NOISE SOURCES IN THE SEA AND THE IMPACT FOR THOSE WHO LIVE THERE

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ABSTRACT

In recent years the volume and spatial extent of anthropological noise pollution of the oceans has become clearer as underwater acoustic research has matured in the open literature following the run-down of the cold war. In parallel, the range, depth and dependence of marine mammals on sound for communication and environmental sensing has been brought sharply into focus by an increased attention to marine mammal research. We are now aware that present levels of anthropological noise might represent a significant threat to some marine animals. Uncertainties in the understanding of function and hearing sensitivity of marine mammals prevents us from reaching firm conclusions, but the detrimental impact could be severe. A sketch review is given of the known sources of natural and man-made noise, methods by which marine mammal responses can be estimated and the possible damage mechanisms. Ambient noise levels from shipping and other human activities are presented for Northern and Southern Hemisphere sites. Shipping appears to have raised background noise significantly throughout the Northern Hemisphere. Available evidence and moderate extrapolation of known features of marine mammal hearing leads us to conclude that total noise levels are likely to be adversely affecting several species.

1. INTRODUCTION

In air, sound propagates rather poorly compared to underwater. Even very loud sounds, such as jet engines on aircraft, can only be heard for $O(10^3)$m. A similar acoustic power, if injected into the deep sound axis channel of the ocean, can travel full global distances, $O(10^6)$m. Indeed, a new experiment aims to measure the suspected warming of the world's oceans by doing just this, using sources of only a few hundred Watts total power whose signals can be received across the major ocean basins (Baggeroer & Munk). Light, by contrast, propagates extremely poorly, travelling only a few tens of meters before being absorbed. It is thus that sound and hearing replaces light and vision as the primary sensory system for marine mammals. Consequently, this group of animals has evolved extremely sophisticated and sensitive hearing, employing both passive and active acoustics to navigate through their environment, find their food and communicate. We must therefore closely examine the acoustic environment of the oceans if we are to understand the possible impact of man's activities.

Ambient noise in the ocean spans at least five decades in the frequency domain and is the product of a plethora of sources, both natural and anthropological. It includes geological disturbances, non-linear wave-wave interaction, turbulent wind stress on the sea surface, shipping, distant storms, sonars and seismic prospecting, marine animals, breaking waves and spray, rain and hail impacts and turbulence. It is characterised by an extreme geographical and temporal variability. To make some sense of this enormously complex field, early researchers chose to make simple delineations in frequency space that appeared to be dominated by different physical mechanisms. A simplified picture of natural noise sources is provided in Fig. 1, adapted from (Urick).

