the ocean (UNRI OMP, 2008). Passive SONAR consists of hydrophone receivers used to simply listen to the sound that is produced underwater, no sound is actually generated by the listener (UNRI OMP, 2008).

The US Navy currently works with two main types of active SONAR, the SURTASS LFA (surveillance towed array sensor system low-frequency active SONAR) and tactical mid-frequency SONAR (Southall et.al., 2007). The SURTASS LFA operates at a frequency of about 300 Hz, while the mid-frequency SONAR operates primarily between 1-5 kHz (Southall et.al., 2007). These sounds are multipulsed and because they are emitted with a specifically horizontal directionality, can travel great distances (Southall et.al., 2007). Pulses from these types of SONAR have been recorded to travel tens of kilometers through the ocean (Southall et.al., 2007).

The air gun arrays are primarily used for oil and gas exploration in the ocean. These large, towed, arrays consist of long lines of hydrophones and noise makers (Southall et.al., 2007). The air gun lines deployed generate pulsed blasts of intense sound in the 300 Hz range every few seconds that propagates down the ocean floor, is reflected, and then measured
on the return echo (Southall et al., 2007). By analyzing the echoes that are received by the hydrophones, prospectors can determine the types and thicknesses of rock layers at the ocean bottom and the location of oil or gas deposits. Sound waves from these arrays have been recorded as far as 12 km from their source area (Southall et al., 2007).

These represent just a few of the large contributors to sound in the ocean. Scientific study of all the potential generators of sound is necessary to determine relative contributions and impacts on marine life. Generators of sound, as stakeholders in developing policy in relation to controlling human generated sound in the ocean are discussed further in Section 5.1
4.0 MARINE LIFE AND SOUND

4.1 Adaptations to Underwater Environment

In the underwater world where reduced light penetration limits visibility to a few hundred meters at best, marine animals have adapted to use sound to paint an ‘acoustic image’ of their world (Ocean Studies Board, 2003). As discussed above, sound travels much farther underwater than it does in the air. Furthermore, the sound does not degrade as quickly. This allows some marine species to produce and receive vocalizations over great distances or to detect localized sounds at levels beyond the range of human hearing. Marine animals likely use sound as a primary means of interpreting and interacting with their environment. Sound becomes their means of communicating with each other, detecting and warning of approaching predators, detecting prey species, navigating, and maintaining familial and pod bonds (University of Rhode Island, Marine animal use of sound, 2008).

Marine animals have adapted to their sound-based environment by developing specialized hearing and echolocation organs. Cetaceans (whales and dolphins) have an inner ear structure that is remarkably similar to that of terrestrial mammals, but lack an external ear structure. Instead, sound is perceived through vibrations of a thin ‘window’ of bone in the jaw, which transmits sound vibrations through fatty tissue through the middle ear (the structure of which is poorly understood) to the inner ear. Sound production is carried out by the passage of air through sacs and nasal passages in dolphins and some cetaceans. In some whales, this sound is perhaps amplified by resonating air sacs before being emitted directly through a fatty organ called the melon in the front of the head. These sounds,
either short pulses of sound or clicks, are used as an echolocation device, with the cetacean using the elapsed time before the sound echoes back to determine distance and direction of other objects (University of Rhode Island, Sound production and reception, 2008).

Fish populations have developed a two-part structure of an inner ear and a lateral line that allows them to hear. The density of a fish body is similar to that of water, so sound passes directly through the fish’s body to the ear bones (otoliths), which are denser and vibrate more slowly than the surrounding tissue. This vibration difference stimulates the fine cilia, or hair, within the inner ear to create sound perception. The lateral line is a sensory organ along the side of the fish that allow it to perceive movement, including the kinetic component of sound. Some fish have swim bladders that compress with sound waves and transmit vibrations to the ear as well. (Edds-Walton & Finneran, 2006). Fish vocalizations are produced in several way, the most well-known being the drumming of sonic muscles against air bladders (University of Rhode Island, How do fish hear sounds?, 2008) Fish vocalizations can be a variety of grunts, clicks, drumming, and snapping that are used to attract mates and warn off predators (University of Rhode Island, The importance of sound, 2008).

