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The effects of noise on marine animals in the context of their natural acoustic environment

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ABSTRACT

Marine animals use sound extensively in an environment where vision is usually very limited and sound travels to much larger distances that it does in air. We also make extensive use of sound in the ocean and there is concern about the impact that the noise of human activities has on marine animals. This paper will review what is known about the effects of noise on marine animals in the context of their natural acoustic environment and also relate this to the effects of noise on terrestrial animals, particularly humans. It will discuss the wide range of audibility that marine mammals experience as a result of the variation in natural ambient noise and sound propagation, and how the noise from human activities compares with the noise from natural sources. It will also consider how the extensive knowledge of noise effects on terrestrial animals can be related to effects on marine animals. The challenges for further research will also be discussed, particularly the need to determine the longer term biological effects of noise.

INTRODUCTION

There has been widespread public concern about the effects of noise on marine animals, particularly whales, for around 15 years. Much of the early impetus resulted from misconceptions and some of these have come from misunderstanding of the acoustics. Some of these misconceptions remain among non experts, and there is still much misleading material on web sites. One of the problems is the interdisciplinary nature of the subject and at times the failure to obtain proper acoustic advice. Over the same period, there has been a substantial amount of research on the effects of noise on marine mammals and some on the effects on fish. This paper discusses what is known about the effects of noise on marine animals, in the context of their natural acoustic environment and in terms of what can be learnt by comparison with the large amount of information available on hearing in terrestrial mammals. It will also correct some of the misconceptions that remain.

This paper will not deal with the impacts of underwater explosions, even though the rapidly expanding shock wave from an explosion eventually becomes a typical linear acoustic wave. Explosions can cause substantially greater damage to marine animals than sound generated by other sources of noise, so should be treated separately. The effects on animals can range from tissue damage to death and there is a surprising amount of information useful in managing these effects (Richardson et al., 1995).

THE OCEAN ACOUSTIC ENVIRONMENT EXPERIENCED BY MARINE ANIMALS

Marine animals make extensive use of sound in an environment where vision is limited but where sound travels to great distances. The absorption of sound is very low compared to the absorption in air and so sound travels greater distances than in air. Some of the concern about the effects of noise on marine animals comes from the somewhat idealised concept that the ocean is a quiet and acoustically serene environment. In fact, the ocean acoustic environment is very dynamic, causing wide variations in the effectiveness of sound usage by marine animals. An irony of the good propagation of sound in water compared with air is that sound travels to great distances not just from the source of interest, but from all other sources, so that there is a high and variable background noise from all these other sources. Signals have to be detected against this background noise, so there is not necessarily an advantage to animal communication for propagation to be so good, particularly for animals communicating over relatively short distances.

Propagation of sound in the ocean is complex and varies substantially between environments and with changing oceanographic conditions, causing substantial variation in distance for a particular value of propagation loss. The ambient noise of the ocean is also very variable. Natural ambient noise varies typically by 20 dB or so over relatively short time scales and variations of 30 dB can occur. Such variation is evident in Figure 1 which shows a summary of ambient noise in the Indo-Pacific region around Australia (Cato, 1997). The wind dependent noise is generated by oscillating bubbles in breaking waves and this itself causes about 20 dB variation over a wide frequency band for a range of wind speeds typical of normal variation in ocean weather conditions. The biological choruses shown are regular events that increase noise levels by 20 to 30 dB above typical quiet conditions. Rain also causes high levels of noise.

This variation substantially affects the distance over which animals can communicate. The sonar equation (Urick, 1983) relates the amount by which the received signal exceeds the threshold of detection of a sound to the propagation loss, background noise and source characteristics, and shows how