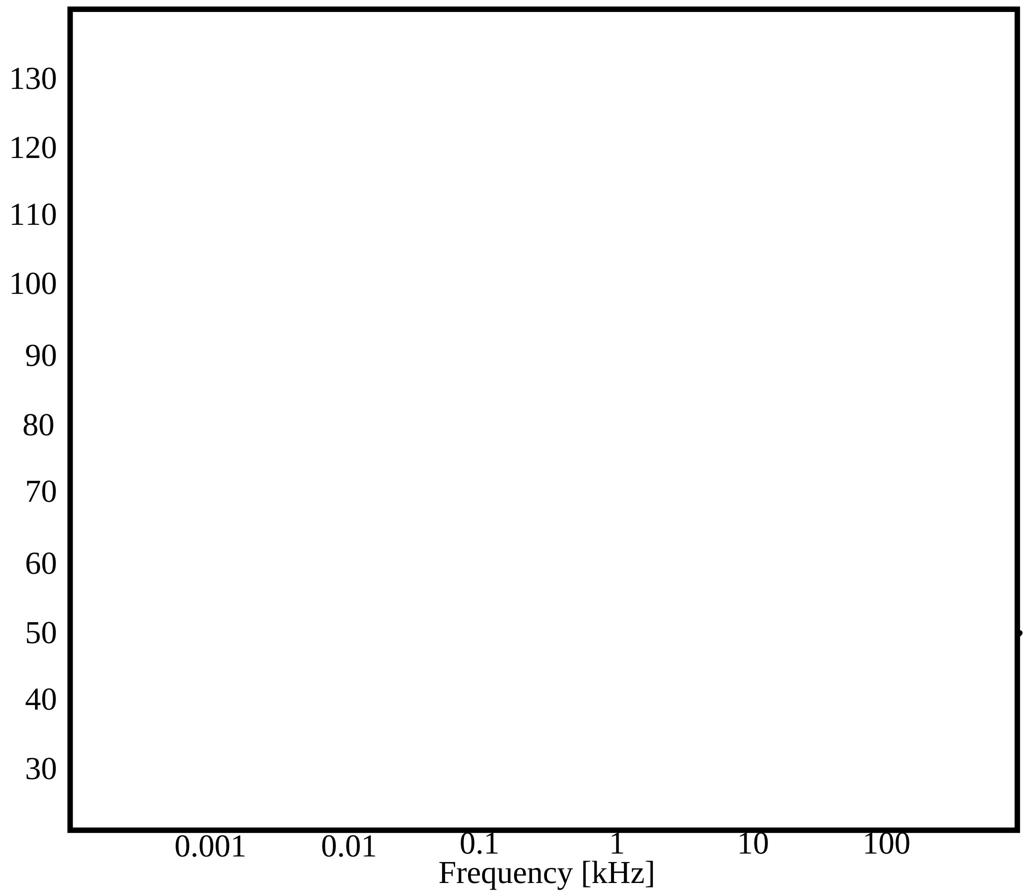

Figure 1. Spectral zones of ambient noise and contributing mechanisms. The black curve represents a typical deep-ocean noise spectral density. The boxes indicate approximate bandwidths of influence of various noise-producing mechanisms. Their vertical position does not indicate anticipated spectral strengths.

The simple curve given in Fig. 1 as a typical deep-water noise spectral density belies the complexity of spatial and temporal variability. In the next section, we present evidence that man-made noise has risen to a level which dominates the acoustic environment over large portions of the globe in some bandwidths.

Current classification of noise impacts on animals separates damage into two main groups; physiological damage and psychological impact resulting in behavioural changes. These groups and some finer distinctions are discussed in the section on noise damage mechanisms.

The following section investigates the means by which we assess the impact of noise on marine mammals. These consist of direct visual observation, acoustic monitoring, telemetry and the nascent development of psycho- and physiological-acoustic modelling.

The use of sound by marine mammals, and even the hearing sensitivity of many species, is poorly understood or even completely unknown. In the section on marine mammal responses to noise, we suggest that there may be many species who could be severely adversely impacted (particularly deep-diving species).

MAN-MADE NOISE IN THE SEA

Some major classes of man-made noise in the sea are:
Shipping, from supertankers to jet skis, spanning 10 Hz – 50 kHz
Offshore Oil/Gas exploration & production
Sonars, especially military high-power equipment
Experimental acoustic sources, SUS, tomographic, ATOC etc.
Fish 'bombing' and other underwater explosive & civil engineering activities
Overflying aircraft, especially supersonic

The most powerful sources, associated with gross tissue damage at short ranges, arise from seismic surveying, explosions, acoustic experimentation and large ships (especially icebreakers and at low frequencies) (Richardson et al). Extremely loud sources, such as airgun blasts conducted during oil exploration, involve the production of some of the most intense of man-made noises and often extend over large areas and periods. The juxtaposition of these intense sound sources and such sensitive animals understandably gives rise to concerns about the effects seismic research, underwater civil engineering works and oil/gas production could be having on marine mammals. The impact of these sources at large range will depend on the propagation conditions, specifically if significant acoustic energy is injected into long-range propagating ducts.

Even though the impact of explosive and seismic air gun activity could be severe, these sources are relatively rare compared to shipping, which is generally of lower intensity but contributes in greater numbers and over a large spatial extent. We present evidence in Fig. 2 that the continual background 'hum' of distant shipping has polluted the entire Northern Hemisphere oceans. The potential impact of this noise, ubiquitous in space and time, could be more subtle, but far more catastrophic in the long-term. Sperm whales, for example, are thought to have a fecundity rate only 4% above natural attrition (Hal Whitehead, personal communication). If this is the case, even a marginal decrease in fitness for life of this species could result in total extinction in the future.

Although it is difficult to compare ambient noise data from different sites and times, due to the complexity of the ocean environment and changing measurement techniques, an attempt has been made to gather some relevant results in Fig. 2. All the data used are averaged, wherever possible, to remove short-term temporal variability (very large in shallow water, still significant in deep). Most data are from deep measurements. The following points should be noted when considering Fig. 2.

The polygonal shaded areas for 70 n.m. S. of Bermuda and the Mediterranean cover a range of wind speeds, higher winds giving the upper part of the polygon, lower winds associated with the bottom.

The spread in the polygonal shaded area for the Timor Sea off N. Australia is partly due to the variability associated with biological chorusing, and partly wind.

The dashed line in the top right of the fig. showing high shipping in Singapore harbour is taken from data measured down to 10 Hz, but below 100 Hz the values are in excess of 100 dB, right off the graph scale.