These specialized hearing and vocalization organs are adapted to account for ambient noise from wind and waves, rain, seismic events, and other marine life. This natural system has been compromised by the introduction of manmade sound from the industrialized world. This manmade, or anthropogenic, sound can interfere with normal communication, increase ambient noise levels, and cause physical and behavioral harm to some marine species. As discussed previously, this sound comes from shipping, marine construction,
airguns for seismic surveys, and military tactical sonar, among other sources (Nowacek, Thorne, Johnston, & Tyack, 2007).

Manmade sound can cause behavioral and physiological responses in marine life, including both mammals and fish. There is considerable scientific and stakeholder consensus that efforts must be made to minimize harmful effects to marine life (Ocean Studies Board, 2003). The difficulty lies in determining what is harmful to which species under what conditions. This is complicated by differences in sound transmission depending on salinity, temperature, thermal layers, distance, and orientation of both the sound producer and receiver (Edds-Walton & Finneran, 2006).

4.2 Scope of Issue

In looking at this problem, research should focus not only on marine mammals such as whales and dolphins, but also on fish populations. Some attention should also be given to turtles, crabs, squid, and invertebrates. Research to date has mainly focused on individual animals, but population-level effects are also of great concern, especially in terms of the potential harm to fisheries (NOAA, 2004). This population-level research has seen little work because of inherent difficulties in researching marine populations on that scale (Ocean Studies Board, 2005).

4.3 Research Obstacles

Research suggests that loud sounds can cause physiological injury to both fish (Edds-Walton & Finneran, 2006) and marine mammals (Nowacek et al, 2007). Unfortunately, it appears that nearly every species has its own unique threshold at which it can perceive
sound, a unique optimum hearing range in which it communicates and detects prey and predators, and unique levels at which injury can occur. The research to determine these levels is time consuming and painstaking work (Edds-Walton & Finneran, 2006). It is generally considered that if a marine animal cannot perceive a sound, it is considered non-harmful to them. With this threshold of ‘harmful sound’ differing with each individual species, there are significant obstacles to determining a regulatory standard. A recent effort to develop criteria for marine mammals resulted in eighty unique exposure criteria, which the researchers acknowledge that their categories were incomplete (NOAA, 2004).

4.4 Physical Harm

As stated earlier, manmade sound can have physiological and behavioral effects on marine animals. Aside from the regulatory obstacles, the physiological harm is twofold. Like terrestrial animals, sounds of sufficient decibels and duration can produce both temporary and permanent hearing damage. This is characterized as a threshold shift, meaning that the outer limits of sound perception are shifted, reducing the range of hearing. Most research involves studying temporary threshold shifts, which appear to be far more common at the currently used sound levels (Nowacek et al, 2007). Again, each species appears to have its own levels that cause a threshold shift. At best, researchers try to determine the levels for individual species in laboratory work.

Second, if loud enough, sound may produce actual tissue damage. Underwater explosions can clearly cause fatal tissue damage (Edds-Walton & Finneran, 2006). There is circumstantial evidence that some sonar may cause auditory trauma in some species, but the mechanism is unknown. Some stranded whales have shown signs of hemorrhaging
around the auditory organs and gas bubble formation, but the cause is unknown, as will be explored later.

4.5 Behavioral Effects

Manmade sound may cause behavioral shifts, which may, in the long term, be more harmful than tissue damage to individual animals. The sudden or persistent presence of a loud or irritating sound may cause marine species to swim away from the sound, either temporarily or permanently. This risks exposing the animal to new predator groups or forcing them into areas with less favorable food supplies, temperatures, or environment. There is research showing that schools of fish move away from the sound of fishing boats, swim away from icebreakers in the arctic, and may leave the area of persistent airgun use (Ocean Studies Board, 2003).

In fish, the responses to unusual sounds include startle responses, alarm behavior, and avoidance by swimming away (Edds-Walton & Finneran, 2006). In mammals, research shows changes in depth and duration of dives, blow patterns, and vocalization (change in duration and frequency of calls) when certain noise is present (Ocean Studies Board, 2003). These behavioral change are usually temporary, but long-term changes have been found in some cases.

These behavioral effects are highly species-dependent and variation is shown within each species. Some of the factors in this variability include: environmental factors in sound transmission, location and source; individual sensitivity and tolerances; activity at the time of sound perception (ie protecting young, feeding, migration); and the age and gender of individual (Ocean Studies Board, 2003). A significant factor in the variable response is
observed habituation and sensitization with repeated exposures to sound. Some species, if exposed to a sound with a lack of negative effects, will become habituated to the sound and will cease reacting to the sound. Others, if exposed to a sound associated with negative effects, will become sensitized to the sound and react at lower levels. (Southall et al., 2007).