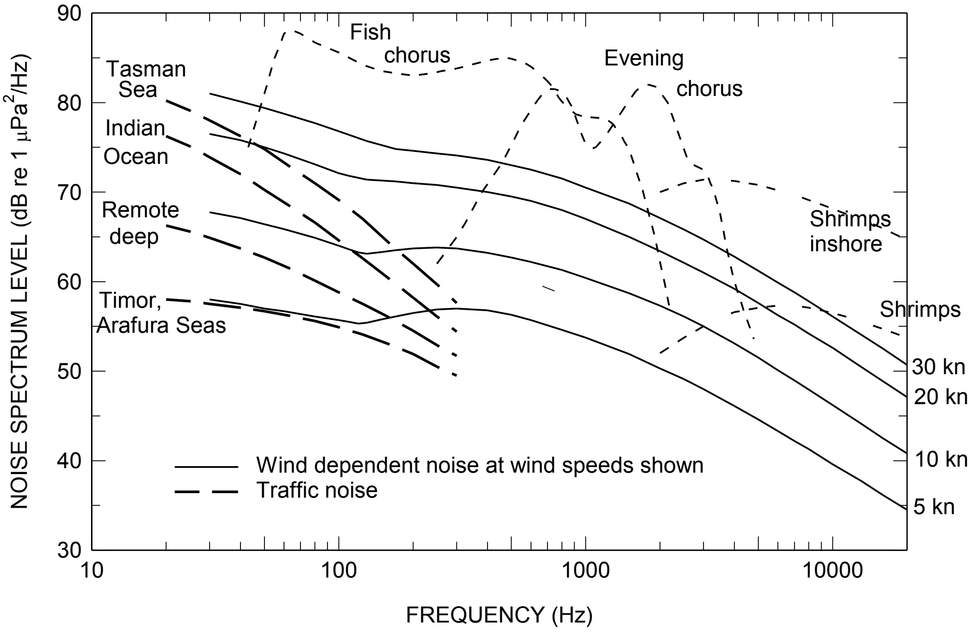

Figure 1. Summary of ambient noise in the Indo-Pacific region around Australia, showing the main components: wind dependent noise from breaking waves, biological choruses and traffic noise for the regions shown.

increased noise can be traded with decreased propagation loss to maintain the same signal excess. One form of the passive sonar equation is (in decibels):

$$SE = SL - TL - NL - DT$$

where *SE* is the signal excess at the receiver over that required for detection, *TL* is the transmission or propagation loss, *NL* is the background noise level at the receiver and *DT* is the threshold signal to noise ratio for detection (and for simplicity here includes directivity). It is evident that changes in one parameter of the sonar equation can be balanced by changes in another to maintain the same signal excess at the receiver. For example, a 20 dB increase in noise can be balanced by a 20 dB decrease in propagation loss to maintain the same signal excess. This would reduce the distance of the source for the same signal excess by a factor of 10 for typical spherical spreading. It is apparent from the sonar equation that the combined effects of the large variation in propagation and ambient noise cause wide variation in detection range or the distance that a sound source of interest is audible to an animal. This variation will be significantly more than the typical variation of a factor of 10 caused by varying ambient noise.

Marine animals are often subject to natural noise that is much higher than the highest levels of ambient noise. Many vocalise in large schools, causing high level choruses such as those of Figure 1. Fish, invertebrates and whales produce choruses (e.g. Fish, 1964; Cato, 1978; Au et al., 2000) that may be audible for considerable distances. Within the mass of calling animals, however, noise levels may be much higher than those shown in Figure 1. Usually chorusing animals are producing similar sounds so that masking is substantial.

Marine animals have evolved in this environment so that it is reasonable to assume that they cope adequately with such wide variations in noise and propagation loss, and thus such large variations in the distances over which their use of sound in effective. It is important to take this into consideration when assessing the effects of noise from human activities. For example, the received noise levels from human activities can be compared with the ambient noise and its variation as a way of obtaining an idea of the significance of the impact.

COMPARISONS OF EFFECTS OF NOISE BETWEEN NOISE AIR AND WATER

Some of the impetus in the concern about the effects of noise on marine animals has come from failure to obtain input from experts in the areas of importance with the consequence that incorrect conclusions were made about the potential impact of the noise. Some of these led to exaggerated conclusions about the severity of the impact. An important example is the incorrect comparisons of sound levels of sources in water with sound levels that humans are subject to, as a way of judging the potential impact. This led to an upsurge in concern. For example, it was noted that the source level of a source that was proposed for deployment was 195 dB re 1 μPa at 1 m while the levels at which humans find uncomfortable or painful are in the range 120 – 140 dB re 20 μPa. The reasoning was that 195 dB is higher than 120 dB, so the effects of this source on marine animals would be worse than sounds that are uncomfortable of painful to humans. This led to considerable concern about the way that this source would affect whale hearing.

