

A Review of the Impact of Anthropogenic Noise on Cetaceans

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ABSTRACT

The physiological and behavioural effects of anthropogenic noise may be detrimental to cetacean populations world-wide. Evidence indicates that some cetaceans are exposed to high levels of anthropogenic noise over a large percentage of important habitats. There is a lack of understanding of the short and long term consequences of this exposure to noise, due to insufficient research, and the difficulties involved in judging noise effects in isolation from other threats. It is possible that short term and long term disruption of important breeding or feeding behaviours will pose threats to entire populations of cetaceans. Existing data suggest that anthropogenic noise may have led to an increase in cetacean mortalities from entanglement in fishing nets, collisions with vessels and mass stranding events, most likely as a result of auditory damage, or masking of important acoustic signals.

Coastal ecosystems are threatened by pollution, over-exploitation of natural resources, increases in shipping and recreational boating, development and global climate change. The synergistic interactions of these environmental threats, together with the effects of noise, are likely to have severe consequences for cetacean populations in coastal areas. In addition, some sources of noise, such as the Acoustic Thermography of Ocean Climate (ATOC) source, are designed to project sound over vast geographical areas, and therefore have the potential to impact on cetacean populations globally.

There is an immediate need for systematic research regarding the effects of anthropogenic noise on cetaceans. Data are particularly required for mysticetes, and deep diving odontocetes such as beluga whales, beaked whales and sperm whales. The establishment of hearing thresholds and response thresholds to low frequency anthropogenic noise should be a priority, along with studies of the long term impact of behavioural disturbance, auditory damage and masking of acoustic signals. Cumulative effects with other environmental threats, such as pollution and global climate change, must also be considered in assessing the impact of noise.

INTRODUCTION

Many human activities threaten cetacean populations on a local, regional, and even global basis. One of the most controversial threats is noise pollution. Anthropogenic noise in the ocean is a cause for concern because such noise has the potential to cause physiological damage, alter feeding and breeding behaviour, compromise hearing and affect the migration of cetaceans. This paper gives an account of the current scientific knowledge concerning the effects of anthropogenic noise on cetaceans, including the long term significance of these effects, and the direction that future research could usefully take in

this area. Details of underwater sound propagation, anthropogenic noise characteristics and the current knowledge regarding cetacean acoustics are given in Appendices A, B and C respectively.

THE EFFECTS OF ANTHROPOGENIC NOISE

Cetaceans have evolved to rely heavily upon sound for many functions necessary for their survival. Underwater anthropogenic noise is predominantly low frequency, i.e. below 1 kilohertz (kHz), and can reach sound pressure levels¹ (SPL) of over 200dB re 1 μ Pa at source (e.g. icebreakers in the Arctic; Erbe, 1997). There is documented evidence for a range of physiological and behavioural effects of anthropogenic noise on many cetacean species. It is not clear to what extent these effects have long term implications for cetacean populations. However, current information suggests that anthropogenic noise has the potential to affect cetaceans in a number of ways which will reduce fitness at the level of individuals, populations and species. The effects of disturbance, auditory damage, masking and non-auditory tissue damage are discussed below. Indirect effects, such as adverse effects on prey species, are not covered in this review.

Disturbance

Disturbance is the most commonly observed effect of noise on cetaceans, and probably the most difficult to assess in the long term. There is little known about the long term biological effects of behavioural changes on individuals or populations. Even less clear is the biological significance of infrequent and minor disturbances, involving only brief changes in behaviour. Noise-induced disruption of feeding, breeding, migration and care of young has the potential to result in reduced food intake, breeding success or survival rate of offspring. The detrimental impact is likely to be particularly severe in cases where cetaceans are temporarily or permanently displaced from areas that are important for feeding or breeding. The energetic implications of behavioural disturbance are considered below, as well as the adverse effects of noise-induced stress.

Disruption of normal behaviour

Cetacean behaviour varies naturally according to numerous factors, such as the animal's age, sex and state of activity, as well as environmental influences such as the location, season and time of day. The significance of a particular acoustic signal, and the way in which an animal responds to it, may vary according to any of these factors. This means that it is very difficult to establish a baseline against which effects of disturbance can be compared. For example, cetaceans are often less responsive to disturbance when engaged in feeding or mating than when resting (Richardson and Würsig, 1997). Few studies have monitored cetacean behaviour before, during and after exposure to known levels of

¹ Sound is commonly measured using ratios of intensity or pressure, adopting a standard reference for use in the denominator of the ratio. The ratio is stated in decibels (dB). For example, the sound pressure level (SPL) measures the ratio of the sound pressure to a reference pressure of one micropascal (μ Pa). The SPL of the sound at source (the source level) usually refers to the estimated level at a distance of 1 metre (expressed as x dB re 1 μ Pa-m).

anthropogenic noise. In addition, it is rarely known if a behavioural change is a response to a specific noise, rather than to a visual or other disturbance (Richardson *et al.*, 1995a).

A large volume of literature describes disruption of cetacean behaviour due to noise from recreational boats, shipping, industrial activities, seismic exploration, oceanographic tests, sonar, acoustic deterrents and aircraft. Typical short term responses of cetaceans to anthropogenic noise are sudden dives, orientation away from the sound source, changes in vocal behaviour, longer dive times, shorter surface intervals with increased blow rates, attempts to physically shield young, increased swimming speed and departure from the ensonified area. In general, cetaceans appear more sensitive to sound when it is novel, or its intensity level is increasing (Edds and Macfarlane, 1987). Reaction thresholds also tend to be lower for continuous noises than for pulses (Richardson, 1997), and lower for moving, or erratic signals than for stationary ones (Watkins, 1986; Edds and Macfarlane, 1987).

Evidence of disturbance from boats and ships

Schevill (1968) moved among cetaceans in a specially silenced research boat without disturbing them, concluding that most reactions to vessels are a result of the noise emitted, rather than the physical presence of the boat.

Polacheck and Thorpe (1990) found that harbour porpoises (*Phocoena phocoena*) exhibited an avoidance reaction to survey vessels. Evans *et al.* (1994) found that harbour porpoises in South East Shetland avoided vessels of all sizes, sometimes moving right out of the area. They also discovered that porpoises were more likely to avoid infrequent vessels than routine vessels, such as the daily ferry.

Evans *et al.* (1992) examined the effects of speedboats and playback of their sound on bottlenose dolphins (*Tursiops truncatus*) in Cardigan Bay, and observed responses of shorter surface periods, longer dives and movement away from vessels at ranges of 150-300 metres (m). They suggested that quieter boats, travelling at high speed, disturb dolphins more than slower, larger boats, that emit higher intensity noise, as the noise produced by a high speed boat rises above ambient levels for only a short time before its closest point of approach, thereby provoking a startle response.