4.6. Masking

Another issue is the masking of biological sound by manmade sound. As mentioned earlier, each species has an optimum sound level in which it communicates, navigates, and locates predator and prey species. Usually, this sound is at a different frequency than most ambient sound. If manmade sound is introduced at a frequency similar enough to that used by the marine animal, it can ‘drown out’ or mask the biological sounds (NOAA, 2004). This could have population level effects and may cause changes in vocalization. This is particularly a concern with shipping, which can increase the decibel levels of ambient noise as well as low-frequency sonar, which can mask sounds from certain whales over long distances. As mentioned earlier, one response to this masking has been a change in the duration and frequency of vocalization.

4.7 Stress

Some researchers are concerned about the stress effects of long-term exposure to manmade sounds. Little research has been done in this area because of design difficulties, but researchers speculate that the increased nervous system response from stress reactions could cause individual-level growth, reproductivity, and general health effects (Edds-Walton & Finneran, 2006). These individual level effects, if seen throughout a
population, could have significant effects on the long-term health of our nation’s fisheries.

There are suggestions that stress responses could be an issue for local populations (non-migratory) of fish. This is an area where further research could be invaluable to determining if there is, in fact, a problem.

4.8 Whales and Sonar

There has been considerable public attention focused on the issue of mid-frequency active sonar (MFA) and whale strandings. There is general agreement now that military mid-frequency sonar exercises may, in certain circumstances, lead to the stranding of deep-diving beaked whales (NOAA, 2001). There have been a number of strandings of beaked whales closely related in time and space to MFA sonar use. While there certainly appears to be a correlation, it is still a circumstantial connection (Ocean Studies Board, 2003). The incidents involved the mass strandings of deep-diving beaked whales (which rarely strand, normally) showing some hemorrhaging and signs consistent with auditory trauma.

Despite these physical signs, no one yet has determined a mechanism through which sonar exposure could cause these effects. Some theories include acoustic resonance causing gas bubbles, disorientation causing panic surfacing and decompression, and gas bubbles formed by sonar in supersaturated tissues (NOAA, 2002). These remain theories at this time, but beaked whale tagging exercises suggest no natural causes for such injuries (Tyack, Johnson, Soto, Sturleses, & Madsen, 2006). Further complicating the issue, MFA is used thousands of times each year around the world by over 300 ships without causing known strandings. A joint Navy and NOAA report on a stranding event in the Bahamas suggested that stranding might have been caused by a combination of surface duct
conditions, unusual bathymetry (especially steep slopes in tropical area), a confined area, and heavy sonar use over an extended period (NOAA, 2001).

4.9 Conclusion

This has only touched on some of the issues around biological effects of manmade sound on marine life. If there were one overriding theme, it would be uncertainty. There clearly appears to be the potential for significant harm to a variety of marine species. The trouble is that there is simply not enough data to understand which sounds affect which species under which circumstances with any certainty (Nowacek et al, 2007). We can find patterns and extrapolate anticipated impacts, but the impacts on animals that remain out of sight and hard to detect, count, or study are largely a guessing game. That leads to the question of how to regulate a problem when we can't identify the extent or mechanisms of the problem.
5.0 OCEAN NOISE – A REVIEW OF EXISTING POLICY

Regulation of pollution in the ocean has been a challenge for policy makers ever since the recognition that the ocean was not a limitless resource and could be impacted by human actions. The recognition of noise in the ocean as a type of pollution is new because until recently the technology did not exist to experience underwater sounds, especially as experienced by marine life. Noise is a different kind of pollution than those traditionally regulated in the ocean because it is a form of energy, rather than a material, such as oil or sewage. Another challenge to policy formation and ultimately management of ocean noise is the trans boundary nature of the pollution, which makes national and international co-operation essential.

5.1.0 The Stakeholders

It is important to understand the stakeholders involved in policy formation. Non-governmental organizations have been important in framing the issue of ocean noise as well as bringing the importance of the problem to the media and the public.

