Report of the Ad-hoc Group on the Impacts of Sonar on Cetaceans and Fish (AGISC) (2nd edition)

By correspondence

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Contents

1   Introduction

This is the second edition of our report. A first edition, covering effects on physical background, sonar usage and effects and mitigation in relation to marine mammals was produced early in 2005. This second edition contains improved sections on physical background and mitigation for marine mammals, and an entirely new section on fish.

1.1   Participation

The following members of the Ad hoc Group on the Impact of Sonar on Cetaceans and Fish (AGISC) participated in producing this report (see Annex 1 for addresses).

Tony Hawkins	UK
Finn Larsen	Denmark
Mark Tasker (chair)	UK
Chris Clark	USA
Antonio Fernández	Spain
Alexandros Frantzis	Greece
Roger Gentry	USA
Jonathan Gordon	UK
Tony Hawkins	UK
Paul Jepson	UK
Finn Larsen	Denmark
Jeremy Nedwell	UK
Jacob Tougaard	Denmark
Peter Tyack	USA
Tana Worcester	Canada

1.2   Terms of Reference

At the MCAP meeting January 2004, an Ad hoc Group on the Impact of Sonar on Cetaceans and Fish (AGISC) was established and was given the following terms of reference:

  i.   Review and evaluate all relevant information concerning the impact of sonar on cetaceans and fish;

  ii.   Identify the gaps in our current understanding;

  iii.   Prepare recommendations for future investigations and research;

  iv.   Prepare draft advice on possible mitigation measures to reduce or minimize the impact of sonar on cetaceans and fish.

1.3   Justification of Terms of Reference

The terms of reference derive from a letter from Catherine Day (Director General of EC DG Environment) to David Griffith (General Secretary, ICES), dated 25 September 2003. In this letter, the European Commission indicated that it had for some time received complaints about the impact of sonar on marine mammals. These complaints claimed that the emission of intense, low and medium frequency tone bursts has a disturbing effect on cetaceans. Information had also been forwarded indicating that these sonars might have an impact on fish and fish behaviour.

European legislation (mainly the Habitats Directive (92/43/EC)) requires Member States of the European Union to take measures to establish a system of strict protection for all cetaceans in European waters. The European Commission does not have a comprehensive and

authoritative review of information concerning the impact of sonar, and thus finds it difficult to develop a clear position on the issue.

The Commission therefore asked ICES to undertake a scientific review and evaluation of relevant information concerning the impact of sonar on cetaceans and fish, to identify the gaps in current understanding and to make recommendations for future investigations or research. The Commission is also interested in advice on possible mitigation measures to reduce or minimise the impact of sonar on cetaceans and fish.

1.4 Framework for response

The Group's response to these terms of reference has been compiled by correspondence. Sections were initially drafted by Group Members and then agreed by circulation to all members. Much of the report is based on existing review literature (not all relating to sonar directly), updated and amended as appropriate.

1.5 Overview by the chair

The effects of human inputs to natural systems have been a topic of interest and study for many years, however much the greatest amount of work has been carried out on chemical inputs, both in the form of contaminants and nutrients. The subject of energy input has historically received much less attention. The anthropogenic input of sound to the marine environment started with the coming of mechanically propelled ships, but until the advent of sonar, nearly all sound input was a by-product of another activity as opposed to deliberate. Both forms of input though carry the risk of affecting other marine life. Evidence has been available for some time that anthropogenic noise has the capacity to disturb those forms of marine life dependent on sound for communication and sensing in the seas. Much less evidence has been available on damage, injury or lethal consequences at the individual level, and none at the population level. A series of incidents in recent years when certain deep-diving whale species stranded or died co-incident with the use of high-powered sonar alerted many more to the risks posed by sound. Research elsewhere indicated that other forms of loud sound might affect fish.

The behaviour of sound in the marine environment is complex and is equally complex to describe. We have attempted to describe the physical background briefly in the first main part of this report, but are aware that this may be too brief and simplistic for some. We refer those readers to standard texts for further information. This section includes a brief description of the types of sonar in use today. It proved difficult to find information on the characteristics of many forms of sonar.

The next section of the report deals with the mechanisms for hearing in cetaceans and describes the potential effects of sound on these mechanisms and the behaviour of these animals. Until recently, most concern has focussed on the effects on hearing and communication systems of cetaceans but recent evidence is indicating that damage may also be caused through other mechanisms, and perhaps indirectly through dangerous alterations in behaviour. There is however little experimental evidence currently in the public domain of the effects of sonar on the acoustic systems, physiology or behaviour of cetaceans. Logistically, any such experiments are easiest to conduct in the laboratory on individual animals, but extrapolating the few available items of information to wild populations is at present very difficult and uncertain.