Belugas (*Delphinapterus leucas*) in the St. Lawrence Estuary were monitored before, during and after exposure to noise from a small motor boat and a ferry. Reactions to the approach of the vessels included reduced diversity of call types and call rates, and repetition of specific calls within 1 kilometre (km) of the vessels. Within 300m, the beluga whales shifted the peak frequency of their signals from 3.5kHz to 5.2-8.8kHz (Lesage *et al.*, 1993).

Finley *et al.* (1990) studied the reactions of belugas and narwhals (*Monodon monoceros*) to ice-breaking ships in the Canadian High Arctic. Belugas reacted with a flee response and narwhals with a freeze response, the characteristics of which were typical of their responses to predation by killer whales (*Orcinus orca*). Belugas avoided the approaching

ships at ranges of 45-60km, and seemed aware of an approaching ship at a distance of 85km (indicated by what were considered to be alarm signals). The reactions began when broad-band (20-1000Hz) received levels of ship noise were 94-105dB re1 μ Pa. The belugas were aware of the ships at far greater ranges than would be predicted from calculations based on captive auditory thresholds², placing some doubt on the applicability of laboratory audiograms to natural situations (Finley *et al.*, 1990). The belugas moved up to 80km from their original location in response to the ship, and remained absent for 1-2 days (Finley *et al.*, 1990; Finley and Greene, 1993). This extreme sensitivity may result from a combination of good sound propagation, and a scarcity of ships in the area (Richardson and Würsig, 1997). Effects on narwhals appeared to be more transient, normal activities being resumed when received broad-band levels were as high as 120dB re1 μ Pa. Stewart *et al.* (1982) also observed beluga avoidance reactions to playback of boat noise at noise levels which they believed would be barely perceptible. They concluded that belugas may be more influenced by habitat and activity at the time of the disturbance, rather than by the intensity of the noise.

Observed responses of sperm whales (*Physeter catodon*) to boats include reduced surface times, with fewer blows per surfacing, shorter intervals between blows and reduced frequency of dives with raised flukes (Gordon *et al.*, 1992).

Bauer *et al.* (1993) found that swimming speed, respiration and social behaviours of wintering humpbacks (*Megaptera novaeanglia*) were affected by vessel traffic, in particular with respect to vessel numbers, speed and proximity. A case study indicated that a calf was sensitised by a large vessel, the calf subsequently breaching in response to noise from a small boat engine, which had not previously elicited a response. Baker *et al.* (1982; 1983 - in Richardson *et al.*, 1995b) studied the responses of feeding humpbacks to vessels. At 2-4km from the vessels the responses included shorter dive times, longer blow intervals and faster swimming speeds. At less than 2km, the responses were longer dive times, shorter blow intervals and slower swimming speeds, i.e. the whales avoided vessels by remaining submerged. Glockner-Ferrari and Ferrari (1985) studied the same humpback population in their breeding ground (Hawaii), and attributed a consistent decrease in the percentage of mothers and calves in inshore waters to high levels of boating activity and aircraft. Green (1991) also found that parasail boats displaced Hawaiian humpback whales, including cow/calf pods, from near shore areas.

Macfarlane (1981 - in Gordon and Moscrop, 1996) noted that fast erratic approaches of boats close to blue whales (*Balaenoptera musculus*) caused flight reactions, separation of pairs of animals, shorter respiration rates, and displacement from the area. Edds and Macfarlane (1987) found that short term flight reactions of blue whales and fin whales (*Balaenoptera physalus*) occurred in response to vessels in the St Lawrence estuary,

² The absolute auditory threshold of a captive beluga to 1kHz tones has been measured at 104dB re1 μ Pa. The critical ratio at this frequency (the amount by which the pure tone signal must exceed the background noise in order to be audible to an animal) has been measured at 17dB (Johnson *et al.*, 1989). According to these measurements, the beluga would be unable to detect icebreaker noise, even at full power, at ranges of more than 20km (Finley *et al.*, 1990).

especially if the vessels were moving at high speed, or erratically.

Grey whales (*Eschrichtius robustus*) in San Diego Bay responded to vessel noise by abandoning calving lagoons, returning only after vessel traffic decreased (Reeves, 1977 - in Richardson *et al.*, 1995b). Bryant *et al.* (1984 - in Gordon and Moscrop, 1996) reported that grey whales abandoned the Guerrero Negro Lagoon for several years while it was subjected to human disturbance, including intense shipping and continuous dredging. After a decrease in shipping activities, grey whales reoccupied the lagoon.

Richardson *et al.* (1985) found that bowhead whales (*Balaena mysticetus*) swam rapidly away from vessels at ranges of 0.8-3.4km, with shorter surface and dive times. The whales were effectively scattered, with mean inter-animal distance increasing from 7.5 to 37 whale lengths, this effect persisting for at least one hour.

Evidence of disturbance from whale watching

There is the potential for whale watching to have a disruptive effect on cetacean behaviour, if the vessels persist in following or remaining near groups of cetaceans for long periods of time. Janik and Thompson (1996) found significant decreases in surfacing frequencies of bottlenose dolphins in response to a dolphin watching boat which attempted to remain near the group. The dolphins showed little response to other boats in the area.

Heimlich-Boran *et al.* (1994) noted significantly longer dive times and closer grouping of short-finned pilot whales (*Globicephala macrorhynchus*) in response to a large number of whale watching boats in the Canary Islands. Respiration patterns were found to normalise eventually, however examples of unusually aggressive behaviour were documented during the observations. Sperm whales in New Zealand avoided commercial whale watching boats at a distance of 2km (Cawthorn, 1992).

Watkins (1986) discovered that responses of baleen whales to boats in Cape Cod waters were variable with species and changed over time. In general, minke whales (*Balaenoptera acutorostrata*), humpback whales and fin whales appeared to habituate to boats, while right whale behaviour remained unchanged. Fin whales in the Gulf of Maine showed significantly reduced dive times, and reduced number of blows per surfacing sequence when whale watching boats were present (Stone *et al.*, 1992).