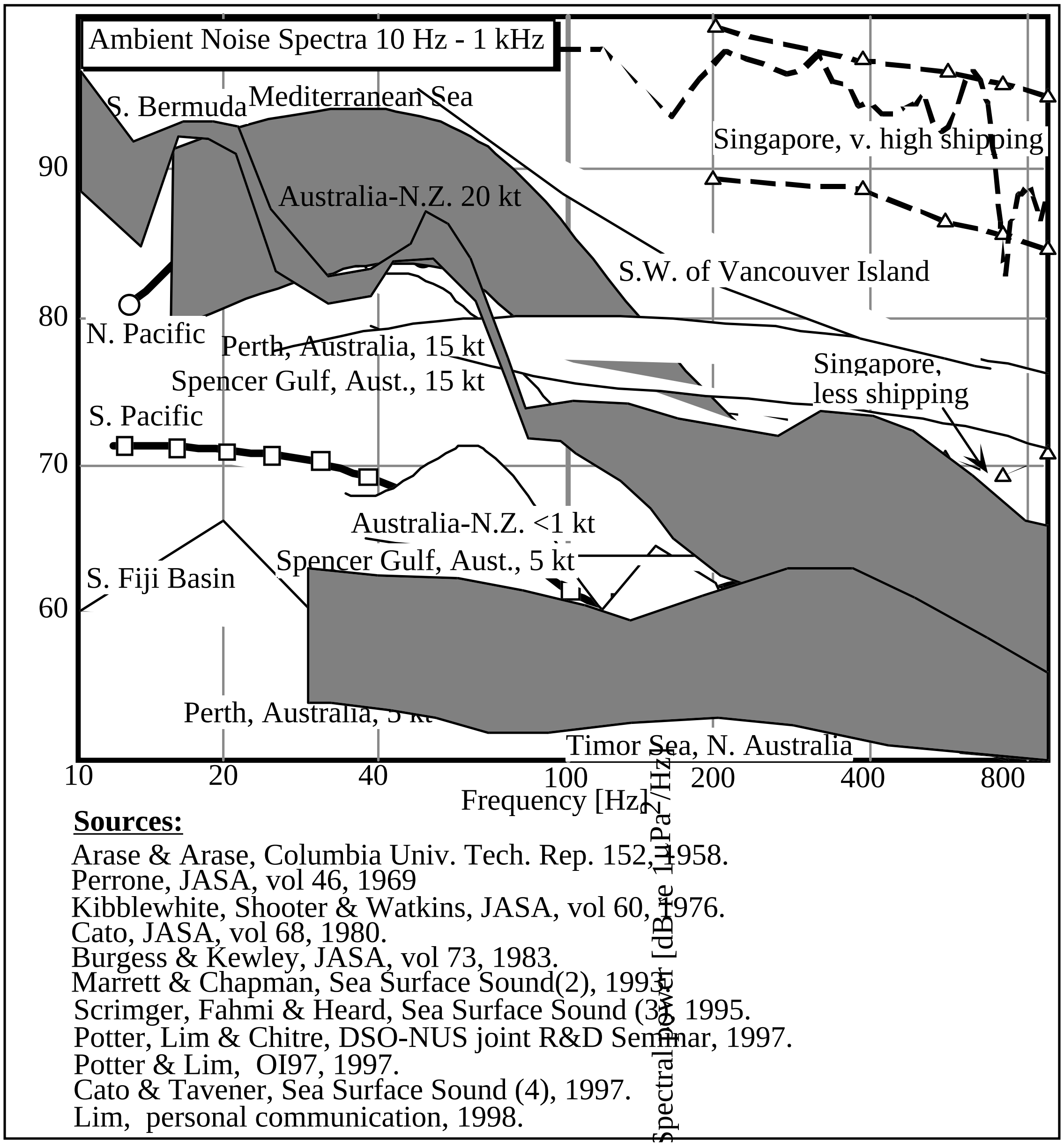

Figure 2. Collage of ambient noise measurements in the deep ocean.

While it is difficult to trace each curve separately in Fig. 2, the groupings of curves tell an interesting and consistent story which we summarise here:

The noisiest 10 or so measurements are all taken in the Northern Hemisphere or (for just three cases) Southern Hemisphere with considerable winds (15-20 kt).

The quietest six measurements are all in the Southern Hemisphere and with wind 1-5 kt.

Where wind raises the noise, it seems to do so right down to 30 Hz (at least), and the resulting spectrum is flatter than that due to shipping, which has a marked peak. This peak shifts to lower frequencies in shallow water. The low-frequency wind noise effect is always obscured in the Northern Hemisphere due to shipping.

Where shipping is heavy, it will cause more noise than any wind condition, e.g. the Singapore harbour curve. Shipping in the Northern Hemisphere raises the ambient noise level 10-20 dB (in low wind conditions) almost everywhere we have measurements. Localised heavy shipping (Singapore is one example) can raise the level 30-40 dB.

Below 200 Hz (corresponding to the core of the shipping noise spectrum), the N. Pacific average is typically 10-15 dB louder than the S. Pacific.

There are local ‘hot-spots’ of ambient noise all over the globe, of course. The authors have been in the North and Norwegian Seas on many acoustic experiments, and listening to the raw output from hydrophones deployed from the research vessel, the entire soundscape is often dominated by the repetitive 'boom...boom...' of distant geophysical surveying. This incessant cacophony, an acoustic equivalent to the fabled ‘Chinese water torture’ deeply disturbs some individuals who are exposed to the sound over long periods. Perhaps it does the same to whales. Other likely ‘hot spot’ areas resulting from oil and gas exploration and production are the Arab Gulf states' waters, Gulf of Mexico and North of Venezuela. Still more ‘hot-spots’ will be associated with the high density of shipping in regions near major ports & sea routes such as Singapore, Rotterdam, New York, Los Angeles, the English Channel, Malacca Straits, Panama Canal, S. China Sea, Gibraltar Straits, Bosphorus and many more.