Section 4 reviews observations and deductions from cases where whales have stranded or been found dead in association with the nearby use of military sonar. As with many observational cases, obtaining the best and most pertinent evidence proved difficult both from the corpses and in other cases of strandings, from the military authorities. In order to improve

deductions, we ideally need to complete three of four cells in a 2 x 2 matrix - naval operations occurred or not occurred versus marine mammal strandings occurred or not occurred. We have knowledge of some stranding events associated with naval operations, and possibly some information on the number of stranding events without naval sonar being present, but we do not know how many naval sonar operations occurred (in suitable beaked whale habitat) without any observed marine mammal strandings. It is though agreed that high-powered, mid-frequency sonar can affect beaked whales in particular. These effects can lead to death, either at sea or as a consequence of stranding ashore. These effects may be caused by a lethal behavioural change leading to physiological damage, or possibly by direct physiological damage. Hypotheses exist to explain these effects. It seems likely that these effects also occur at lower received sound levels than previously thought likely to cause damage and as a consequence the sphere of effect of these sonars is not known. Coupled with the lack of knowledge of the population size or distribution of beaked whales, we cannot be certain of whether population level effects might occur. However, at present it appears that these military sonars are not used widely. This could change in the future if these sonars were more widely deployed on ships or were used in non-exercise situations. Effects would be most severe in areas important for beaked whales.

Section 5 provides an overview of possible measures to mitigate the effects of sonar on marine mammals as well a brief description of the measures being undertaken by some the Navies of some nations in relation to military sonar.

Section 6 outlines some of the gaps in understanding around this issue and makes some suggestions as to how they might be addressed. Section 7 notes that other facets of the issue of noise in the ocean could have potentially more significant effects than direct lethal effects on individuals. In particular, the apparently increasing levels of anthropogenic low-frequency noise (mostly from shipping) may have consequences for the large baleen whales that use these frequencies for communication. General conclusions on marine mammals are summarised in Section 8

Section 9 describes relevant aspects of fish biology and the potential impact of sound, particularly sonar, on fish. There are very few studies of this and it should be noted that those studies cannot be regarded as being representative of the wide diversity of fish species that occur in the oceans. Effects of sonar have been noted at the individual level. Despite this, wide-ranging species of fish of commercial importance are unlikely to be affected at the population level with current rates of usage (and areas of usage) of military sonar. Other sonars (and noise sources) are more widespread. Research is suggested on the more subtle and on the cumulative effects of noise on fish.

Section 10 provides the groups recommendations that may form the basis of advice from ICES.

1.6 Acknowledgements

2   Physical background

2.1   The nature of sound

Sound consists of a symmetrical fluctuation in pressure around the hydrostatic pressure, accompanied by a back and forth motion of the component particles of the medium. For a plane wave travelling in open space without any interaction with objects or boundaries, the relationship between sound pressure (p) and particle velocity (v) is $p = (\rho c)v$, where ρ (kg/m³) is the density of the medium and c (m/s) is the speed of sound in the medium. The acoustic energy flux or intensity (I) of a sound wave is the product of the pressure multiplied by the particle velocity, and has the units of Joule per square meter per second ($J/m^2\text{-}s$) or watts per square meter (W/m^2). For a plane wave the intensity (or energy flux) is given by $I = p^2/(\rho c)$. It is equivalent to the amount of energy in Joules passing through a unit area per unit time as the sound wave travels unbounded in the medium.

2.2   Units for measuring sound

Underwater sound is usually expressed using the logarithmic decibel (deciBel) scale. Underwater sound is conventionally presented in decibels referenced to 1 microPascal, i.e. as dB re 1 μPa, and this convention has been adhered to in this report.

2.2.1   Use of the decibel scale in water

The fundamental unit of sound pressure is the Newton per square metre, or Pascal. However, when describing underwater acoustic phenomena it is normal to express the sound pressure through the use of a logarithmic scale termed the Sound Pressure Level. There are two reasons for this. First, there is a very wide range of sound pressures measured underwater, from around 0.0000001 Pa in quiet sea to around 10,000,000 Pa for an explosive blast. The use of a logarithmic scale compresses the range so that it can be easily described (in this example, from 0 dB to 260 dB re 1 μPa). Second, many of the mechanisms affecting sound underwater cause loss of sound at a constant rate when it is expressed on the dB scale.

The Sound Pressure Level (SPL) is defined as: $\text{SPL} = 20 \log (P/P_{ref})$

where P is the sound pressure to be expressed on the scale and P_{ref} is the reference pressure, which for underwater applications is 1 μPa. For instance, a pressure of 1 Pa would be expressed as an SPL of 120 dB re 1 μPa.