Evidence of disturbance from industrial activities

Richardson *et al.* (1987) compared the distribution of bowhead whales and industrial activities in the Canadian Beaufort Sea, and speculated that a decrease in bowhead use of the main industrial area since 1980 was a result of cumulative effects of industrial activity which started in 1976. The effects of changing distributions of zooplankton and other environmental factors are not known. Playback studies have found that most bowhead whales avoid drillship or dredging noise with broad-band (20-1000Hz) received levels around 115dB re1µPa, levels that could occur 3-11km from typical drilling and dredging vessels (Richardson *et al.*, 1990). This equates to a response threshold of about 110dB re1µPa in the 1/3-octave band where industrial noise is most prominent. Higher intensity

noise is endured by bowhead whales if the only migration route requires close approach to the sound projector (Richardson and Greene, 1993)

Malme *et al.* (1983; 1984 - in Richardson *et al.*, 1995b) presented playbacks of oil production noises as more than 3500 migrating grey whales swam past a platform. Avoidance responses began at broad-band received levels of around 110dB re1 μ Pa, and increased as noise levels were elevated. More than 80% of whales showed avoidance at received levels over 130dB re1 μ Pa.

Evidence of disturbance from seismic exploration

During seismic surveys a predominantly low frequency, high intensity sound pulse is emitted every few seconds by an array of air-guns, reflected back to the ocean surface by the rock strata, and received by a streamer of hydrophone groups (Evans and Nice, 1996). The sound pressure level depends on the size of the air-gun array.

Goold (1996) monitored common dolphin (*Delphinus delphis*) before, during and after a seismic survey in the southern Irish Sea, and observed an avoidance reaction by the dolphins in the area monitored (1-2km from the survey vessel). The survey employed a 2120 cubic inch air-gun, which is smaller than the arrays typically used by prospecting companies (Goold, *pers. comm.*). Goold and Fish (in press) estimated that the signal would be clearly audible to dolphins at a range of 8km (received spectrum power level at a range of 750m being 90dB re1 μ Pa²/Hz at the 20kHz end of the spectrum).

Evans *et al.* (1993) monitored small cetaceans in the Irish Sea before, during and after seismic exploration. Although most sample sizes were too small for statistical analysis, a significant decline in the number of individual bottlenose dolphins was found, suggesting that a proportion of the population had moved out of the area during the period. It is not known if this movement reflected a response to seismic activity, or seasonal movements.

Sightings surveys show that sperm whales were displaced to a distance of 60km from an area in the Gulf of Mexico, where seismic surveys were taking place (Mate *et al.*, 1994). Sperm whales were also found to stop vocalising in response to relatively weak seismic pulses from a ship hundreds of kilometres away (Bowles *et al.*, 1994). Studies by Rankin and Evans (1998) in the Northern Gulf of Mexico indicate that seismic exploration has a negative impact on aspects of communication and orientation behaviour of sperm whales, but no effects on the distribution of other odontocetes.

In a series of studies using a 4000 cubic inch air-gun array, 10% of grey whales showed avoidance to received broad-band levels of 164dB re1 μ Pa, 50% showed an avoidance reaction at 170dB re1 μ Pa, and 90% at 180dB re1 μ Pa. Whales were seen to move into the shallow surf zone and into sound shadows of rocks (Malme *et al.*, 1983; 1984 - in Richardson *et al.*, 1995b).

Koski and Johnson (1987 - in Richardson *et al.*, 1995b) noted that bowhead whales swam rapidly away from a seismic vessel at a distance of 24km. Ljungblad *et al.* (1988) observed

initial behavioural changes of bowheads more than 8km away, at received noise levels of 142-157dB re1 μ Pa. Richardson *et al.* (1985) found subtle alterations in surfacing, respiration and dive cycles in response to seismic vessels, indicating that the absence of a conspicuous response does not necessarily prove that an animal is unaffected. Richardson *et al.* (1986) observed bowhead whales engaging in normal activities as close as 6km to the vessels, where estimated received levels were 158dB re1 μ Pa.

McDonald *et al.* (1995) acoustically tracked a blue whale while carrying out an air-gun operation, producing a pulse at 215dB re1 μ Pa-m (10-60Hz band). The whale started its call sequence when the air-gun ship was 15km away, and approached the ship to a range of 10km (where it was subject to an estimated received level of 143dB re1 μ Pa). After a gap in calling, the whale started a new call series and moved diagonally away from the ship.

Evidence of disturbance from sonar

Sonar has been used by whalers since World War I. The operational output of military sonar systems is not generally known, however it can be assumed that they emit substantially higher intensity sound than non-military sonar (Richardson *et al.*, 1995b). Operational output of the United States (US) Navy's Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) system is reportedly up to 235dB or more (NRDC, 1998).

Watkins *et al.* (1985) noted that sperm whales reacted to military sonar at distances of 20km or more from the source. Sonar at frequencies of 6-28kHz caused cessation of calling and sometimes avoidance (Watkins *et al.*, 1985; 1993).

A series of playback experiments have recently been carried out to test the impact of SURTASS LFA at received SPLs no greater than 160dB re1 μ Pa. No overt responses have been observed in feeding blue and fin whales off southern California, however a consistent decrease in the number of whales producing long patterned sound sequences has been found (Clark *et al.*, 1998). Deflections in the migratory path of grey whales have been observed during playback, but results have not yet been analysed (C. Clark, *pers. comm.*).

Maybaum (1993) found that humpbacks in Hawaii showed avoidance behaviour in response to playbacks of sonar pulses of 3.3kHz, and sonar sweeps of 3.1-3.6kHz. He postulated that the reactions stemmed from the resemblance between sonar signals and sounds that whales associate with threats or warnings.

Evidence of disturbance from acoustic thermography

The use of sound to study the ocean is widespread, and involves the use of air-guns, sonar, explosions, and sound projectors. Acoustic thermography studies temperature changes by measuring sound speed in the ocean, using long range, low frequency sound (Munk and Wunsch, 1979).

The Heard Island Feasibility Test transmitted sound for one hour of every three, with source levels of 209-220dB re $1\mu\text{Pa}\cdot\text{m}$ at a depth of 175m (the estimated depth of the deep sound channel near Heard island). The centre frequency was 57Hz, with a maximum bandwidth of 30Hz. Sperm whale and pilot whale signals were heard in 23% of 1181 minutes of baseline acoustic monitoring before transmission, but were absent in 1939 minutes of monitoring during transmission (Bowles *et al.*, 1994). Sperm whale clicks were eventually heard 36 hours after the end of the transmission. Sighting samples were too small to estimate changes in densities of cetaceans.