There are, of course, fundamental mistakes in this comparison. Firstly the pressure scales in air and water are different: 195 dB re 1 μPa is 169 dB re 20 μPa (since the difference in level of the reference pressures is 20 log(20) = 26 dB). Secondly, the value stated for the source in water is the source level, not the received level in the water. Source level is defined as the level at 1 m from of a point source that produces the same sound field in the far field as the real source. At 100 m from the source, for example, the sound level would be 155 dB re 1 μPa or 129 dB re 20 μPa. Thirdly, the comparisons were made for the levels in the environment (air and water) and not in the cochlea of the inner ear where the sensing of sound occurs, i.e. it failed to take account of the substantial differences in hearing mechanisms between terrestrial and marine mammals. In fact, this comparison vastly overestimated the likely effect on whales.

Partly as a consequence of such simplistic comparisons, the substantial differences in the acoustic properties between air and water, and the differences between the auditory systems of terrestrial and marine mammals, there has been some reluctance to explore how the substantial amount of knowledge of hearing in terrestrial mammals may be applied to marine mammals. Such comparisons can be made so long as there is proper allowance for the differences in the media and the auditory systems.

The auditory chain differs significantly between mammals, especially between marine and terrestrial animals (Ketten, 2000). The *cochlea*, part of the inner ear, however, shows the least variation and this is where the sensing of sound takes place. In terrestrial mammals like humans, the auditory chain comprises the outer, middle and inner ears, as well as the auditory nerve (Yost, 1994). The outer ear consists of the external ear, or *pinna*, and the ear canal. The middle ear comprises the ear drum and three small bones, or *ossicles*, connected in a lever arrangement between the ear drum and a window to the cochlea, thus transmitting acoustic signals from the ear drum to the cochlea. The cochlea contains the hairs that sense the acoustic motion and is filled with a liquid physically similar to sea water.

It is important, therefore to consider what is happening in the cochlea, where the sensing takes place, if any comparisons are to be made between hearing in air and water. There is substantial mismatch in acoustic impedance between air and the fluids (liquids) in the cochlea but little between water and cochlear fluids. It is generally considered that the complexity of the auditory chain in the outer and middle ear in terrestrial mammals provides the means of matching the impedance between the environment (air) and the cochlea, to ensure that most of the acoustic energy gets into the cochlea. Hence it is expected that the intensity in the cochlear will be similar to that in the environment whether air or water.

On this basis, expert opinion is that the most appropriate way to compare the effect of sound levels on marine mammals with that of terrestrial mammals would be to compare intensities in the media (Ketten, 2000). In a plane wave, intensity I is related to pressure p by $I = p^2/(\rho c)$, so that for the same intensity in air and water, the pressure in water is related to the pressure in air by

$$p_w^2 = \frac{\rho_w c_w}{\rho_a c_a} . p_a^2$$

where the subscripts w and a refer to water and air respectively. For typical values of ρ and c for the two media, this shows that for the same intensity in air and water, p_w would be about 35.5 dB larger than p_a, if measured in the same units. This difference of 35.5 dB is, of course, the ratio of acoustic impedances in the two media. If we allow for the 26 dB difference in the reference levels in the decibel scales between air and water, as discussed above, we find that for the same intensity in air and water, the sound pressure level (re 1 µPa) in water would be 61.5 dB higher than the pressure level (re 20 µPa) in air. Hence a comparison of the effects of sound between air and water is most appropriately obtained by subtracting 61.5 dB from the pressure level in water in dB re 1 µPa to compare with levels in air in dB re 20 µPa. A simple comparison between the sound pressure levels between air and water without these corrections would lead to prediction that sound levels in water would have a severity, in terms of impact on marine animals, consistent with levels that are 62 dB (in round figures) higher than the actual level.

A response to this has been to question whether the cochlea is an intensity or pressure sensor. The reasoning being that if it is a pressure sensor, the correction would only be 26 dB, not 62 dB. In fact, is does not matter whether it is a pressure sensor, particle motion sensor or intensity sensor, since the relationships between these properties would be similar in the cochleas of a marine mammals and a terrestrial mammals. This can be seen explicitly by noting the transfer function for pressure in the human auditory chain, i.e. the outer and middle ears. The process of matching impedances between the air and the cochlea results in an amplification in pressure which measurements show to be in the range 30 to 40 dB varying with frequency (Yost, 1997). It is not a coincidence that this is numerically similar to the impedance difference between air and water. It is a necessary consequence of the different relationships between intensity and pressure in the air and in the cochlear fluids. Of course, these comments apply to typical relationships between pressure and intensity, and only to plane waves. It is also a very simplified analysis of the auditory system and significant variations occur with frequency.