NOISE DAMAGE MECHANISMS

Potentially, man-made noise can have a number of impacts on marine mammals. These effects are often divided into two groups. Under US legislation enacted to protect marine mammals these are termed Type I and II effects.

(1) Physical and physiological effects that directly cause some form of temporary or long-term damage to the animals.

(2) Behavioural effects where the animals' natural behaviour is disturbed.

In practice, many different types of impact may arise from long-term and short-term exposure. In addition, there can also be indirect effects, mediated by the effects of noise on prey species. The more subtle effects associated with long-term exposure to low-level noise are much more difficult to observe and quantify than the more obvious trauma associated with high-level noise which causes direct tissue damage.

The potential for extremely long range propagation in the ocean and the long life span and slow reproductive rate of some marine mammals suggests a potential for effects on temporal and spatial scales far beyond those normally considered.

A schematic of the types and degrees of impact we consider relevant is shown in Fig. 3.

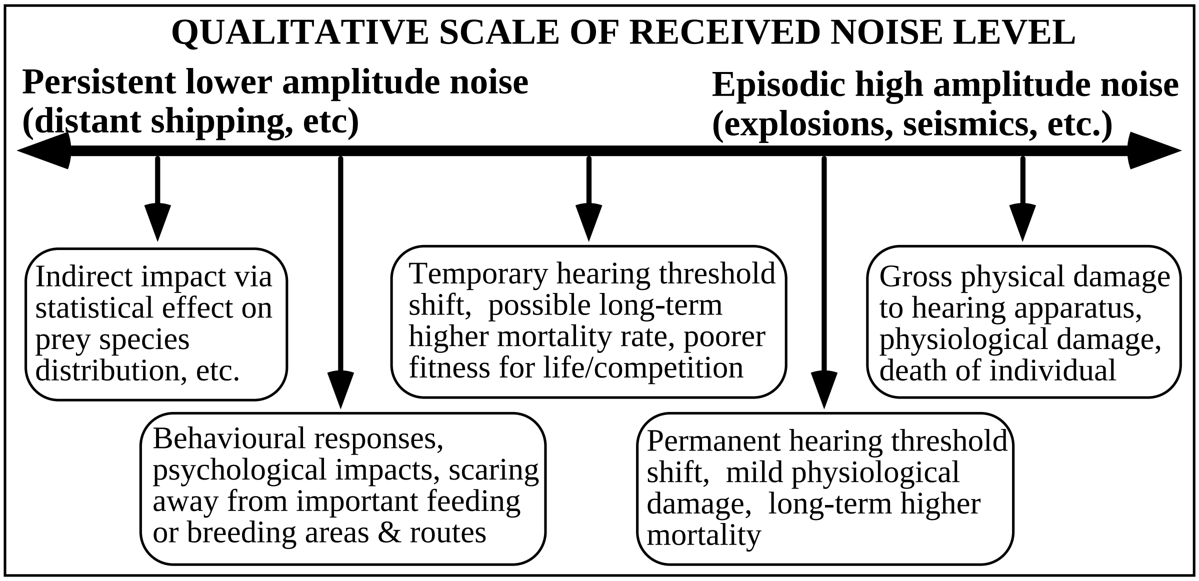

Figure 3. A schematic of the types and degrees of noise impact on marine mammals.

INVESTIGATING THE EFFECTS OF MAN MADE NOISE ON MARINE MAMMALS

Ideally, field studies would be conducted in which marine mammal scientists could control when and where the noise sources under consideration were active. This has only rarely been possible and only under a limited set of conditions. In some situations, observations can be made before, during and after some noise event but more often research is conducted while the noise-creating activity is underway. Secondly, marine mammals are a large and diverse group. Findings from one species do not generally apply to others. Another important consideration, which is often overlooked, is the temporal and spatial scales over which effects may occur, outlined in the previous section.

Three methods have been used to date to assess the effects of noise on marine mammals: direct observations, acoustic monitoring and remote telemetry. A possible fourth method is the psycho-physiological modelling that is being developed by fusing expertise in the fields of CAT scanning, finite element and boundary element modelling and neuro-physiological studies of the mammalian ear. We discuss the three established methods in turn.

Direct observations

Direct observations are mainly conducted in the field, and extrapolated from work on better-studied animals, including man. Marine mammals are perhaps the hardest mammalian group to study. Virtually all relevant aspects of their biology (including sensory capabilities, undisturbed behaviour and its adaptive significance, distribution and abundance) are only poorly understood. Conducting marine mammal research at sea is always difficult and costly. We outline some of the standard techniques to provide an understanding of why direct information on the effects of noise on marine mammals is so sparse, and to appreciate how hard won are those pieces of information that we do have.