5.1.1 Non-Governmental Organizations

Non-Governmental Organizations (NGOs) by definition are not organized by governments or intergovernmental agreements, but are capable of being involved in national or international affairs due to their level of organization or expertise. (McCarthy, 2004) The most important NGOs in the United States that have been involved in ocean noise policy formation have been the Nationals Resources Defense Council (NRDC), Seaflow, Inc., and several animal welfare and marine mammal advocacy groups. International coordination of
NGOs has been lead by the International Ocean Noise Coalition, which has organized over 150 NGOs, which have concerns about the ocean noise issue. The NGOs represent the sector of the public that is concerned about the animals, primarily whales, but also fish and other marine species that may be affected by ocean noise. NGOs have advocated for their point of view through the use of media, including journalism, video, websites, emails and direct mail to the public. The NDRC and others have also used the legal system to attempt to stop activities by the Navy and research vessels when they felt it endangered marine mammals. Other stakeholders are primarily those whose activity generates anthropogenic sound and those who regulate them.

5.1.2 The Military

The military, primarily the US Navy, have the most documented use of sound in the ocean and are the most controversial of all noise generators. Naval vessels from all over the world use sonar, both passive and active for navigation and for finding enemy submarines or underwater devises. The military also has exploded mines and torpedoes underwater which creates a pressure pulse which are known to cause death and injury to marine mammals. Active sonar can be high frequency, which can even be located on a torpedo for short range targeting, or low frequency and high power able to range over large distances and are of most concern in the issue of ocean noise. Generally, the military position is that their uses of sonar and other noise producing activities are necessary to the security of their country and resist regulations that would limit their use. However, the Navy of the United States and other countries, such as Australia have voluntarily limited their use of sonar in some areas of specific concern and shared research about underwater ambient
sounds in some cases. US Navy has also mitigated their impacts by a number of voluntary measures when using sonar such as implementing whale spotters and halting exercises when a whale is detected in the area.

5.1.3 Oceanographic Research

Oceanographic research also uses active sonar to determine bathymetry, research water masses and study ocean bottom characteristics. Some seafloor research techniques use explosives and air guns similar to those used in seismic surveys. One of the most controversial uses of low frequency sonar monitors global warming trends in the ocean in the Acoustic Thermometry of Ocean Climate project located out of Scripps Institution of Oceanography in San Diego. This is a new type of research in which sounds can be detected almost halfway around the world. The NRDC and coalition partners strongly opposed this type of research, but research on the marine mammals that would be affected showed no significant disturbance (Brown, 1998).

5.1.4 Commercial Shipping

Many commercial interests generate noise. Shipping is probably the biggest contributor to background noise through engines, flow noise, propellers, pumps, compressor and generators. This type of noise is low frequency and large ships that are fully loaded or pushing or towing a load generate the most noise. (McCarthy, 2004) The number of ships being built and used as well as ship size has increased and is expected to keep increasing as long as international trade demands. The noise from shipping has not necessarily increased due to advances in technology, but this has not been widely studied. However, noise from
shipping is probably most intense in the shipping lanes, which may be significant depending on the location of marine animal habitats.

5.1.5 Off shore oil exploration

Offshore exploration for oil and then the extraction may increase as land based oil reserves are depleted. Air guns are the most common way for seismic surveys to generate sounds. Drilling activities also generate noise that contributes to the ambient sound and additional noise is generated by the support functions associated with the drilling platform, such supply ships, aircraft and so forth. Drilling activity in recent years has been located in deeper waters, which indicates more exploration is occurring in deeper waters. This leads to increases in the impacts of the sound since it can travel farther in deeper waters. On the other hand, advances in technology and reduced activity of exploration vessels may indicate a decrease in noise generation by this industry.

5.1.6 Dredging, Tunneling and Driving

Dredging, tunneling and driving of piling can also contribute to ocean noise in coastal regions. These activities use machines with low-frequency sound signatures that may disturb marine species in the intensely used coastal habitats. These effects would be expected to be localized, as would the activities of fishing, which may use sound for finding fish. Aquaculture uses Acoustic Harassment Devices (AHD) to deter species that might interfere with their fish or gear. Unintended effects have been claimed since species other than those targeted may be impacted. For example, whale researchers claim that killer whale have abandon areas that they used to migrate into because of AHDs designed to keep seals out of salmon pens (Bressen, n.d.).
5.2 Developing Policy

In developing future policy to regulate ocean noise, we must determine who would manage the policy and under what jurisdiction.