2.3   Parameters for estimating noise

In order to provide an objective and quantitative assessment of degree of any environmental effect it is necessary to estimate the sound level as a function of range. To estimate the sound level as a function of the distance from the source, and hence the range within which there may be an effect of the sound, it is necessary to know the level of sound generated by the source and the rate at which the sound decays as it propagates away from the source. These two parameters are:

- the level of sound generated by the source or Source Level (SL) and
- the rate at which sound from the source is attenuated as it propagates or Transmission Loss (TL)

These two parameters allow the sound level at all points in the water to be specified, and in the current state of knowledge are generally best measured directly at sea, although acoustical models exist which may give reasonably reliable results for propagation from sonar systems in

homogeneous deep water. However, these data have usually to be extrapolated to situations other than those in which the noise was measured; in these cases the commonest method of modelling the level is from the expression:

Received Level (RL) = SL-TL

Conventionally, the RL is calculated in dB re 1 μPa, but a similar expression may be used to estimate the received level of other measures of sound such as its impulse. Note that both RL and SL are absolute values, while TL is a rate.

If the level of sound at which a given effect of the sound is known, an estimate may be made of the range within which there will be an effect. Sound can behave in very different ways in shallow water compared with deep water and is therefore much more difficult to model.

2.3.1   Source level

The Source Level of a source is defined as the level of sound at a nominal distance of 1m, expressed in dB re 1 μPa. However, there are several assumptions implicit in this definition. Sound is composed not just of sound pressure but also a motion of the component particles of the medium (particle velocity). In the area very close to the sound source (the near field) there are very large particle motions for a given sound pressure and this has implications for organisms sensitive to particle motion – such as many fish, but less so for cetaceans. However, this area is very small (a few metres at the greatest) so population level effects are extremely unlikely and even effects on individuals would not be frequent. In addition, some sound sources, such as airgun arrays or steerable sonars, are composed of several sound sources that are operated simultaneously. When one is within several times the diameter of the source(s) the sound field is variable. It is therefore good practice to measure the sound pressure in the far field, at sufficient distance from the source that the effects of particle motion and complexities of multiple sound sources close together have reduced, and to use this pressure to estimate the apparent level at a nominal 1m from the source. However, this apparent level may not predict the actual level at ranges near an array of sources. An array of sources each of which operates at one particular source level may have a higher apparent source level far from the array. However as an animal approaches the array, it is unlikely that it would experience a sound level greater than one of the individual sources from which the array is made up. A 'measurement' of the apparent level can be made by assuming inverse dependence of pressure on the range, R, from the noise source, or by extrapolating the far field pressure. There is in general no reliable way of predicting the noise level from sources of man-made noise, and hence it is normal to measure the Source Level directly when a requirement exists to estimate far-field levels.

2.3.2   Impulsive sound

Powerful impulsive sounds are generated by the use of explosives underwater, by the airgun arrays used in seismic surveying, and by some forms of construction activity such as underwater pile driving. These sources generate impulsive waves of short duration, high peak pressure, and a wide frequency bandwidth, and may consequently have an effect on marine organisms.

Historically, two key parameters have been used to describe the severity of an impulsive source, the peak pressure and the impulse. The peak pressure of a blast wave P_{max} is the maximum level of overpressure, that is, the pressure above the local ambient pressure caused by the sound. This is usually at the initial peak of the waveform and is easily read from a recording of the sound.

The **impulse** I is defined as the integral of pressure over time and is given by

$$I = \int_0^\infty P(t)\delta t$$

where I is the impulse in Pascal-seconds (Pa.s), $P(t)$ is the acoustic pressure in Pa of the blast wave at time t and t is time. Impulse may be thought of as the average pressure of the wave multiplied by its duration. The importance of impulse is that in many cases a wave acting for a given time will have the same effect as one of say twice the pressure acting for half the time. The impulse of both these waves would be the same.

Several workers (Johnstone, 1985; Ross *et al*., 1985; Larsen and Johnsen, 1992) have showed the impulse of the shock wave (Yelverton *et al*., 1975) to be the best predictor of damage to fish and other aquatic animals from explosives. However, this measure tends to give conservative estimates for shallow water (5-10m depth) and is not considered suitable in areas having hard, reflective beds or under ice (Engelhardt *et al*., 1985).

The sound duration as well as the sound level is important in estimating the damage that may be caused by a sound. To compare sound events of varying duration and intensity the SEL or Sound Exposure Level (in dB) may be determined by converting the total noise energy measured during a noise event to an equivalent dB level for a single event that would be only one second in duration. The SEL accounts for both the magnitude and the duration of the noise event. The SEL may be calculated by summing the cumulative pressure squared (p^2) over time and is expressed as dB re $1\mu Pa^2$-s. Yet another method of quantifying the noise environment is to determine the value of a steady-state sound that has the same sound energy as that contained in the time-varying sound. This is the Equivalent Sound Level (Leq).