On the basis of comparing sound intensities in the media (air or water) as an appropriate comparison of levels in the cochlea, the typical ambient noise level in the ocean over the audio frequency band (100 dB re 1 µPa) would be of the same intensity as a noise level of about 40 dB re 20 µPa in air, while the typical range from low to high noise in water would be about 20 to 60 dB re 20 µPa in air.

ANTHROPOGENIC SOURCES OF NOISE

Shipping

Some of the main examples of anthropogenic noise of interest in the effects of noise on marine animals are discussed below. By far the most widespread anthropogenic noise is that produced by shipping and boating. Not only are ships and boats widely distributed throughout the ocean, but they also produce a general background noise that is significant even when individual sources cannot be discerned. This nondescript background noise was first identified by Wenz (1962) in his classic paper on ambient noise in the ocean and called *traffic noise*. Because of the good low frequency propagation of sound in water, ships throughout an ocean basin may contribute to the traffic noise, even if they are not individually detectable. It tends to dominate the ambient noise spectra in the frequency band below about 200 Hz in areas of high shipping densities.

Traffic noise in the Indo-Pacific region near Australia varies by more than 20 dB between different areas, generally in accordance with the variation in shipping densities and propagation conditions. In some areas, traffic noise is negligible compared to natural ambient noise (Cato, 1976). In Figure 1, traffic noise levels are presented as the average for each region, the temporal variation in any region being about ± 5 dB about the averages shown. The highest levels are observed on the continental shelf of the Tasman Sea off the east coast, where the propagation is good along the shelf and from deep water, and there is considerable shipping. These levels are almost as high as those presented by Wenz (1962) for the high traffic noise areas around North America. Traffic noise is almost negligible in the shallow tropical waters to the north of Australia and in partially enclosed waters such as gulfs. The wide variation in traffic noise levels may be indicative of traffic noise over much of the world's oceans, more representative in fact than those around North America and Europe where most data have been obtained.

Sonars

All ships and most boats have active sonars of one sort or another, many ships having more than one. The term active sonar is used here to mean any array of transducers that transmit narrow band signals and use the information contained in the echo received. They are general similar even though their frequencies and power outputs vary. Sonars include echo-sounders, side scan and multibeam sonars for building images of the sea floor, fish finding sonars, and naval tactical sonars. Most sonars focus the power in a beam directed towards the objects of interest. Sonars operate at significantly higher frequencies than shipping noise (order a few kilohertz to several hundred kilohertz). The increased absorption as a function of frequency, combines with the fact that the most common sonars are directed downwards (e.g. echo sounders), limits the distance at which the most common sonars are likely to contribute significantly to the noise. Sonars that radiate closer to horizontal such as naval tactical sonars, are used by a very small proportion of the world's ships and for relatively short intervals, so might not be expected to contribute significantly to a general background noise. Rather they should be considered for their local effect.

Air guns and pile driving

Air guns used in seismic surveying by the oil and gas industry produce high levels of noise by the rapid release of compressed air from the chamber of the air gun. The result is a low frequency transient signal. They are usually used as arrays phased to direct most of the power downwards and into the sea floor, though a significant amount of energy does radiate near horizontal.

Pile driving is also a source of high levels of noise, resulting from the regular hammering of the piles into the sea floor to provide a foundation for marine structures such as wharves, bridges and wind farms. A pile extends through the water into the sea floor and the impact of the hammer radiates along the length of the pile into the water column and into the sea floor. The sound field will be a complicated combination of radiation from a line source in water and some radiation into the water from sound travelling through the sea floor.

Seismic surveying and pile driving may produce high noise levels locally and be audible over significant distances, but are too limited in their distribution to contribute significantly to a general background noise in throughout the ocean in that way that shipping noise does.

Source considerations

As noted above, a mistake that has been made is to take the source level of a source of noise as the level that animals would actually be exposed to. Source level in underwater acoustics is a way of specifying the output of a source and is defined as the level at 1m from a point source that produces the same level at a distance in the far field as the real source does for the same distance. From this is should be possible to calculate the received level as a function of distance by allowing for propagation loss from 1 m. This, however, would only apply for distances significantly larger than the source dimensions, i.e. distances beyond the range for which the source spatial structure has an effect. The importance of this is discussed below.

Usually source levels are calculated from measurements of the sound received at much greater distances from the source than the source dimensions by taking account of the propagation loss to the distance of measurement.