The Acoustic Thermometry of Ocean Climate (ATOC) Program employs two generators, broadcasting sound with an SPL of 195dB re $1\mu\text{Pa}\cdot\text{m}$ in the 35Hz band-width centred around 75Hz (Au *et al.*, 1997). The generators are located 15km from the island of Kauai, Hawaii, and approximately 89km south west of San Francisco, California (MMC, 1998). Aerial surveys off central California showed that humpback and sperm whales were distributed significantly further away from the ATOC source during sound broadcast (Calambokidis *et al.*, 1998). Studies using playback of low intensity ATOC sounds have elicited few responses from sperm whales and humpback whales (Gordon *et al.*, 1998; Frankel and Clark, 1998). Au *et al.* (1997) measured hearing thresholds of a captive Risso's dolphin (*Grampus griseus*) and a false killer whale (*Pseudorca crassidens*) to a one-second pulsed ATOC signal. Both species had relatively high thresholds to the sound (139-142dB re $1\mu\text{Pa}$), indicating that the dolphins would have to dive to a depth of around 400m, directly above the source, in order to detect the sound.

Evidence of disturbance from acoustic deterrents

Acoustic alarms are being developed for use in deterring marine mammals from certain areas. Acoustic deterrent devices (ADD) are used in gillnet fisheries, and more powerful acoustic harassment devices (AHD) are used to deter mammals from aquaculture pens (Taylor *et al.*, 1997).

Devices emitting 300 millisecond pulses, with a broad-band source level of 132dB re $1\mu\text{Pa}\cdot\text{m}$ and fundamental frequency of 10kHz, were effective in dramatically reducing harbour porpoise by-catch in fishing nets (Kraus *et al.*, 1997). The sound levels were chosen to be audible at 15dB re $1\mu\text{Pa}$ above ambient sound levels at a distance of 100m. It is not known whether the reduction in porpoise by-catch resulted from a direct effect of noise on porpoises, or an indirect effect on their preferred food (herring).

A study to repel whales from ferry routes in the Canary Islands using playback of a variety of sounds found that sperm whales reacted strongly to 10kHz pulses, particularly when breathing at the surface after a long dive (André *et al.*, 1997).

Evidence of disturbance from aircraft

Most observations of aircraft disturbance have been made from the disturbing aircraft itself, greatly limiting what can be observed, and precluding comparison of behaviour before, during and after disturbance.

Richardson *et al.* (1985) observed avoidance reactions of bowheads when aircraft approached or circled at or below 305m above sea level. Bowhead whales were less responsive to passing aircraft when actively engaged in feeding, social activities or mating, than when resting (Richardson *et al.*, 1995a).

Malme *et al.* (1984 - in Richardson, 1997) observed reactions of grey whales to playback of helicopter noise. Three simulated passes per minute elicited minor avoidance reactions in 50% of the whales, at received broad-band pressure levels of 120dB re1 μ Pa. The playback excluded the strong low frequency components of helicopter noise.

Box 1 Displacement of Cetacean Populations

There are many documented cases of cetacean abandonment of areas that have been subjected to a high level of anthropogenic noise. A lack of knowledge regarding other environmental factors usually precludes the establishment of an undisputed direct causal link between the displacement and anthropogenic noise.

Displacement of populations of bottlenose dolphins (Evans *et al.*, 1993), harbour porpoises (Evans *et al.*, 1994), beluga whales (Finley *et al.* 1990), and sperm whales (Mate *et al.*, 1994) has been reported in association with seismic exploration and vessel traffic. It is thought that humpback whales (Glockner-Ferrari and Ferrari, 1985; Green, 1991), blue whales (Macfarlane, 1981 - in Gordon and Moscrop, 1996), grey whales (Bryant *et al.*, 1984; Reeves, 1977 - in Richardson *et al.*, 1995b), and bowhead whales (Richardson *et al.*, 1987) have abandoned areas in response to boating activity, aircraft, and industrial activity such as dredging.

The direct effect of displacement on whale populations is not known, however it is conceivable that displacement from important areas, such as near shore breeding and calving grounds (e.g. Reeves, 1977; Glockner-Ferrari and Ferrari, 1985; Green, 1991), will have a detrimental impact on population survival and growth.

Energetic implications

Some species of marine mammal have finely tuned energy budgets (Brodie, 1981 - in Richardson *et al.*, 1995b; Reijnders, 1992), and additional stresses may reduce their survival or reproductive capabilities. If an individual does not carry 'spare' energy, any unusual disturbance is likely to affect its potential for survival. This concern is particularly pressing in the case of pregnant or lactating females, and young calves. Male blue and fin whales need to increase their body weight by at least 50% during summer, in order to survive the winter months, while pregnant females must attain an increase in body weight of about 60-65% (Lockyer, 1981a). In the case of newly mature female sperm whales, the extra energy required for pregnancy equates to a 10% increase in food intake, while lactation requires a 63% increase in food intake (Lockyer, 1981b). If optimum feeding conditions are infrequent, temporary displacements could have significant energetic consequences, particularly if they occur repeatedly during the feeding season (Richardson *et al.*, 1991).

Fortuna *et al.* (1998) analysed respiration patterns of bottlenose dolphins in various behavioural states. 'Diving' was found to be the most energetically expensive, followed by 'dive-travelling' and 'following a fishing boat'. This indicates that repeated disturbance causing a diving response (which has been observed in baleen and toothed whales,

Richardson *et al.*, 1985; Gordon *et al.*, 1992; Janik and Thompson, 1996) is energetically very demanding. In addition, if disturbance causes early diving and shorter surface time, there will be less time on the surface to replenish oxygen supplies so dive times will be shorter. This means that the same amount of time and energy will be spent on travelling for a shorter feeding period. Dives will also be more costly if the animal is pushed beyond its aerobic limit and incurs an oxygen debt. Thus deep diving whales, such as sperm whales, beaked whales and pilot whales, may be particularly vulnerable to adverse effects of disturbance from noise (Gordon and Moscrop, 1996).

Stress

Long term stress-mediated effects due to noise include lowered resistance to disease, and endocrine imbalances which may affect reproduction (Geraci and St. Aubin, 1980). Stressed mammals commonly produce increased levels of the hormone corticotrophin (ACTH), which controls the secretion of adrenal hormones, such as corticosteroids (e.g. cortisol) and catecholamines (e.g. adrenaline), by the adrenal cortex. Chronic activation of the adrenal cortex may lead to harmful physiological effects (Seyle, 1973). Increased levels of cortisol, for example, result in a reduction of white blood cells that are responsible for immune response (Gwazdauskas *et al.*, 1980).

Cetaceans exhibit stress symptoms similar to other mammals, and may be especially sensitive to over-stimulation of the adrenal cortex in the face of pre-existing stress (Thomson and Geraci, 1986). It is therefore possible that cetaceans residing in areas affected by continuous, high level noise, such as shipping lanes or coastal areas, are persistently at risk from noise related stress. In particular, the additive effects of noise and stress-inducing human activities, e.g. harassment by fishing boats, could be severe in these areas.