It is important when measuring impulsive sounds to record examples of the waveforms, so that alternative metrics may later be applied.

2.3.3 Sound propagation and transmission loss

The level of a sound diminishes as it spreads out from its source. A sound of 230 dB one metre from the source drops to 224 at 2m, 218 at 4 m, 212 at 8m out to 190 dB at 100m if the medium is homogeneous out to 100m. The reason for this extensive loss is that the energy emanating from the source expands in all directions, spread over a sphere of ever-increasing volume. This is called spherical spreading.

Sound consists not only of a variation in pressure, but also of a back and forth motion of the medium. While sounds are normally monitored by measuring the sound pressure, many fish respond to the particle motion (measured as the particle velocity, particle displacement or particle acceleration). As we have seen in section 2.1, in a free sound field the particle velocity can readily be estimated from the sound pressure. However, close to a source, in the 'near field', much larger particle velocities are associated with a given sound pressure. Estimating the changes in particle motion with distance from a source depends on the nature of the source. Note that the 'near field' can be quite extensive (extending for several metres) for low-frequency sound.

Losses far from the source are complex and depend on the depth of water, temperature, salinity and other factors. Not all frequencies propagate equally. High frequency sounds have a short wavelength and are absorbed by seawater, reflected by material in the water and converted to heat faster than low frequency sounds that have a long wavelength. For that reason, low frequency sounds propagate farther than a high frequency sound of the same source level. However, even though they propagate further, their levels continually decrease through spreading loss. These effects may be different in very shallow water, when low frequencies can attenuate faster than high frequencies.

Sound rarely spreads out uniformly. The path that sound takes through water is affected by the presence of a reflecting bottom and surface, and by factors that change water density, mainly

temperature, salinity, and depth. Thus for instance, a sound produced near the surface over deep water in summer could to dive immediately toward the bottom where, because of pressure, it turns and rises, reaching the surface some 30 km away. It could continue this diving and rising in a pattern called convergence zone propagation. In the winter, the same sound would tend to stay near the surface because propagation conditions prevent the sound from reaching great depth. If the water is very shallow, sound bounces between the surface and bottom and decreases close to shore. The relevance for marine mammals is that the exposure they receive from a human source is very variable and depends not only on distance from the source and frequency, but their depth, the depth of the water, and the time of year.

Sound propagation over long ranges in the ocean is therefore relatively unpredictable and cannot be influenced by man. Sound may also travel horizontally through the seabed, re-emerging back into the water at a distance. Refraction and absorption further distort the impulse, leading to a complex wave arriving at a distant point that may bear little resemblance to the wave near the source. Finally, sound may be carried with little loss to great distance by being trapped by reflection and refraction between layers of water at different densities in the water column (sound channels). Sound propagating in a channel is said to have cylindrical spreading. Predicting the level of sound from a source is therefore extremely difficult, and use is generally made of simple models or empirical data based on measurements for its estimation.

2.4 Ambient noise

Background, or ambient, noise occurs in all oceans and seas. There are many sources of ambient noise that may be classified as either:

- physical - wind driven, turbulence, seismic (earthquakes etc) and microseisms, thermal, rainfall, seabed generated and icebergs;
- biological - animal sounds and movement;
- man-made - shipboard machinery, propeller, water flow around, and discharges from, the hull.

These diverse sources all contribute to the generation of background noise levels but the ambient level is not the result of noise sources alone; it also depends on propagation conditions and the absorption of sound in seawater (Francois and Garrison, 1982).

Wenz (1962) and Urick (1986) describe levels of ambient noise in the ocean. The level of ambient noise in the sea increases continuously as the lower frequencies, below about 50 kHz, are approached. In the northern hemisphere, from 200 Hz to 10 Hz shipping noise is dominant. In the southern hemisphere, this band is less dominated by shipping. In both hemispheres there is considerable variation, with maximum ambient noise in this band being close to major shipping lanes.

Overall trends of the level of sounds in the sea can be broken down into anthropogenic and non-anthropogenic components. For instance, there is evidence that global climate change may have resulted in higher sea states (Bacon and Carter, 1993; Graham and Diaz, 2001), which would increase ambient noise levels. Over the past few decades, however, it is likely that increases in anthropogenic noise have been more prominent. In order of importance viewed on a global scale, the anthropogenic sources most likely to have contributed to increased noise are commercial shipping, offshore oil and gas exploration and drilling, and naval and other uses of sonar.