A point source is a somewhat artificial concept, since it implies that a source is concentrated at a point. Some sources may be quite compact and approach the point source concept, but others are significantly more than 1 m across. The sound field in the vicinity of a source may be quite complicated, hence the need to measure at significant distance. Some sources are in fact arrays of individual sources and the phasing of the sources in an array is designed to ensure that the sound in the far field is formed by constructive interference of the outputs of the individual sources. This is a way of focusing the energy of the source in a particular direction. Many sonars and seismic air gun arrays are designed in this way. For example, and air gun array consists of many individual air guns usually in a horizontal layer designed to focus energy downwards because the interest is in obtaining reflections from the rock strata beneath the sea floor.

Another factor to consider is that there is an upper limit on the sound pressure that can be generated in water by vibration of a solid object like a sonar transducer or part of a ship. This results when the pressure fluctuation becomes comparable to the static pressure, so that the negative or low pressure side of the fluctuation cancels the static pressure and the total pressure goes to zero. As the pressure in water becomes very small, cavities are formed from small inhomogeneities, a process known as cavitation. The cavitation bubbles around the face of a transducer disrupts the transfer of power from the transducer to the water, though processes such as absorption and scattering. As a consequence, the useful output of transducers is limited to a value below the cavitation threshold, which is typically around 220 dB re 1 µPa at shallow depths and audio frequencies (Urick, 1983). Individual transducer elements of sonars are limited to this threshold and are usually limited by design to a lower level say 215 dB re 1 µPa providing some margin to ensure that the limit is not reached.

The individual elements of a distributed source such as seismic or sonar arrays are phased to ensure that the waves emitted interfere constructively in the far field in order to focus the energy where it is needed. The output of such distributed sources is still described in terms of source levels at 1 m, the equivalent of a point source radiating the same signal in the far field. This often results in source levels for the array that are significantly higher than those of the individual source elements or the actual sound levels generated in the water. Interference close to the array will be destructive as well as constructive, providing a complex near field where the highest noise levels in the water will be significantly less than the source level.

EFFECTS OF NOISE

Levels of impact

It is useful to divide effects of noise into two categories:

(a) very high received levels with the potential to affect hearing or general physiology and

(b) levels below those of (a) where the effects will be generally behavioural or masking of sounds of interest to the animal.

Hearing and physiological effects require such high levels that they are likely to occur only very close to the source and thus impact a relatively small number of animals over a relatively small area. The severity may be reasonably closely related to some measure of the received sound level. Although there have been claims and theories that very high levels of noise can directly cause physiological effects, this has not been demonstrated.

Behavioural effects occur over a much wider range of levels. Behavioural reactions to noise are less directly related to the received sound level, since the reactions depend on many other factors, which together form the context of the sound exposure. This context includes the behaviour of the animal at the time, the social category (e.g. male or female with young), whether the animal is vocalising, the distance of the source and the movement of the source relative to the animal. Whether or not an animal responds to a sound will depend on what that sound means to the animal: for example, it may interpret the sound as indicative of a threat. Richardson et al. (1995) cite many experiments which measured the threshold levels at which baleen whales show behavioural reactions to noise, and these thresholds varied over a range of 50 dB. The lowest levels would have been just audible above the low levels of ambient noise at the time. Behavioural reactions therefore can occur over much greater distances than hearing or physiological effects.

The effects of masking by noise of sounds of interest will be more closely related to the received sound level, but will also depend on the level of the background noise, the received levels of the sounds that are the signals of interest to the animal and the redundancy in these signals.

Generally, the effects of category (a), the very high received levels, are fairly constrained and are more easily managed than those of the lower received levels (category b). Category (a) effects occur over a small area around the source and it is possible to either avoid concentrations of vulnerable animals or to use monitoring techniques (visual or acoustic) to determine the presence of animals and cease transmission if the animals are too close.

Temporary Threshold Shift

Temporary threshold shift is a useful gauge of higher levels of impact. It is a temporary reduction in hearing sensitivity as a result of exposure to a period of high level sound. As the name implies, the effects of a bout of TTS is temporary and reversible, with no longer term effect. While individual periods of TTS are completely reversible, human studies have shown that repeated, persistent TTS over a long period eventually leads to permanent hearing damage. For example, workers in a factory subject to noise 8 h a day during the working week may be in danger of suffering permanent hearing loss after a period of years, depending on the noise level. As a consequence, industrial regulations limit noise exposure to an amount such that most of the population would suffer little permanent hearing loss.