Visual observations from ships have been used to study cetaceans but very rarely pinnipeds. Even large whales are difficult animals to observe at sea. They can only be seen for the brief periods that they are at the surface and then only a very simple subset of behaviours can be observed. These simple behaviours may or may not be good indicators of disturbance, and assessing the significance of any changes detected is fraught with difficulty. An additional concern is the extent to which the observation platform itself might be affecting the animal's behaviour. For example, dolphins are most often seen at sea when they come to boats to bow-ride.

Circling aircraft provide a higher vantagepoint and are less likely to affect the animal's behaviour. However, they can provide only brief observation periods, are extremely expensive and become increasingly impractical as the range between the study site and an airport increases.

Observations from coastal vantagepoints do not rely on an expensive platform and do not affect the behaviour of the target animals. Surveyor's theodolites can be used to locate and track animals seen at the surface. Inevitably, because observations are restricted to inshore waters with adjacent high vantagepoints and it can be difficult to follow the behaviour of individual animals.

Underwater acoustic monitoring

Underwater acoustic monitoring of the more vocal species provides a variety of behavioural cues. Generally, acoustic monitoring can be carried out from smaller vessels that are less expensive to operate and less likely to affect the behaviour of the animals being studied. Acoustic monitoring for some large pelagic species can also be carried out by fixed hydrophone assets such as the military SOSUS arrays. Other advantages of acoustics are that the range for acoustic detection is often greater than visual range, monitoring can continue through the night and in poor weather conditions and there is a substantial potential for automation of data collection and analysis. Acoustic monitoring is obviously limited to when the animal is vocalising, but this may represent a much larger percentage of time than when it is on the surface and hence still be a great improvement on coverage. Vocalising and surfacing behaviour are often complimentary, so the two techniques are not in competition but compliment each other. While there is merit to studying the impact of noise using acoustic methods, not all marine mammals species are vocal and in most cases the significance of changes in vocal behaviour is harder to interpret than behavioural changes.

Telemetry

Telemetry is an exciting and rapidly developing technological area that can potentially provide large quantities of reliable data, including information on underwater behaviour and even on some physiological responses, such as heart rate. Collecting detailed data usually requires the use of a tracking vessel. Satellite tags can potentially yield lower grade data without a tracking vessel, over extended periods. One of the most significant hurdles to marine mammal telemetry is tag attachment. Pinnipeds can be captured on or close to land and good results have been obtained by gluing transmitters to their fur. Acceptable long term attachment to cetaceans remains a largely unresolved problem and a better approach may be to aim for a larger number of short term attachments using suction cups. Another serious problem with telemetry studies is ensuring that animals are exposed to the appropriate signals, and being able to assess what these signals are (perceived sound levels). Once the subject has been tagged the researchers have no control over its movements, and it may well never enter an area of significant noise activity. Telemetry studies are also characterised by very small sample sizes.

MARINE MAMMAL RESPONSES TO NOISE

Marine mammal audiograms, particularly for the larger animals and at lower frequencies, are very poorly known (Green et al.). Even marine mammals' uses of sound for echolocation, communication and navigation are very poorly understood. A suggestion that the Humpback Whale (*Megaptera novaeangliae*) could employ backscattered echoes of it's song (presumed intended for mating purposes) as an echolocating sonar has caused a storm of protest from some, yet is broadly supported as being worthy of research by others (Mercado, personal communication). Even entirely new uses for sound, such as for Ambient Noise Imaging (Potter & Chitre) may be employed by marine mammals (Potter et al.), yet not a single experiment has been carried out to date to test these exciting ideas. Given such a background of ignorance, it is extremely difficult to even establish a meaningful framework for estimating the impact of noise on these animals.

Following the Heard Island experiment (involving a loud acoustic source), the associated marine mammal observation programme declared no significant impact (Bowles et al.). Nevertheless, this study has been criticised for being planned too hurriedly, and of insufficient coverage to be able to draw any significant conclusions. Some reactions were observed, indicating that the source was at least heard and considered important to some animals in the area. Detection of minor behavioural changes or possible subtle effects such as masking of significant sounds could not be determined.

We consider three classes of marine mammal response. Chronic stress (associated with high noise levels), long-term behavioural modification & masking (associated with lower, more persistent noise) and indirect effects. We do not consider physical trauma in this section (althougn it is a very important damage mechanism), since the response is invariably simple, death.

Chronic Stress

Sound, often at quite low levels, is a cause of stress in man and can lead to a number of health problems due to the chronic activation of stress related hormonal complexes. Elevated levels of noise are also known to impair some mental and psychomotor functions in man (Kryter). Noise also disrupts normal sleep and rest patterns with levels between 30 and 80 dB above the hearing threshold being sufficient to waken sleeping humans.