Stress can be indicated by certain cetacean behaviours. For example, Heimlich-Boran *et al.* (1994) noted unusual aggressive behaviour of Hawaiian pilot whales, apparently in response to large numbers of whale watching boats. The continued presence of cetaceans in areas with many ships, fishing boats, and other noisy activities, suggests that some species habituate to man made noise. Habituation has been indicated in various odontocete and mysticete species in response to vessels (Evans *et al.*, 1993; Watkins, 1986). It is rarely known however, whether more cetaceans were present before the activities began, or whether there are suitable alternative habitats for the cetaceans to move to. Brodie (1981 - in Richardson *et al.*, 1995b) noted that animals are likely to stay in an area, despite disturbance, if there are no alternative sites that meet their requirements, and that this may induce stress.

Document evidence of human-induced stress in cetaceans

Thomson and Geraci (1986) found that bottlenose dolphins, when chased and captured, exhibited increased levels of cortisol, and associated decreased levels of white blood cells. Animals that already had elevated levels of cortisol due to handling showed no further increase in cortisol levels in response to injections of ACTH, suggesting that the adrenal cortex was already maximally stimulated. Two of the dolphins given ACTH died.

In the only direct study published to-date, no indicators of stress were found in captive cetaceans subjected to noise. Thomas *et al.* (1990) subjected four captive belugas to playback of noise from a drilling platform (source levels 153dB re1 μ Pa-m). Levels of blood catecholamines (adrenaline and noradrenaline) were not found to be elevated after playback, and no significant behavioural changes were observed. Thomas *et al.* (1990) noted the possibility that captive whales are habituated to low frequency noise from water pumps, and advised caution in applying the results to free-ranging belugas in the absence of long term monitoring.

Hearing Impairment

Hearing impairment due to anthropogenic noise can occur by two different mechanisms: direct physical damage to the auditory system; or *masking* of the signal of interest by the noise. In each case, the ability of cetaceans to detect acoustic cues will be reduced.

Auditory damage

The potential for sound to damage auditory structures has been extensively demonstrated in humans and terrestrial mammals. Temporary loss of hearing, (i.e. a temporary elevation of hearing threshold) is known as a Temporary Threshold Shift (TTS). Sound levels that cause TTS in mammals after short exposure appear to be similar to those causing a Permanent Threshold Shift (PTS) after long exposure (Richardson *et al.*, 1995b). PTS can also occur instantaneously from exposure to very high sound levels, such as during an explosion (Scheifele, 1997). Recent anatomical and behavioural studies suggest that cetaceans may be more resistant than many land mammals to TTS, having evolved in a relatively high noise environment. Data suggest, however, that they do suffer from hearing loss as a result of increasing age (Ketten, 1998; Ridgway and Carder, 1997).

Studies of potential or actual auditory damage

Ridgway *et al.* (1997b) studied four bottlenose dolphins and two beluga whales for temporary shifts in masked hearing thresholds, using one second tones at 3, 10, 20 and 75kHz. The dolphins began to show measurable TTS at received levels of 192-201dB re1 μ Pa, depending on frequencies and individuals. One beluga showed no TTS at the highest intensity studied (201dB re1 μ Pa), while the other showed TTS at a level of 198dB re1 μ Pa (Ridgway *et al.*, 1997b).

By converting the Occupational Safety and Health Administration (OSHA) standards for humans to underwater standards for cetaceans, Scheifele (1997) concluded that levels of noise that could cause PTS in belugas (at frequencies of 500Hz, 1kHz and 10kHz) were occurring in two out of three sites studied in the Saint Lawrence River Estuary. As noise levels varied over the day, it is unlikely that the beluga population was subjected to the OSHA criterion for PTS in humans, which is exposure for about eight hours a day, for ten years. Scheifele noted however that a number of the assumptions made in the conversion were sufficiently conservative to reasonably expect PTS to occur at lower noise levels than predicted.

Taylor *et al.* (1997) calculated that harbour porpoise could suffer severe disturbance and temporary loss of hearing within 1km of an AHD used on fish-pens. Immediate auditory damage and injury could occur within 7m of the device. This is of particular concern as some devices can be triggered at full power, either manually or by net sensor.

Masking

Masking is the increase in hearing threshold for one sound due to the presence of another sound (Erbe, 1997). Fletcher (1940 - in Johnson *et al.*, 1989) suggested that masking of a signal is especially pronounced if the frequency spectrum of the masking noise overlaps within a *critical band* around the frequency of the signal. The wider the critical band, the more likely the noise is to have a masking effect on cetacean signals.

Most anthropogenic underwater activities produce predominantly low frequency sound. This noise could potentially mask the communication signals of baleen whales, and some toothed whales, such as sperm whales, belugas and narwhals, that commonly use frequencies below 1kHz. Continuous noise is thought to be more disruptive than pulse signals (Richardson *et al.*, 1995b), and low frequency sounds are thought to have a greater masking effect than high frequency sounds (Erbe, 1997). Specific data on low frequency masking effects are lacking, and no direct measurements have been made for baleen whales.

Strategies to increase the detectability of echolocation and communication signals, such as increasing frequency and intensity level, have been observed in belugas (Au *et al.*, 1985; Lesage *et al.*, 1993) and dolphins (Au, 1993). Despite these strategies, it is likely that the efficiency of communications will be reduced, which in turn could limit ways of overcoming stressful or dangerous events (Lesage *et al.*, 1993). Gordon and Moscrop (1996) suggest that the ability to detect low intensity sounds is likely to be of considerable importance to the well-being of cetaceans. Long range calls appear to be more susceptible to masking by ship noise than are short range calls (Cosens, 1993). If cetacean communication signals are masked by anthropogenic noise, there will be obvious implications for population cohesion and other social interactions.

Masking studies

Masking effects have mostly been studied in relation to high frequency echolocation signals and white noise (Au, 1993). Masked hearing thresholds in the presence of low frequency noise have been studied with respect to the beluga whale (Erbe, 1997; Johnson *et al.*, 1989).

Erbe (1997) studied the masking effects of icebreaker noises in the Arctic on the acoustic signals of trained captive belugas, and developed *maskograms* to illustrate zones of masking around the various noises. Icebreaker bubbler systems (SPL 194dB re1 μ Pa-m) had a maximum radius of masking of 15km, while propeller noise (SPL 203dB re1 μ Pa-m) had a masking radius of 22km. Contrary to previous studies, ambient noise from naturally occurring ice-cracking events did not appear to contribute to the masking of beluga signals.