Ross (1987; 1993) suggested that ambient sound levels have increased by 10 dB or more between 1950 and 1975. These trends are most apparent in the eastern Pacific and eastern and western Atlantic, where they are attributed to increases in commercial shipping. Ross (1993) assumed that a doubling of the number of ships explained 3 to 5 dB, and greater average ship

speeds, propulsion power, and propeller tip speeds explained an additional 6 dB. However, recent work (Wales and Heitmeyer, 2002) calls some of these indices into question.

Only one actual measurement of long-term trends in ocean noise is available, and for only one site in the oceans. Andrew *et al.* (2002) used the same U.S. Navy acoustic array used by Wenz (1969) to make modern recordings. A low frequency noise increase of 10 dB over 33 years was observed at a site off the central California coast. The explanation for a noise increase in this band is the growth in commercial shipping, in terms of both number of ships and gross tonnage. From 1972 to 1999, the total number of ships in the world's fleet increased from approximately 57,000 to 87,000, and the total gross tonnage increased from 268 to 543 million gross tons. This increase probably is not representative of the oceans as a whole because shipping density differs regionally.

Mazzuca (2001) compared the results of Wenz (1969), Ross (1987), and Andrew *et al.* (2002) to derive an overall increase of 16 dB in low-frequency noise from 1950 to 2000. This corresponds to a doubling of noise power (3 dB) every decade for the past five decades, equivalent to a 7 percent annual increase in noise. During this period the number of ships in the world fleet tripled (from 30,000 to 87,000) and the gross tonnage increased by a factor of 6.5 (from 85 to 550 million gross tons) (National Research Council, 2003 from McCarthy and Miller, 2002).

A noise budget that covers both anthropogenic and natural sources of noise would be of considerable interest. However, no single noise budget provides a complete assessment of the potential impact of man-made sound on the marine environment. For example, a noise budget can be created that is based only on the characteristics of the source, e.g. source level, so that propagation effects are not taken into account. If, on the other hand, received sound levels are the property of interest, the relative contribution of mid frequency (1 kHz - 10 kHz) sources such as Navy hull-mounted sonar would be significantly reduced with respect to low frequency sources because of the ocean's selective absorption of high frequency sounds, discussed above. For example, mid frequency sonar operating at 235 dB re 1 µPa @ 1 m in the Bahamas event (see Section 4.2.3) was barely detectable by an acoustic range 160 km away, but airguns operating at comparable source levels were detectable over thousands of km (Nieukirk *et al.*, 2004). In addition, since military sonars operate in a few specific areas at any given time, they probably could not be discerned in a comprehensive global noise budget in which the received sound was averaged over space and time. Therefore, local as well as global noise budgets should be constructed, particularly for critical marine mammal habitats. A further step would be to create noise budgets that take account of the auditory capabilities of various groupings of marine organisms (odontocetes such as beaked whales, large baleen whales, specific fish or groups of fish etc).

2.5   Sonar in general

Active sonar is the use of acoustic energy for locating and surveying. Sonar was the first anthropogenic sound to be deliberately introduced into the oceans on a wide scale. There is a variety of types of sonars that are used for both civilian and military purposes. They can use all sound frequencies and can be conveniently categorised into low (<1 kHz), mid (1 to 10 kHz) and high frequency (>10 kHz). Military sonars use all frequencies, while civilian sonar uses some mid but mostly high frequencies.

2.5.1   Low-frequency sonar

Low frequency sonars are used by navies for long-range (in the order of a few hundred kilometres) surveillance. For example, the US Navy has developed the SURTASS-LFA (Surveillance Towed Array Sensor System – Low Frequency Active) system that uses a vertical array of 18 projectors using the 100-500 Hz frequency range. The source level of each

projector is approximately 215 dB re 1 µPa @ 1m and the 'ping' length is 60 to 100 sec (Johnson, 2001). Over the last few years, this system has only been used on a limited number of occasions, and is now regularly used in military testing or exercises. Many other countries of the world are developing low frequency sonar (Pengelly and Scott, 2004) to detect quiet diesel-electric submarines.

2.5.2 Mid frequency sonar

Military mid frequency sonars are used to survey areas tens of kilometres in radius and are used to find and track underwater targets. A US Navy hull-mounted system (AN/SQS-53C) sonar system uses pulses in the 2 – 10 kHz range (normally 3.5 kHz) and has operated at 235 dB re 1 µPa @ 1m with ping lengths of about 2.5 sec. Another system (AN/SQS-56) uses this same frequency band but with lower source levels (223 dB re 1 µPa @ 1m) (Evans and England, 2001). Similar mid-frequency sonars are used by many navies of the world, including the Spanish navy during the Canary Islands event (see Section 4.2.4). Most usage of these systems has been confined to comparatively well-defined exercise areas, which make up a small proportion of the world's oceans. Even in these areas, activity times are relatively short and episodic, and propagation distances are small because of the frequencies involved. In addition, only a small proportion of the world's military ships carry these sonar systems. These systems were formerly used for antisubmarine work in open water, but are now most often used in coastal areas, submarine canyons or other choke points where quiet diesel-electric submarines may hide within acoustic clutter.