Stress is often associated with release of the hormones ATCH (adrenocorticotrophic hormone) and cortisol. Transportation stress (associated with noise and vibrations) causes elevated plasma cortisol levels in domestic animals. Increases in hormone levels are typically associated with changes in behaviour, e.g. increased aggression, changes in respiration patterns or social behaviour. Nevertheless, noise induced stress from playbacks of drilling platform noise on captive beluga whales had no significant effects on swim patterns, social interactions, dive or respiration rates or blood catecholamine levels (Thomas, A. et al.).

Even in humans, the role that sound plays in causing a variety of stress-related complaints is often not obvious and we must assume that it will be near-impossible to prove that such effects exist with wild marine mammals in the field. Even so, the pervasive effects of stress on so many aspects of the health of individuals and populations makes it a matter of real concern.

Long-term behavioural modification & masking

There have been no direct studies to investigate whether or not repeated man-made noise pollution in an area can lead to long term disturbance and exclusion from habitat. However, some authors have drawn attention to examples where repeated loud noise events do not appear to have caused animals to desert areas of preferred habitat. We should be reticent in taking much comfort from these observations however. Firstly, such observations tend to be qualitative rather than quantitative; they are rarely backed up by surveys or analysis to show what the population levels might have been in the absence of airgun noise. Secondly, the option of moving to different habitats or changing migration routes may be a far more drastic undertaking than many imagine. There may be strong reasons why an alternative route or habitat cannot be found, or the animals may be hearing impaired and unable to navigate their way to a safer area. Circumstantial evidence for this kind of impact has been found in the occurrence of skin lesions and increased vulnerability to disease in some noisy areas. There is no evidence that stress due to acoustic disturbance has caused these, but unexplained health problems within cetacean populations should serve as a warning against making complacent assumptions.

Moving on to the subject of masking, any background noise can reduce an animal's ability to detect other sounds. Generally, two sounds will only mask each other if they are sufficiently close in frequency; that is to say, one is in the "critical band" of the other. The width of critical bands scales with their centre frequency and they often extend over approximately 0.1-0.2 of an octave. Studies of masking have usually considered the masking of a pure tone by other tones or by noise in a frequency band around it. The situation is more complex when, as would be the case for masking by seismic sources, both the noise and the signal are broad band and the noise is transient rather than continuous. Noise may mask a signal if its level within the critical band is close to or above the level of the signal in the same band, i.e. the signal to noise ratio is less than or equal to unity. The signal-to-noise could be negative (perhaps -12 to -20 dB) if the signal is sufficiently important in nature for the animal to have developed specific processing to detect it. This is commonly known as the 'cocktail party syndrome'. There will be many situations when there is significant biological advantage for an animal to be able to detect very faint sounds. Indeed this is believed to have been the evolutionary pressure for the creation of sensitive hearing, so there is the potential for harmful masking to occur at very great ranges. (Au, Carder et al.) reported changes in the vocal output of a beluga whale when it was moved to an environment with higher levels of continuous background noise. In the noisier environment, animals increased the average intensity and frequency of its vocalisations as though it were compensating for the masking effects of the increased background noise levels.

There is no information on the extent to which the majority of man-made noise (being at low frequencies) masks biologically significant noises for marine mammals. Since we suspect that the main potential for masking will be at the lower frequencies, this suggests that small cetaceans are less likely to be affected than baleen whales. Baleen whales are believed to be low-frequency specialists, most of their vocalisations are below 1kHz and some, such as blue and fin whales, make sounds below 50 Hz. It has been suggested that baleen whales could use low frequency sound to communicate over great distances, and recent monitoring using the military SOSUS system has lent support to this. Recently, attempts were made to monitor baleen whales off the West Coast of the British Isles using a SOSUS array of hydrophones. Levels of background noise were so high in the summer months due to oil-related seismic surveying that monitoring had to be abandoned for long periods (Clarke, personal communication). One can only assume that baleen whales' ability to monitor its acoustic environment might be similarly compromised by such noises. This is an important point. Whatever the vocalisations are for, if we assume they have some purpose (otherwise evolution would not support their continuance) then the effectiveness must be compromised by man-made noise wherever the signal-to-noise is seen to be degraded. Animals do not have such superior signal processing compared to our digital techniques that they are unaffected when we have to abandon data collection.

Indirect effects

Noise may not always have an immediate impact on cetacean populations but may indirectly effect them through its effects on prey abundance, behaviour and distribution. Cetaceans can be divided into two major groups by their dietary requirements, (1) Piscevores, and (2) Planktivores. Odontocetes fall into the former group and mysticeti into the latter, although it should be noted that diets are not 'catholic'.