5.2.1 International (Global) Policy

Scientific evidence suggests that noise in the ocean can travel over long distances and therefore crosses international boundaries. Some anthropogenic sounds can also be considered pollutants and regulated as such because of the ability to injure or kill marine life and potentially have a damaging impact on animal behavior. McCarthy (2004) argues that ocean noise is similar to air pollution as a trans-boundary pollutant and citing the “Trail Smelter Case of 1941” as legal precedent; she asserts that an international policy should regulate ocean noise. The International Maritime Organization, part of the UN, regulates some pollutants from ships, such as radioactive materials and could also regulate ocean noise. At present there is no policy to regulate noise in the ocean on a global level.

5.2.2 International Policies

International Policy particularly that in Europe has generally been more progressive than that in the United States. The regional treaty, Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (ASCOBANS), first recognized the danger of noise pollution in 1994, then passed a resolution to request noise generators to reduce the impacts of noise on cetaceans, and in 2006, passed a second resolution requesting member states to develop specific guidelines to minimize risks of noise to small cetaceans. In June of
2004, the International Whaling Commission called for multinational cooperation to monitor ocean noise and the development regional noise budgets.

Specific action by the European Parliament in 2004 placed a moratorium on the use of high intensity active sonar until a global assessment of the environmental effects of the use of this type of sonar has been determined. This is consistent with the European approach to environmental management called the precautionary approach. This approach prevents an activity that might be harmful from proceeding until it has been proven to be safe. The burden of proof falls on the party that generates the activity - in this case, noise. Also in 2004, the Agreement on the conservation of cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) recognized ocean noise as a dangerous pollutant and called on member states to avoid any use of anthropogenic noise in habitats of vulnerable species. In 2007, the regional group urged parties to reduce noise and develop tools to assess impacts and establish mitigation measures. The European Union includes underwater noise in the definition of pollution in its 2008 Marine Strategy Directive, in which action is required by member states to achieve the “good environmental status” of European marine waters by 2020. In addition, ocean noise pollution is covered indirectly by the Habitats Directive, which prohibits all forms of “deliberate disturbance” of cetaceans.

The United Nations Convention on the Law of the Sea has addressed noise specifically in paragraph 107 of its resolution 61/222 on "Oceans and the law of the sea", adopted on 20 December 2006. It "encourages further studies and consideration of the impacts of ocean noise on marine living resources, and requests the Division to compile the peer-reviewed
scientific studies it receives from Member States and to make them available on its website.” As of yet, the UN has not moved beyond the demand to collect more data and does not have a clear policy to regulate ocean noise.

The international Maritime Organization (IMO), a United Nations Agency, has a Marine Environmental Protection Committee dedicated to developing policy tools to protect the international marine environment. In April 2008 the IMO recognized the harmful effects of commercial shipping noise and invited member states to participate in a dialogue to determine mitigation. In June, the United States introduced a work program that requests action to reduce noise from by the implementation of new technologies that dampen the sound.

International Policy has moved forward, primarily in Europe, but also in Canada, where in 2002 the recovery plans for four endangered species listed naval sonar as a threat. In Spain, in 2002, a moratorium was placed on the use of sonar within 50 miles of the Canary Islands (Fortescue et al 2005).

The military, particularly the US Navy and NATO have worked both internally and in cooperation with scientific groups to develop mitigation measures for the use of sonar in response to the threats to marine mammals. Both NATO and the US Navy have recognized that naval sonar has been a likely cause of whale deaths, and have implemented some voluntary mitigation measures such as limiting the areas and in the season in which sonar is used. Many nations including the US, Canada, UK, Norway, Netherlands and Spain have been developing naval tools to model and assess risk to ocean mammals from sonar activities in different regions (Fortescue et al 2005).
5.2.2 Policy in the United States