Some non-military sonars also operate in this frequency band. Bathymetric sonars use these frequencies for wide-area, low resolution surveys. The Fugro Seafloor survey model SYS09 for instances uses both 9 and 10 kHz transducers operated at 230 dB re 1 µPa @ 1m. Sub-bottom profilers typically use 3.5 kHz transducers operated at source levels of 204 dB re 1 µPa @ 1m. The regional resolution GLORIA survey sonar uses 6-7 kHz band (no source level published).

2.5.3 High frequency sonar

Military high-frequency sonars are either used in attacking (mines or torpedoes) or defending (mine countermeasure, anti-torpedo) systems and are designed to work over hundreds of metres to a few kilometres. These sonars use a wide range of modes, signal types and strengths. As with other military sonars, their usage is generally confined to exercise areas, except when they are used for commercial-like uses such as depth sounding.

Fish finders and most commercial depth sounders operate at high frequencies. Usually, but not always, they project a lower power signal and have narrower beam patterns and shorter pulse lengths (a fraction of a second) than military sonars. These systems cannot be used at shallow depths at high powers due to cavitation (Urick, 1975). Most of the systems focus sound downwards, though some horizontal fish-finders are available. Fish finding sonars operate at frequencies typically between 24 and 200 kHz, which is within the hearing frequencies of some marine mammals, but above that of most fish. Globally there are a great many recreational, fishing and commercial vessels, most of which are fitted with some sort of sonar. These vessels are most heavily used in shallow shelf-seas, with sonars used less by those merchant vessels crossing deep water areas. Usage occurs throughout the year and both by day and night. Some horizontally-acting fish-finding sonars work at frequencies at the lower end of the 'high-frequency' range and are relatively powerful. An example is the Furuno FSV-24 sonar that operates at 24 kHz and can detect and track shoals of tuna at 5000m horizontally. Source levels of these sonars are not published.

Some depth finding sonars can also be powerful. Boebel *et al.* (2004) describe the Atlas hydrosweep DS-2 deep sea multi-beam sonar. This has source levels exceeding 220 dB re 1 µPa @ 1m at 15.5 kHz with relatively short (24ms) pulses.

It is worth noting that sonars may operate at one frequency of sound, but generate other frequencies. These extraneous frequencies are rarely described (but are usually of a much lower intensity than the main frequency) and may have wider effects than the main frequency used, especially if the extraneous frequencies are much lower than those used (and could consequently propagate further).

3 Biological Background – Cetaceans

3.1 Hearing in cetaceans

3.1.1 Anatomy and physiology

Cetacean ear anatomy and physiology differ from the general pattern seen in terrestrial mammals in several ways. These differences are likely to be related to the specific problems of sound reception in water in contrast to air or, in odontocetes, to the echolocation abilities of the animals.

3.1.1.1 Sound path to middle ear

Cetaceans have no outer ear and their ear canal is either vestigial (toothed whales and dolphins - odontocetes) or filled with wax (baleen whales - mysticetes). In odontocetes it is now thought that most sound enters the head and reaches the ear not through the ear canal, but through the surface of the lower jaw and is transmitted via a channel of fat to the middle ear tympanic bulla (Brill *et al.*, 2001; Møhl *et al.*, 1999, Norris, 1964). Anatomical and physiological features also suggest that one or more additional fatty channels, lateral to the middle and inner ear, may be involved (Ketten, 2000). There may be further pathways for sound to reach the ear.

The sound path from water to middle ears in mysticetes is unknown. Anatomical similarities between bulla and middle ear ossicles in mysticetes and odontocetes, coupled with the presence of fat bodies in close contact with the middle ear (attaching onto the tympanic bulla), suggests that a fatty channel could also be involved in sound transmission in mysticetes (Thewissen, 2002).

3.1.1.2 Middle ear

The middle ear ossicles have undergone marked changes in cetaceans, compared to terrestrial mammals. These changes are no doubt in part or in full adaptations to underwater sound reception and connected to the loss of outer ears. The function of the middle ear is debated, but Hemilä *et al.* (1999) offers a model, where movement of the tympanic bulla relative to the periotic bulla is caused by sound conducted through the lower jaw fat channel and transmitted via the ossicles to the inner ear.