Experiments with echolocating dolphins have shown that their target detection and discrimination capabilities can be severely reduced by the introduction of masking noise (Au and Nachtigall, 1993). Au *et al.* (1985) produced quantitative evidence that some cetaceans can shift the frequency and intensity level of their vocalisations in response to the masking effects of ambient noise. A beluga whale was moved from San Diego Bay to Kaneohe Bay, Hawaii, where ambient noise levels were typically 12-17dB re1 μ Pa higher. The whale produced echolocation clicks with higher frequencies (increasing from peak frequencies of 40-60kHz to peak frequencies of 100-120kHz) and of higher intensity (approximately 18dB) in Kaneohe Bay. Similar effects on communication signals have been documented by Lesage *et al.* (1993) in the response of belugas to boat noise, and by Au (1993) in bottlenose dolphins.

Grey whales also modify calls to optimise signal transmission and reception, in response to increasing levels of playback noise (Dahlheim, 1993). It has been suggested that grey whales have evolved to function in a particular ambient noise environment, and that they may therefore be especially sensitive to change in that environment (Crane and Lashkari, 1996).

Detrimental effects of hearing impairment

Masking and auditory damage will affect the ability of individual animals to detect acoustic cues from echolocation, conspecifics, natural sources and anthropogenic sources. These cues are likely to be vital for navigation, location of food, social interaction (including cooperative feeding bouts and the maternal bond), mating and migration (see Appendix C). Adverse effects on any of these activities could have a long term detrimental impact on cetacean populations. At the most extreme, mortalities could occur from predation, collision with boats (André *et al.*, 1997), entanglement in fishing nets (Todd *et al.*, 1996), or the inability to obtain food (Popper *et al.*, 1997). Therefore, masking, temporary hearing loss (TTS) *and* permanent hearing loss (PTS) can have implications for the long term welfare of individuals and populations of cetaceans.

A high rate of entrapment of humpback whales in fishing nets is usual in Newfoundland, due to concurrent high densities of humpbacks whales and high levels of fishing activity. However, the rate of entrapment in Trinity Bay, as a percentage of the total for Newfoundland and Labrador, increased from 5.48% in 1990 to 23.73% in 1992. This coincided with the onset of intense industrial activity in the Bay, consisting of drilling activity and underwater explosions, with typical peak source levels of 140-150dB re1 μ Pa-m near 400Hz. Two whales that were found dead near the explosions showed evidence of substantial mechanical trauma (in both ears of each animal), consistent with blast injury in humans (Ketten *et al.*, 1993). It is likely that the dead whales were killed by the explosions. Furthermore, during this period of industrial activity, two entrapped and released humpbacks were recognised as animals that had been entrapped before, a circumstance that had not been previously observed in Newfoundland by any members of the research team. Todd *et al.* (1996) studied the behaviour of the humpback population and found no discernible reactions to noise. They concluded that the most probable explanation for the increase in entrapment rate, and the observed lack of behavioural

response to noise disturbance, was a decreased sensitivity of humpbacks to acoustic cues, as a result of hearing damage, brought on by long term exposure to the industrial noise.

Two sperm whales, a mature female and a male calf, were struck by a cargo ship off Gran Canaria and killed. The whales were resting at the surface between feeding dives, and made no attempt to avoid the vessel (weather and sea conditions were calm). Computerised tomography scans showed that ears from both animals had reduced auditory nerve volumes. In addition, one animal had patches of dense tissue in the inner ear. There were no fractures or evidence of previous collision related injuries. Preliminary findings were consistent with auditory nerve degeneration and fibrous growth in response to inner ear damage (André *et al.*, 1997). When sperm whales in the area had been subjected to playback of low frequency noise they had exhibited no behavioural responses (compared to strong responses to 10kHz sounds). In conjunction with the scan results, this suggests that noise from shipping had impaired the hearing thresholds of the sperm whales for low frequency sound, increasing the probability of collision with vessels (André *et al.*, 1997).

Non-Auditory Physical Damage

Shock waves from high level sound can result in tissue damage, particularly at interfaces between tissues of different density (Turnpenny and Nedwell, 1994). As marine mammals contain air spaces in their lungs and gastrointestinal tract, it is possible that these organs are particularly vulnerable to damage from shock waves (Richardson *et al.*, 1995b). Obviously, marine mammals in the vicinity of large explosions are likely to suffer fatal injuries to tissues and organs. In some areas this may be common enough to have significant long term effects on populations (Baird *et al.*, 1994). Although it has previously been accepted that animals would move away from an area before sound levels became uncomfortably high, the fact that no overt behavioural reactions to industrial noise were observed in an area where two whales were killed by explosions, suggests that this may not always be the case (Lien *et al.*, 1993).

Evidence of physical effects

There are no specific data documenting physical damage to tissues as a result of exposure to anthropogenic noise. However, it is unlikely that the noise-induced mortalities that have been recorded are isolated cases, given that dead cetaceans are rarely subjected to post-mortem examination.

A decline in the number of Irrawaddy dolphins (*Orcaella brevirostris*) in Lao PDR and north-eastern Cambodia has been linked to incidental mortalities from explosives used by fishermen (Baird *et al.*, 1994).

Crum and Mao (1996) found that close proximity of marine mammals or humans to low frequency noise at SPLs in excess of 210dB re 1µPa at 500Hz could result in significant growth of existing bubbles in capillaries and other small blood vessels. Although noise of this intensity is rare, they suggested that considerably lower intensity noises could induce

bubble growth if the body fluid was already super-saturated with gas. This occurs when human divers using breathing apparatus are near decompression limits. Some cetaceans make repeated dives to great depth which may produce over-pressure of nitrogen in muscle tissues (Ridgway and Howard, 1982), therefore it is theoretically possible for intense sounds to induce the pathological conditions associated with bubble growth (“the bends”) in cetaceans (Ridgway, 1997).

Taylor *et al.* (1997) calculated that harbour porpoise could suffer tissue damage within 7m of an AHD (see earlier section on hearing impairment).