Fish in particular are affected by intense sound because of the presence of air filled cavities, e.g. swim bladders. Although marine fish typically have less sensitive hearing than marine mammals they are most sensitive at frequencies between 100 and 500Hz where most shipping, explosive and seismic exploration noise is produced. At these frequencies they are certainly more sensitive than those odontocetes studied so far. Effects of explosive pulses on fish range from serious injury at short ranges to avoidance behaviour, possibly over many km (Turnpenny and Nedwell). Reduced catch rates have been reported for several species of fish in areas of intense seismic activity. The pathological and behavioural effects of noise on higher marine invertebrates, e.g. squid and octopus, are not known. However, far-field hearing has been demonstrated for cephalopods and all invertebrates have well-developed mechanosensory systems that could potentially detect broadband and low frequency pulses. Squid are known dietary staple for the sperm whale and beaked whales and any effects of noise on deep-sea cephalopods could potentially have negative impacts on deep diving whale populations.

These studies show a variety of effects on potential prey species. If noise cause fish or squid that are the prey of marine mammals to become less accessible, either because they move out of an area or become more difficult to catch, then marine mammals distributions and feeding rates can be affected. In the long term, this could lead to effects at the population level.

DISCUSSION

All marine mammals dive, in fact many will spend the majority of their lives underwater, and some can spend significant times at very substantial depths. Sperm whales, for example, regularly make dives in excess of 1,000m and have been recorded down to 2,500m. Beaked whales are also known to be impressive deep divers, and may even exceed the diving abilities of sperm whales. Beaked whales are a particular cause for concern because their biology is poorly known, they appear to have discrete offshore home ranges and there are indications that they are particularly vulnerable to the effects of powerful military sonar. Seals are often even more accomplished divers than cetaceans, and elephant seals have been recorded at depths greater than 1000m.

Deep divers are worthy of particular concern for a number of reasons:

- In deep water, it is likely that sound energy will enter the deep sound channel where deep divers spend much of their time. This channel is a refractive propagating duct, bound above by the ocean thermocline and below by increasing pressure, both of which increase sound speed. Once in the sound channel, sound is ducted with little loss, resulting in cylindrical rather than spherical spreading. Diving takes them into areas in which received noise levels can be higher than those measured or predicted close to the surface.
- A diving mammal leaves the surface with stores of oxygen in its blood and muscles that must sustain it through its dive until it reaches the surface again. Some parts of the body, such as the brain, must be kept supplied with oxygen continuously.

Strategies for making the best use of these reserves include shutting down non-essential activities, such as digestion, restricting peripheral blood flow and a dramatic reduction in heart rate (brachycardia). Energetic activities are minimised and swimming will tend to take place at close to the most energy efficient swimming speed. It is possible for muscles to respire for short periods without oxygen (anaerobically) but this incurs an "oxygen debt" which is expensive to "repay" both in terms of energetics and time-budgets. From the perspective of avoiding loud noise sources, this is likely to mean that energetic responses will be limited, particularly to the end of dives when oxygen stores will be minimal.

- It is also possible that, in response to an unknown threat, air breathing divers will choose to head to the surface where they will at least have access to air, even if this takes them closer to the noise source.

These considerations mean that an animal's options for avoiding loud noise sources are reduced and the disruption caused by taking avoiding action greater than it would seem.

It is often assumed that marine mammals will respond appropriately to loud noises, i.e. they will move away from them. Clearly, to be able to do this they need to be able to localise the sound source. Mammals can do this in two ways: using the time of arrival or the difference in intensity between the two ears. Time of arrival information is most useful for transients and broadband signals and intensity differences for higher frequencies due to the increased diffractive effect of the body. Intensity differences depend on the existence of reflective objects close to the ear to create a differential sound field. In terrestrial animals these are typically the head itself and the external pinnae which are specially adapted for this function. The impedance difference between a mammalian head and water is less than it is for air; thus, the head will be a less effective sound reflector. In addition, marine mammals lack external pinnae, probably because they would work less well underwater than in air, and incur substantial hydrodynamic penalty. The speed of sound in water is approximately five times that in air and wavelengths are therefore some five times as long at a given frequency. This further reduces the effectiveness of the head as a reflector. It also reduces the effective separation (in terms of wavelengths) between the ears of marine mammals making binaural time comparison less effective. Finally, multipath propagation (typical in ocean environments) creates a multiple ambiguity in the direction of arrival. Deep divers in mid waters may hear two or more discrete sources of noise. Some underwater environments are highly reverberant (additional echoes caused by reflection) and in these conditions, localisation of sound sources may be even more difficult. In some cases several sources may be audible in different locations at the same time or intermittently, and a noise may get louder as one moves away from it due to the properties of convergence zones. This is potentially a very confusing situation for a marine mammal.

(Richardson, Greene et al.) review the directional hearing abilities of marine mammals. Dolphins have excellent directional hearing at high ($O(10^4)$ Hz) frequencies but their hearing at lower frequencies has not been tested. Directional hearing in seals is less precise, and again has only been tested at kHz frequencies. The directional hearing of baleen whales has not been studied but they do seem to respond directionally to low frequency vocalisations from conspecifics. Observations showing avoidance of airguns, often at considerable ranges, suggest that marine mammals are able to localise it. However, given the particular problems of directional underwater hearing mentioned above we might be overestimating marine mammals' ability to do this if we used the excellent human localisation ability in air as an analogy.