3.1.1.3 Inner ear

The fundamental organisation of the inner ear of cetaceans is similar to other mammalian ears. Odontocete inner ears have anatomical specialisations for ultrasonic hearing, such as high thickness to width ratios of the basal (high-frequency) part of the basilar membrane, supplemented by additional stiffening elements along the cochlear duct (Ketten, 2000).

Mysticete inner ears on the other hand have very thin and broad basilar membranes, larger than all other mammals and consistent with hearing abilities well into the infrasonic range.

3.1.2 Hearing in smaller odontocetes

3.1.2.1 Absolute thresholds – audiograms

The fundamental measure of an animal's hearing ability can be represented in an audiogram, expressing the lowest sound pressures detectable by the animal in quiet conditions and at a range of frequencies. Odontocete audiograms are generally fairly similar in shape, with range of best hearing in the area 10-100 kHz, and best thresholds of 40-50 dB re. 1 μPa. The hearing thresholds of odontocetes increase slowly with ca. 20 dB per decade for lower frequencies and increase steeply at high frequencies. In general, larger species seem to have an upper limit of hearing of around 100 kHz, for example killer whale *Orcinus orca* (Szymanski *et al*., 1999) and false killer whale *Pseudorca crassidens* (Thomas *et al*., 1988). In contrast, smaller species have higher upper limits of hearing of around 150 kHz, for example bottlenose dolphin *Tursiops truncatus* (Johnson, 1967) and harbour porpoise *Phocoena phocoena* (Andersen, 1970; Kastelein *et al*., 2002). As cetacean audiograms more often than not are based on only one or two individuals, one should be cautious in extrapolating especially the upper hearing limits to the species in general. A considerable natural variation between individuals of the same species may be present and it has also been demonstrated that odontocetes can suffer from age-related high frequency hearing loss (Ridgway and Carder, 1997).

3.1.2.2 Dependence on duration – temporal summation

Some controversy exists on the question of the actual threshold determining parameter, whether it is sound pressure or sound intensity (proportional to sound pressure squared) (Finneran *et al*., 2002a). This question may have significant relevance when discussing damage caused by loud sounds. When it comes to discussions relating to thresholds and masking however, the ears of odontocetes behave in a similar way to other mammalian ears. For short durations, below the integration time, thresholds improve with an approximate 3 dB per doubling of duration, meaning that the sound energy (intensity integrated over time) at threshold remains approximately constant. Integration time for bottlenose dolphin is between 50 and 200 ms, depending on signal frequency (Johnson, 1967). In actively echolocating odontocetes, listening for echoes of their own sonar clicks, an entirely different temporal processing seems to occur. Under these circumstances, an integration time of 265 μs has shown up repeatedly for bottlenose dolphin (Au *et al*., 1988; Dubrovsky, 1990; Moore *et al*., 1984).

3.1.2.3 Masking by noise

Critical bands and critical ratios have been measured for three species of odontocetes, bottlenose dolphin, beluga *Delphinapterus leucas* and false killer whale (Au and Moore, 1990; Johnson *et al*., 1989; Thomas *et al*., 1990). When assessing the masking effects of noise, the relevant parameter is the masking bandwidth, which provides information on the effectiveness of a given noise in masking a pure-tone signal. When masking bandwidths are calculated from critical ratios, they are roughly constant in the range of 1-100 kHz and around 1/12 octave in size (Richardson *et al*., 1995). If calculated from measurements of critical bandwidths (only available from bottlenose dolphins (Au and Moore, 1990)), which is a more direct measure of the masking interval, a value close to 1/3 octave is found, in line with values for humans and other mammals.

3.1.2.4 Directionality

Odontocete hearing is not equally sensitive to sounds from different directions. Greatest sensitivity is for sounds coming directly towards the front of the animal, and sensitivity drops quickly as the sound source moves away from the midline. The drop is largest for higher frequencies. Threshold for a 120 kHz signal is about 20 dB higher 25 degrees from the midline for bottlenose dolphins (Au and Moore, 1984). The index of directionality expresses the sensitivity of the animal relative to a receptor which is equally sensitive to sounds from all directions and equal to the maximum sensitivity of the animal. For bottlenose dolphins, the index of directionality varies from 10 dB at 30 kHz to 20 dB at 120 kHz (Au and Moore, 1990). One effect of the directionality in sensitivity is a lesser influence from noise or other interfering sounds, when these sounds reach the animal from the side or from behind.

3.1.2.5 Hearing in larger odontocetes

No audiogram or other reliable measure of larger odontocete (sperm whale *Physeter macrocephalus* and beaked whale) hearing is available. Carder and Ridgway (1990) obtained an audiogram using brainstem response on a sperm whale calf. In other species, this technique provides similar U-shaped responses to increasing sound frequency as behavioural techniques, but the frequency where thresholds of hearing are lowest (best) are generally much higher. Sperm whale clicks are around 5-20 kHz, but Carder and Ridgway (1990) reported responses to sounds up to 60 kHz.