From the point of view of management of impacts of high level noise exposure on marine animals, a useful management approach is to avoid exposing animals to levels that would cause a small amount of TTS. This approach provides some level of precaution, given the temporary nature of TTS. Exposure of marine animals to high level sources is usually for limited periods, so the effect of persistent long term exposure faced by industrial workers does not apply. This is level of exposure is well below the level that might cause permanent hearing damage. In an extensive review of effects of noise on marine mammals to develop a set of noise criteria, Southall et al. (2007) chose 40 dB as the amount by which noise exposure would need to exceed the threshold of TTS in order to cause permanent hearing damage (permanent threshold shift) as a result of the exposure. This was based on assessment of many studies with humans and some terrestrial mammals. They chose 40 dB as typical of the lowest difference, thus including some level of precaution.

Extensive studies of TTS in humans and laboratory animals have shown that it depends not just on the received noise intensity but also the duration of the noise exposure. The relative dependence on intensity and duration is complex and there are other factors involved, but is more closely related to the energy (per unit area) of noise exposure than to the instantaneous intensity. In other words it depends on the accumulated exposure to noise, not on the loudness at any instant. In reviewing studies in studies of TTS in humans, terrestrial and marine mammals, Southall et al. (2007) concluded that using energy of noise exposure as criteria for onset of TTS was a reasonable first order approximation. Finneran et al. (2002, 2003) also found that this gave the most consistency when studies on small amounts of TTS on marine mammals were compared.

In practice, it is acoustic pressure that is measured and mean square pressure level is usually reported instead of intensity level (since mean square pressure is proportional to intensity in a plane wave). Correspondingly, the integral of mean square pressure as a function of time over the duration of the signal is determined instead of the energy (per unit area). In decibels, this is referred to as the *sound exposure level SEL* in units of dB re 1 μPa^2.s which is given by

$$SEL = 10\log_{10}\left(\int_T p^2 dt\right)$$

where p is the instantaneous acoustic pressure and T is a time interval encompassing the signal of interest.

Some examples from the literature of the measurements of the *SEL* required to produce small amounts of TTS in marine mammals and fish (mostly less than 6 dB for the marine mammals) are given in Table 1.

Table 1. Some examples of sound exposure levels causing small amounts of temporary threshold shift in marine mammals and fish.

Species	SEL (dB re 1 μPa^{2}s)	Source	Reference
Sea lion, harbour seal, elephant seal	183 – 206	Octave band noise playback	Kastak et al., 2005
Bottlenose dolphin & white whale	182 – 201	Tones playback	Schlund et al., 2000
White whale	186	Seismic water gun	Finneran et al., 2002
Tropical reef fish	> 190	Air gun array	Hastings et al., 2008
Riverine fish	185, 187	Air gun array	Popper et al., 2005

Studies in humans (Miller, 1974) have led to the generalised graphs from which it can be determined that, for a TTS between 6 and 10 dB, the exposure for one minute is 110 – 120 dB re 20 μPa in air. The same equivalent energy in water would be 190 – 200 dB re 1 μPa^{2}s. The difference includes the 62 dB discussed above (for relating sound pressures in air and water) and the 18 dB difference due to the duration difference of 1 min compared with 1 s.

From this comparison, it appears that the range of sound energy levels to cause TTS in humans lies within the range for marine mammals. The similarity in the range of levels to cause small amounts of TTS across marine and terrestrial species, gives some confidence that the lower values would provide suitable criteria to avoid hearing damage when marine animals are exposed to noise. The received sound levels as a function of distance from a source can be calculated from the source level and propagation loss. The sound exposure level requires some estimate of the duration of exposure with allowance for the change in the distance from the source as an animal moves away. From this it is possible to obtain estimates of the minimum distance an animal can be from a source without suffering TTS. Generally such distances are small enough for animals to be detected visually from the transmitting vessel and thus the transmission reduced or stopped if they come too close to the source.

Behavioural reactions and their significance

There have been several reports of mass strandings of whales at about the same time and in the same general area as naval exercises using high powered tactical sonar, although there is uncertainty in the actual causes of the strandings (summarised by D'Amico et al., 2009). Beaked whales were over-represented in these stranding events. Although a number of theories have been provided to explain how sounds from sonars might directly affect whales, these theories are not well supported by evidence. Some preliminary results of behavioural response studies where beaked whales were exposed to sounds of sonar, killer whale sounds and pseudo-random noise suggest that the whales move away from the source whatever the sound transmitted and at received levels well below that expected to cause temporary threshold shift (Boyd et al., 2008, and cruise reports available from http://www.nmfs.noaa.gov/pr/pdfs/acoustics/brs2007_finalcruisereport.pdf and http://www.nmfs.noaa.gov/pr/pdfs/acoustics/brs2008_finalcruisereport.pdf). The response was significantly more pronounced than that for other species of toothed whale tested. The pattern of the movements of the ships and the strandings suggest effects may have occurred at significant distances, too large for the effects to have been other than behavioural. Consequently, expert opinion suggests that the most likely cause of the stranding is a behavioural reaction to the exercises, possibly to the noise from the sonars.