Box 2 Cetacean Strandings

Frantzis (1998) has linked a mass stranding of 12 Cuvier’s beaked whales in the Kyparrisiakos Gulf, Greece, to noise from tests of the North Atlantic Treaty Organisation’s Low Frequency Active (LFA) sonar. The LFA system can output broad-band pressure levels up to 230dB re1µPa, centred at frequencies between 250 and 3000Hz. The tests were carried out from 11th May to 15th May, 1996, and the strandings occurred on the 12th and 13th of May. Given that Cuvier’s beaked whales are deep diving, rarely strand, and in this case did not strand at the same place (mean distance apart was 3.5km), it is unlikely that the strandings and the sonar testing were independent events. Autopsies on the dead whales revealed no diseases or physical abnormalities, and the animals had recently fed. The estimated probability of a mass stranding occurring for other reasons during the period of testing was less than 0.07% (Frantzis, 1998). Simmonds and Lopez-Jurado (1991) also reported an occurrence of beaked whale strandings in the Canary Islands that coincided with the times at which naval fleets had been operating sonar in the area.

Simmonds and Mayer (1997) have speculated that a spate of multiple sperm whale strandings (24 in the winter of 1994-1995) in the North Sea and north of Scotland could have resulted from a deflection in the normal southerly migration route due to seismic and other industrial noise in the area west of the Shetlands. It is thought that the North sea is out of the normal range of sperm whales, as it is shallow, and lacks their usual prey of Arctic squid.

Three dead humpback whales were found close to the ATOC source in California, between September and November 1995. It is thought likely that the ATOC source was in operation for engineering tests during the estimated times of death for all three whales (Hall, 1996). One week after ATOC transmissions began in Hawaii, a dead whale (probably a humpback or sperm whale) was sighted by fishermen near the sound source, although this report was unconfirmed (Clark and Frankel, 1997). A dead juvenile sperm whale was washed up on the north-east shore of Oahu, Hawaii shortly after. The fact that sperm whale strandings are rare in Hawaii (ten strandings in 58 years) has caused concern that the ATOC sound source may be linked to the recent deaths (Weilgart, 1998). As autopsies were not carried out for any animal, any association with anthropogenic noise is speculative.

ZONES OF INFLUENCE AND DATA REQUIREMENTS

One way of attempting to assess the effects of noise on cetaceans is the concept of zones of influence (Richardson and Malme, 1995). Four zones are proposed: audibility; responsiveness; masking; and hearing loss, discomfort or injury. The zone of audibility is taken as the maximum potential radius of influence. It is limited either by the hearing threshold of the individual, or by the intensity of the sound related to ambient noise in that frequency range. It is assumed that animals do not always respond to sound that they can

detect, therefore the zone of responsiveness is usually smaller than the zone of audibility. In addition to the properties of the influencing sound, the extent of the zone of responsiveness will depend on a number of factors, including type of response, species, sex, age, activity and habitat. The zone of masking is determined chiefly by the properties of the anthropogenic noise and ambient noise, and the properties of the sound signal of interest. Other variables, such as directionality of the noise and the signal, and the hearing capabilities (such as frequency discrimination) of the cetacean, will also affect the zone of masking. Finally, the zone of hearing loss, discomfort or injury is presumed to be the smallest zone, where physical damage to the individual can occur.

The zones of influence concept can be used to establish mitigation measures to limit the impact of anthropogenic noise on cetaceans. By combining information on average ambient noise levels, known hearing ranges of cetaceans, source levels of anthropogenic noise and likely propagation conditions, it is possible to make some predictions of where anthropogenic noise is most likely to affect cetaceans. In attempting to estimate these zones, significant data gaps are apparent.

Data Requirements in Estimating Zones of Audibility

To estimate the zone of audibility, details of the anthropogenic sound, ambient noise level, and propagation conditions are required. In addition, the absolute hearing threshold of the cetacean species is needed for a range of frequencies, in particular for the dominant frequency of the noise in question. Hearing thresholds are a major data gap when trying to assess the impact of noise on cetaceans. There are no direct measures for baleen whales, and audiograms established for toothed whales are based on very small sample sizes (usually one or two individuals), and often not measured for low frequency noise. The effects of intra-specific variability and the effects of age on hearing thresholds are not known, even in the most studied species. Furthermore, most studies have measured thresholds for pure tones against white noise, whereas important sounds are often broadband against ambient noise (which varies in amplitude over frequency). Carder and Ridgway (1994) have developed a portable system that can present sound stimuli between 20Hz and 200kHz, to conduct hearing tests on stranded whales. Recent studies have used long duration, amplitude-modulated tones (rather than transient stimuli), thus widening the applicability of auditory evoked potentials (see Appendix C) to cetacean auditory thresholds (Dolphin, 1997).

Recent beluga audiograms at depths of 300m indicate that whales hear as well at depth as near the surface, although further studies are needed in this area. Zones of influence are therefore likely to be just as great throughout the depths to which whales dive (Ridgway *et al.*, 1998). Sperm whale foraging dives have been recorded at depths of more than 2000m (Watkins *et al.*, 1993), and depths of 1000m have been recorded for the narwhal, this being the maximum range of the depth transducer used (Heide-Jørgensen and Dietz, 1994). Beaked whales are also thought to be deep diving whales (Simmonds, *pers. comm.*). Deep diving whales may be at particular risk from low frequency tests such as ATOC, which emits sounds at a depth of 900m.

Data Requirements in Estimating Zones of Responsiveness

To estimate this zone, the response threshold of the cetacean species to the anthropogenic noise is required. This threshold should be specified accurately, so that it is meaningful and applicable to other studies and situations. For example, Malme (1993) found that more than or equal to (\geq) 50% of grey and bowhead whales will avoid continuous industrial sound levels $\geq 120\text{dB re } 1\mu\text{Pa}$, whereas to elicit the same response for half second air-gun pulses, effective SPLs 30 to 50dB higher are required. Responses that may be particularly useful indicators are those that can be related to stress behaviour, or energetic aspects of the disturbance. Response thresholds will vary according to the individual, the activity, habitat, time of year. The properties of the disturbing sound, other than frequency and intensity, must be also be taken into account as they can contribute to its disruptive effect e.g. bearing, rate of change of bearing, rate of increase in intensity, and similarity to other known noises. Therefore, observations need to cover a range of individuals and situations in order to establish a general zone of responsiveness of a particular species for a particular sound. A significant data gap is the effect of combinations of sound sources, e.g. seismic pulses, combined with the 'looming' noise effect of an approaching ship.

Any behavioural responses need to be assessed against a background of undisturbed behaviour monitored over a sufficiently long period of time. Such baseline data is very rarely available. Other environmental factors that may affect cetacean behaviour, such as prey distribution, must also be established (Richardson *et al.*, 1985). There are few data on repeated disturbance, and whether or not cetaceans habituate or sensitise to the noise in these cases.