The primary instrument of US ocean policy that has been used to protect marine life from excessive noise is the Marine Mammal Protection Act (MMPA), which has imposed a moratorium on “taking” of marine mammals in US waters. “Takings” applies to hunting, harassing or killing the animal, but also includes injury and behavioral disruption ([http://www.nmfs.noaa.gov/pr/pdfs/mmpa_factsheet.pdf](http://www.nmfs.noaa.gov/pr/pdfs/mmpa_factsheet.pdf)). The MMPA requires anyone who might harm marine mammals to first obtain a permit from a wildlife agency. Many noise generators, however, do not enter into the permitting process. This law was weakened in 2003 with the amendment to authorize exemptions for national defense. The US Navy applies for permits for takings from the National Marine Fisheries Service. The Endangered Species Act (ESA) has also been used in some specific cases, such as in bridge construction in San Francisco (Stocker, 2004) to limit ocean noise and the US Coast Guard does enforce and prosecute violators. The purpose of both the MMPA and the ESA were to protect specific animal species and are not comprehensive enough to adequately address the effect that noise pollution can have on habitat including non-endangered marine animals.

Another potential tool being used by the NRDC and other advocacy groups is the National Environmental Policy Act, which requires an Environmental Impact Statement to be prepared by any federally funded or permitted project or program with potential environmental impacts. Many different projects including oil and gas drilling, US Navy’s SURTASS-LFA project and Scripps Institution’s ATOC project all prepared Environmental Impact Statements with reference to noise generation (McCarthy, 2004). This policy
instrument is very powerful since the methodical and comprehensive approach to examining the pros and cons of a proposed project are useful and its requirement to have the process open to public comment provides an opportunity to challenge government actions. But it is also time consuming, costly and of limited accuracy since it requires a prediction of future impacts.

While US policy on ocean noise is not usually specific, there have been individual cases of source-specific regulation of underwater sound. It is found in the final ruling of the US National Marine Fisheries Service (NMFS) about the operation of seismic air guns. The NMFS set criteria not to exceed 180 dB re 1 μPa for mammals such as porpoises and gray whales and 190 dB re 1 μPa for mammals such as sea lions and harbor seals (Souththall, 2007). The NMFS also has imposed special provisions around particular areas designated of importance to marine mammals. For example the rule, prohibits sonar levels not to exceed 180 dB re 1 μPa within 23 nautical miles of the Olympic Coast National Marine Sanctuary during the months of December, January, March and May (McCarthy, 2004).

On the horizon is new policy including the National Oceans Protection Act of 2008, which has been introduced in the US Senate. One of the principles, “The lack of scientific certainty should not be used as justification for postponing action to prevent negative environmental impacts”, could have an impact on the development of future US policy in the area of ocean noise (an abstract can be found at http://thomas.loc.gov/cgi-bin/query/z?c110:S.3314). While international policy is the best way to address ocean noise because it is a trans-boundary pollutant, the United States, as a leader in world policy as well as a dominant
user of ocean resources and generator of ocean noise, needs to develop a national policy on ocean noise.

A National ocean policy has been slow in development despite extensive work by the Pew Ocean Commission (2003) and the US Commission on Ocean Policy (2004.) The Pew Commission called for the development of a national policy addressing ocean noise, while the US Commission report recognized the importance of sound in the ocean environment and stressed more research.

**5.2.3 State Policy in the United States**

In the absence of either an international or national policy, some smaller jurisdictional areas have addressed this issue. For example, The California Ocean Resources Management Plan adopted in 2004 is the only statewide plan that addresses noise as an issue. It makes no specific recommendations beyond a directive toward more research and the development of noise criteria ([http://resources.ca.gov/ocean/Cal_Ocean_Action_Strategy.pdf](http://resources.ca.gov/ocean/Cal_Ocean_Action_Strategy.pdf)).

Without clear US National policy, the conflict between advocacy groups and noise generators has ended up in court. In November 2008, the Supreme Court ruled that an injunction on the US Navy to stop sonar training exercises off the coast of California by the US district Court in California was not proper and lifted it. This injunction was brought about by a judgment in favor of the National Resources Defense Council that called for the Navy to do a full environmental impact statement before proceeding with the exercise. In the ruling, the Supreme Court justices cited national security concerns associated with the training exercise as more important than possible impacts to marine life.
Currently in the United States, the agencies regulating ocean noise include the National Marine Fisheries Service, a part of NOAA and the Army Corps of Engineers (for dredging and construction).
6.0 NATIONAL OCEAN AND ATMOSPHERIC ADMINISTRATION (NOAA)

In 1998, NOAA established its Acoustics Program in response to increasing concern about underwater sound and the effect it might be having on protected marine species (Southall and Gentry 2005; http://www.nmfs.noaa.gov/pr/acoustics/). The Acoustics Program supports acoustics research to develop ocean noise criteria in cooperation with US Navy. The program also sponsors symposia to communicate findings and coordinate national and global research and reaches out to the public with unbiased information about ocean noise. Another program of interest is the small business innovations research program which has a competitive grant process in which some projects to develop technology that investigates the ocean noise problem have been funded (http://www.oar.noaa.gov/orta/docs/FY2008Abstracts.pdf).