There have been a number of experiments studying the reactions of whales to air guns. Some of these have shown aversion by the whales (summarised by Richardson et al. 1995; McCauley et al., 2003a) while others were inconclusive. These occurred at levels below those expected to cause temporary threshold shift. McCauley et al. (2003b) (found hearing damage in fish exposed to an air gun at close range (5 – 15 m).

Generally behavioural and masking effects are difficult to manage because they are likely to occur over much greater distances and affect a much larger number of animals. However, the fact that an animal shows a behavioural reaction to a noise or it is subject to some masking is not necessarily a problem. If the reaction is short term and the animal soon returns to normal behaviour with no consequence, it may not be considered a problem. Expert opinion, which is reflected in environmental regulations, is that we should be concerned with effects that have "significant" impact. Just what "significant" means in this context is subject to a large amount of discussion, but generally it refers to impacts that are likely to have a longer term biological effect that is detrimental to the animal. This may be in terms of life functions such as breeding, migrations, feeding, through to population level effects such as changes to the size of the particular population of the species. The Australian Government has published a paper giving detailed guidance on what is considered "significant impact" in terms of its environmental regulations (Anon. 2009).

Behavioural reactions that result in whales stranding (e.g. beaked whales fleeing from naval exercises) provide an example where the longer term biological significance is clear: these strandings have resulted in the death of the whales. In most cases of behavioural reactions, however, it is very difficult to determine whether there is likely to be a significant impact, or the extent or severity of that impact.

It is difficult even to determine if a behavioural reaction has occurred in response to noise. Animals exhibit a wide range of behaviour normally, so it is necessary to determine if a behavioural change has been caused by the noise exposure or is coincidental. Generally, this can only be reliably determined in experiments that are designed for this purpose and are based on a good knowledge of the normal behaviour. Such experiments are expensive, especially those involving marine mammals, because of the large amount of time that has to be spent in the field to obtain an adequate sample with a suitable number of controls to allow for the variability between individuals. Some experiments have turned out to be inconclusive because of inadequate sample size.

Relating the behavioural response to the noise to longer term biological effects is even more difficult. An expert review by the US National Research Council (NRC 2005) discusses the issue of biologically significant effects in detail. It notes that while the primary focus of the regulations of the U.S. Marine Mammal Protection Act is at the level of the individual, the basic goal of the Act is to maintain sustainable marine mammal populations. This review proposed a roadmap in which observable behavioural reactions may be linked in a series of steps to population level effects such as the population growth rate. For example, one steps links behavioural reactions to the effects that these have on life functions such as survival, feeding, breeding, response to predators. This is referred to as the Population Consequences of Acoustic Disturbance (PCAD) conceptual framework. It recognized that years of work will be required to accumulate data and develop models for this transfer function, as well as the next transfer function, that leads to vital rates. Unfortunately, there is currently little information linking observed reactions of animals to the longer term biological impact of these reactions.

Masking and its significance

The effects of masking can be modelled by using information about the received sound level of the signals of interest to the animal and the noise from anthropogenic sources if a knowledge of the critical band or critical ratio is known for the species. Richardson et al. (2005) summarises a number of studies of critical ratios in marine mammals and there is a general similarity between species, as well as similarity to human critical ratios. Even if masking occurs, there needs to be an assessment of the longer term biological significance. Many signals used by marine animals have significant redundancy, since the animals are used to living in an environment where masking from natural sounds (vocalisations of other animals, sea surface noise or rain) is commonplace. In animals that produce choruses, the most significant masking is likely to be from the sounds of conspecifics, since they are producing very similar sounds. Redundancy in signals used by marine animals would allow these signals to be effective, even with a certain amount of loss of components of the signal by masking. For example, the long stereotyped sequence of sounds, or song, produced by male humpback whales has substantial redundancy and limited information content because it is so stereotyped (Miksis-Olds et al.,2008). Masking of many of the repetitive sounds may have limited impact on the effectiveness of the song. On the other hand, humpback whale social sounds, which are used for closer range individual communication are occur individually and are far less stereotyped, so may be more limited by masking (Dunlop et al., 2008).