Controlled playback experiments in the field are able to provide much of this information, however responses to the sound itself must also be studied, if only because few sound projectors are powerful enough to simulate all man made noises, particularly the very low frequency components of the sound (Gordon, *pers. comm.*). Behavioural reaction thresholds need to be examined in captive animals and free-ranging animals, to give an idea of how well these two different measures correlate. Evidence suggests that captive mammals may have a higher tolerance to noise than free-ranging mammals (Finley *et al.*, 1990; Richardson, 1997).

In most documented disturbance reactions, specific measurements of the anthropogenic sounds have not been made (Richardson and Würsig, 1997). It is not clear whether it is more useful to report sound levels as received levels, source levels, or levels above ambient. It appears that the 1/3-octave bandwidth basis is most consistent with the properties of mammalian hearing (Richardson and Malme, 1995). On the other hand, policy makers may be more interested in the distance from the sound source at which the zone is measured. Clearly, the more information reported, the easier it is to compare results with other studies, and thus ensure that all new information obtained can contribute to policy making. Useful information could result from the use of time depth recorders in conjunction with acoustic data loggers, providing data on diving behaviour and sound exposure respectively.

Data Requirements in Estimating Zones of Masking

Data on masking effects are limited to a few odontocete species, and are absent for mysticetes. As with hearing thresholds, most data concern detection of pure tones against a white noise background. Cetaceans are often exposed to non-tonal anthropogenic noise combined with natural background noise that varies across frequency and time (Erbe, 1997). In addition to information on masked auditory thresholds, basic data are required regarding the ability of cetaceans, and mysticetes in particular, to discriminate sounds using differences in signal frequency and intensity (Popper *et al.*, 1997). There are no direct data on low frequency directional hearing for marine mammals, however it may be limited due to the longer wavelengths of low frequency sound (Erbe, 1997).

If some whales can communicate over great distances, the zone of masking by anthropogenic noise could be immense. Infrasonic calls from blue whales have been detected at distances greater than 1000km (D. Mellinger, in Richardson *et al.* 1995b). Studies underway using the US Navy's fixed array system, the Integrated Undersea Surveillance System, may assist in providing further data regarding communication ranges (Clark *et al.*, 1997).

Data Requirements in Estimating Zones of Hearing Loss and Tissue Damage

Data relating to noise-induced physiological damage are almost entirely lacking, and data on sound levels that induce TTS and PTS are also scarce. Mysticetes and many odontocetes are not amenable to psychoacoustic testing in captivity. Physiological studies, such as auditory evoked potentials, could provide important information regarding auditory thresholds and TTS values on stranded or entrapped animals. It has been suggested that TTS data are applicable as indicators of sounds that might ultimately cause PTS (Richardson and Würsig, 1995).

The sound pressure levels that cause tissue damage need to be established, although for ethical reasons, direct studies are undesirable. Post-mortem examination of the inner ears of stranded cetaceans could provide a great deal of information, particularly if combined with behavioural observations in the area.

Data Requirements to Assess Long Term Impact

Once the zones of influence have been established, there is a fundamental difficulty in assessing the key long term effects, so that criteria can be designed that effectively mitigate the negative impact of anthropogenic noises.

One of the first steps is to assess the functional significance of cetacean calls, and the components of cetacean vocalisations which are of greatest importance. We can only then assess the long term significance of *not* hearing them (Edds-Walton, 1997). In particular, the importance of weak acoustic signals to cetacean communication is not known. At the most basic level it is not clear what behaviours are associated with mysticete

communication sounds, and the ranges over which mysticetes can communicate (Popper *et al.*, 1997). In addition, data is required regarding the long term impact of disturbance, including the effects of increased energy expenditure and stress associated with the disruption of normal behaviour patterns. These data needs are overwhelming, but new methods are being continually developed (Yazdi *et al.*, 1998).

CONCLUSIONS

The physiological and behavioural impact of anthropogenic noise may be detrimental to cetacean populations world-wide. The evidence indicates that some cetaceans are exposed to high levels of anthropogenic noise over a large percentage of important feeding and breeding habitats. It is therefore likely that short term and long term disruption of critical breeding or feeding behaviours will pose greater threats to entire populations of animals, than more obvious physical effects from exposure of a few individuals to extremely high noise levels.

Current data suggest that anthropogenic noise in the ocean can result in hearing impairment, either through auditory damage or masking effects, and that this will reduce the ability of cetaceans to detect acoustic signals which may be vital for navigation, social interaction, mating, migration, and the location of food. It is possible that anthropogenic noise, in conjunction with other human activities, is causing an increase in incidents of entanglement in fishing nets, collisions with vessels, and mass stranding events. Coastal ecosystems are already threatened by pollution, over-exploitation of natural resources, increases in shipping and recreational boating, development and global climate change (De Fontaubert *et al.*, 1996). The synergistic interactions of these environmental threats, in conjunction with exposure to continuous anthropogenic noise, are likely to have the most severe consequences for cetacean populations in coastal areas, particularly where populations are already depleted.

The long term effects of military sonar and oceanographic experiments that employ low frequency sound, such as the Acoustic Thermography of Ocean Climate Program (ATOC), are not known. Although on-going behavioural studies will provide valuable information, limited access to information regarding the operational output and geographical employment of military sonar is a cause for concern, particularly in the light of recent strandings of beaked whales (see Box 2). The ATOC source is specifically designed to project sound over a vast geographical area, and therefore has the potential to effect cetacean populations on a global scale.

Given that these are the areas of concern, the immediate research needs are:

- the establishment of audiograms in relation to low frequency sound, in particular for baleen whales;
- studies to assess the functional significance of communication signals, and the ranges over which they are used;
- controlled systematic behavioural studies, taking into account the effects of more than one anthropogenic source, and assessed against a background of undisturbed

- behaviour monitored over a sufficiently long period of time;
- controlled systematic behavioural studies, taking account of other environmental factors such as pollution, prey movements and migratory movements;
 - studies to establish the impact of short and long term behavioural disruption, including abandonment of important feeding and breeding habitats, energetic implications, and the effects of stress;
 - post-mortem examinations on stranded cetaceans, that include the examination of inner ear structures.

It is important that research effort focuses on mysticetes, as they are presumed to be more sensitive to, and dependent on, low frequency sound than odontocete species. However, deep diving odontocetes such as beaked whales, narwhals and belugas are also likely to be at risk from the effects of anthropogenic noise, and the sperm whale may deserve special attention as it is very acoustically oriented, dives to great depths, and has a particularly long breeding cycle (Watson, 1981). Any long term impact studies must take into account the effects of other environmental threats to cetaceans, as synergistic interactions are likely to be of primary importance, particularly in coastal areas.

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