NOAA has a broader ‘mandate for stewardship of marine mammals and other marine resources than any other federal agency. Therefore, there is a growing need for NOAA to take an active role in research on the effects of anthropogenic sounds on marine mammals and, indeed, on the entire marine ecosystem’ (NOAA, 2004).

NOAA has an important role to play in the protection of marine life through research and regulation of man-made sound in the ocean. The difficulty facing the agency is the determination of how and even when to regulate manmade sound. The acoustic complexities of the underwater environment, when coupled with the broad range of biological diversity found in marine mammals and fish, make defining a regulatory standard a very difficult objective.
7.0 RECOMMENDATIONS FOR NOAA

7.1.1 NOAA Policy

NOAA policy should be based on science. Much is still unknown about underwater sound and how marine life is affected by anthropogenic noise. A link has been established between some types of noise and some injury to animals and clearly underwater sound is an important part of the ocean environments.

Policy should include ecosystem-based management. The species by species approach now implemented through the MMPA and the ESA is insufficient to protect marine life, only the most sensitive and prominent species. Fish and invertebrates may also be affected by ocean noise pollution, but without obvious impacts. Ecosystem-based approaches also recognize that there is a cumulative risk to species of many different impacts. The establishment and use of Marine Protected Areas (MPA) would be one policy instrument that NOAA could use to implement ocean noise policy. MPA protect the entire habitat, which is consistent with ecosystem-based management. MPAs have already been established in the US and internationally for the protection of marine mammals such as the Hawaiian Islands National Marine Sanctuary. Existing regulations limit activities in some MPAs that include noise and this trend could expand to other MPAs and include buffer zones around these areas. The US could consider proposal of new MPAs and participate in the creation of international MPAs. Zoning has been effectively used on land to protect areas of interest from noise pollution. Ocean zoning could have the same impact, but there would be significant challenges due to the international nature of ocean noise pollution and the migratory nature of some of the marine life targeted for protection.
7.1.2 National and International Ocean Policy

As the lead agency in ocean concerns NOAA through its Acoustics Program should be actively involved with national and international efforts to formulate national and international (global) policy in relation to noise in the ocean.

7.2 Research

7.2.1 Noise Budgets

NOAA should continue to work cooperatively with the US Navy and research institutions to create a noise budget for the ocean to help put anthropogenic noise in context and look for cumulative effects of different types of noise.

7.2.2 Effect of ocean noise on different species

Research should continue into the effects of ocean noise on the many species that could be impacted. While the focus has been on cetaceans and other marine mammals, fish and invertebrates also develop in the acoustic environment in the ocean and may have impacts that are not as obvious, or are part of a cumulative environmental impact. Good quality control is necessary in the science research as well as communications of findings in this globally important scientific issue. Fortunately NOAA’s Ocean Acoustic program is focused on much of this essential scientific study and should continue.

7.3 Regulation

The nature of the regulation of noise generators should be scalable as to the type and nature of noise generator, which includes taking into account the environmental impact
and financial ability of each stakeholder to adopt policy changes. This puts regional stakeholders into a global context. New technologies to limit noise generation by both commercial and recreation watercraft should be developed and implemented. The legislation should also be progressive in that it should allow generators to phase out their noisy equipment over time. This would make the legislation more acceptable to stakeholders (Stocker, 2004).

7.4 Public Outreach

The problem of ocean noise pollution has been framed in the media as a highly emotional conflict between the military and whales. NGOs, in bringing attention to this topic, have used media such as websites, video featuring celebrity hosts and graphic photographs of whales in distress. The military, on the other hand, has not responded to public outcry in a way that has demonstrated their cooperation. NOAA is in a position to be an unbiased, scientifically based source of information for the public about this issue and should fund outreach efforts to provide a balanced view of the problem and potential solutions to ocean noise pollution.
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