Comparison of anthropogenic noise and natural noise can be useful in gauging the level of impact. There is concern that traffic noise may be limiting communication of baleen whales which vocalise in a similar frequency band. This is partly based on extrapolation of the classic wind-dependent noise curves of Wenz (1962) to low frequencies, which resulted in levels that were well below traffic noise levels. Wenz' wind-dependent noise spectra show a broad peak at around 500 Hz with levels decreasing with decreasing frequency down to their lower limit of 100 to 200 Hz (from high to low winds speeds, respectively). This led the idea that there was a "noise notch" at low frequencies, and that this was exploited for communication by baleen whales, especially the blue and fin whales which produce sounds at frequencies below 100 Hz, and that traffic noise has severely compromised their ability to communicate, at least over long distances. The difficulty in assessing this is that most measurements of ambient noise have been made in areas of high shipping densities and thus high traffic noise, and it has been difficult to determine the characteristics of natural ambient noise at these frequencies.

The wind-dependent noise curves of Figure 1, measured in areas of low traffic noise show that noise levels rise with decreasing frequency below 100 – 200 Hz, while still showing evidence of the broad peak at around 500 Hz. These results are consistent with the few results in early and recent work in areas around North America where traffic noise was less significant than usual (e.g. Piggott, 1964). Wenz also noted the wind dependence at low wind speeds and some of the data presented show similar spectral shapes to those of Figure 1. At 30 knots the low frequency wind-dependent noise levels in Figure 1 are comparable to upper levels of "usual traffic noise" given by Wenz. Some areas, however, may show higher levels of traffic noise and there is concern that traffic noise levels may have risen since Wenz' measurements. For example, ambient noise measurements off Pt. Sur, California show higher noise levels at low frequencies at the 50 percentile and they considered that a large proportion of this is due to shipping (Andrew et al., 2002).

METHODS OF MANAGING AND MITIGATING IMPACT OF ANTHROPOGENIC NOISE ON MARINE ANIMALS

The first step in avoiding impacts of noise on marine animals is to avoid conducting ocean activities in areas where and when animals are present. This is often not possible. It may be possible to avoid a particular species of migrating whale in a particular for part of the year, but there will often be other species there then. A commonly used method of management is to apply some exclusion zone, outside which some level of impact is unlikely to occur. If an animal is observed to be in or about to enter the exclusion zone, the operation that is causing the noise is shut down. There may be an outer zone where the presence of an animal requires a reduction of the acoustic power output to some specified level. The exclusion zones are specified in environmental regulations and guidelines, and in management plans. These are most widely used in managing impacts on marine mammals exposed to seismic air gun surveys or to naval activity. An example is the Australian EPBC (Environmental Protection and Biodiversity Conservation) Act Policy Statement for the Interaction between offshore seismic exploration and whales of the Department of Environment, Water, Heritage and the Arts (Anon, 2008). Another is the Australian Department of Defence Maritime Activities Environmental Management Plan. An example of the procedures that would be adopted when using sonar is given at http://www.navy.gov.au/w/images/Procedure_Card.pdf. Many developed countries have regulations or guidelines that follow similar approaches.

CONCLUSIONS

Although much has been learned about the effects of noise on marine animals, there remain significant areas of uncertainty. Most effects will be behavioural reactions or masking of sounds since these are likely to occur over relatively low levels and thus at considerable distances from sources. Effects on hearing will be limited to distances close to high level sources and can be avoided by managing the distance of animals from the sources, e.g. by establishing an exclusion zone, monitoring the presence of marine mammals, and stopping transmission if they come into the exclusion zone.

It is difficult to determine if a behavioural reaction has occurred in response to noise because animals exhibit a wide range of behaviour normally. Generally, this can only be reliably determined in experiments designed for the purpose, and such experiments are very expensive. Few have been conducted that have been adequate for the purpose. It is even more difficult to take this further to determine whether the behavioural responses result in "significant" impacts, i.e. whether they have longer term biological effects. Currently, our knowledge of normal behaviour and communication and their functions are quite limited. Even more limited is the way behavioural changes and masking can be linked to life functions and population effects, as is required if we are to determine the significance on behavioural responses. This is where there is most need for research.

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