It may also be the case that animals are not able to appreciate the potentially damaging consequences of exposure to noise. There are innumerable examples of humans willingly exposing themselves to damaging levels of noise, workers using using power tools and teenagers in dance clubs to mention two. The damaging effect of transients can be particularly difficult to assess. Because the auditory system integrates sound over about 0.5 seconds, transients that are much shorter than this (such as a pulse from an airgun) may not "sound" particularly loud.

For a number of reasons, marine mammals may be unable to take what might seem to a human observer to be the obvious course of action to alleviate the effects of a localised noise such as an airgun array or large approaching vessel. This could be due to an inability to correctly appreciate the situation on the part of the marine mammals, or a failure on our part to understand the biology of the animal concerned. Detailed behavioural observations, such as from telemetry research, will be important in improving our understanding of how marine mammals respond to sound and why.

CONCLUSIONS

As the developed nations' sense of urgency increases with regard to curtailing the rate of anthropological environmental damage, many new environmental arenas are becoming of importance to the public at large and hence their elected representatives. There are both legal and moral reasons for being concerned about the welfare of individual animals as well as the health of populations in general. Certainly, public opinion responds strongly to these considerations. Among these, acoustic pollution of the oceans is becoming increasingly prominent. It appears that man-made noise in the oceans is now a significant factor, at least in the Northern Hemisphere and at identified 'hot-spots' where shipping congregates. There are also problems associated with specific activities such as acoustic experimentation and seismic surveying for offshore oil and gas development. The various mechanisms by which marine mammals can be adversely impacted indicate considerable subtlety in the interaction, and a great deal of additional effort is required before we can expect to predict and understand the potential for damage to populations. Loud noises can cause short-term panic and pain to individual animals. A reduction in the ability to hear will limit a marine mammal's ability to make effective use of its primary sensory modality. Lower-level noises may disorientate and drive animals away from important habitat of migration routes. Auditory masking may be a critical factor. Finally, indirect effects on prey species could reduce the fitness for life. If we are to be responsible to the ocean environment, we need to take strong action to assess and mitigate this potential for harm with some urgency.

REFERENCES

Au, W.W.L., D.A. Carder, R.H. Penner and B.L Sconce (1985). Demonstration of adaptation in Beluga whale (*Delphinapterus leucas*) echolocation signals. *Journal of the Acoustical Society of America*. **77**, 726-730.

Baggeroer, A., & Munk, W. (1992). The Heard Island feasibility test. Physics Today, vol.45,(no.9), 22-30.

Bowles, A. E., Smultea, M., Wursig, B., DeMaster, D. P., & Palka, D. (1994). Relative abundance and behaviour of marine mammals exposed to transmissions from the Heard Island Feasibility Test. *Journal of the Acoustical Society of America*. **96**, 2469-2484.

Clark, C.W. (1990). Acoustic behaviour of mysticete whales. *In Sensory abilities of Cetaceans* (J. Thomas & R. Kastelein, eds.), Plenum Press, New York, 571-583.

Kryter, K.D. (1994). *The handbook of hearing and the effects of noise: physiology, and public health*. McGraw Hill, New York.

Green, D. M., DeFerrari, H. A., McFadden, D., Pears, J. S., Popper, A. N., Richardson, W. J., Ridgeway, S. H., & Tyack, P. L. (1994). Low-frequency Sound and Marine Mammals: Current Knowledge and Research Needs Committee on Low-frequency Sound and Marine Mammals). Ocean Studies Board, National Research Council.

Mercado, E., L Frazer and L.M. Herman (1996). Humpback whale sonar, *Journal of the Acoustical Society of America*, **100,** 2664.

Potter, J.R., E. Taylor and Mandar Chitre. (1997). Could Marine Mammals use Ambient Noise Imaging techniques ? *134 meeting of the Acoustical Society of America*, San Diego, USA. Dec. 1997, **102** (5) Pt. 2, 3104.

Potter, J. R., & Mandar Chitre. (1998). Ambient noise imaging in warm shallow seas; second-order moment & model-based imaging algorithms. Re-submitted to JASA following review & revision.

Richardson, W.J., C.J Greene (Jnr), C.I. Malme & D.H. Thomson (1995). *Marine mammals and noise*, Academic Press, San Diego, California.

Thomas, J.A., A. Thomas, K.R. Thomas and F.T. Awbrey (1990). Behaviour and blood catechaloamines of captive belugas during playbacks of noise from an oil drilling platform. *Zoo Biology*, **9**, 393-402.

Turnpenny, A.W.H. and J.R. Nedwell. (1994). *The effects on marine fish, diving mammals and birds of underwater sound generated by seismic surveys.* Fawley Aquatic Research Laboratories Ltd., **FCR 089/94**, 1-40.

Urick, R.J. (1984). *Ambient Noise in the Sea*.. U.S. GPO Washington, D.C.