3.1.3 Hearing in mysticetes

No audiogram or other reliable measure of mysticete hearing is available. Some inferences may be made from indirect evidence, such as the characteristics of the animals own vocalisations and morphology of their middle and inner ears. Mysticete vocalisations have fundamental frequencies from a few hundred Hz and below, to as low as 10-20 Hz in blue *Balaenoptera musculus* and fin whales *B. physalis* (Edds, 1982, 1988; Watkins *et al.*, 1987). Individual sounds may contain components up to 5-10 kHz (especially grey *Eschrichtius robustus* and humpback whales *Megaptera novaeangliae* (Cerchio and Dahlheim, 2001; Crane and Lashkari, 1996). In line with observations from odontocetes and mammals in general, this suggest that the range of best hearing for mysticetes is in the similar range, i.e. from a few Hz to a few kHz. This range of hearing is also supported by morphology of the basilar membrane, as described above.

3.2 Potential effects of sound on cetaceans

3.2.1 Direct damage to hearing

Potential damage to ears from underwater sound can potentially range from gross tissue damage such as that caused by the detonation of explosive charges underwater through to a temporary loss of hearing sensitivity. There is no direct evidence of tissue damage in cetaceans from underwater sound sources, but there have been no studies that have specifically investigated this. Ketten *et al.* (1993) found tissue damage in the ears of two humpback whales that were caught in fishing gear after explosions had occurred nearby.

Exposure to high intensity noise can cause a reduction in hearing sensitivity (an upward shift in the threshold of hearing). This can be temporary (known as temporary threshold shift (TTS)), with recovery after minutes or hours, or permanent (permanent threshold shift (PTS)) with no recovery. PTS may result from chronic exposure to sound, and sounds that can cause TTS may cause PTS if the subjects are exposed to them repeatedly and for long enough. The

relationship between TTS and PTS is not well-known, even for humans. However, very intense sounds can cause irreversible cellular damage and instantaneous PTS.

TTS appears to be associated with metabolic exhaustion of sensory cells and anatomical changes at a cellular level. PTS may be accompanied by more dramatic anatomical changes in the cochlea including the disappearance of outer hair cell bodies and, in very severe cases, a loss of differentiation within the cochlea and degeneration of the auditory nerve. Lower frequency noises induce threshold shifts over a wider bandwidth than higher frequency noises.

Finneran *et al.* (2002b) measured TTS in a dolphin and a beluga exposed to brief, low frequency impulses from a water gun. They compared their results with those of Schlundt *et al.* (2000), who measured TTS in dolphins exposed to one second tones, and those of Nachtigall *et al.* (2003), who measured TTS in dolphins exposed to continuous octave-band noise for 55 min. The three sets of results closely fit a 3 dB per doubling of time slope. That is, if the exposure duration is doubled and the sound pressure level is reduced by 3 dB (halved), the sound exposure level remains constant at about 195 dB re 1 μPa^2 (s). This is an important finding because it brings some predictability to the subject of noise exposure in dolphins.

There have been no direct observations of noise-induced PTS in cetaceans and such data are not likely to be obtained in the near future due to ethical concerns. However, the onset of PTS in marine mammals can be estimated by comparing the way the ear recovers from ever higher levels of TTS against similar data from terrestrial mammals that did experience PTS.

3.2.2 Non-auditory tissue damage

Much research effort on the potential for anthropogenic sound to affect marine mammals has focused on auditory effects and behavioural modifications following sound exposure. Non-auditory consequences resulting from exposure to sound have historically received less attention (Crum and Mao, 1996). Studies on terrestrial mammals suggest that non-auditory tissues require exposure to sounds considerably more intense than those that affect hearing. Biologically, this extrapolation suggests that direct tissue damage can occur only very close to an intense sound source.

The first hypothesis about non-auditory consequences of less intense exposures was proposed in the report of the Greek stranding event (see Section 4.2.2) and considered the concept of acoustic resonance in air spaces. All structures have a natural frequency at which they vibrate, called their resonant frequency. If such a structure is struck by an incoming sound wave of the same frequency as the resonant frequency the structure vibrates at a greater amplitude than normal; the tissues move more than normal and may tear. Acoustic resonance was suggested as a possible explanation of the Bahamian stranding (see Section 4.2.3), and the hypothesis was accepted as true by the public and the media before the scientific community had adequately considered it. A workshop on acoustic resonance (Evans *et al.*, 2002) concluded that the resonant frequencies of marine mammal lungs are too low for resonance to have been caused by mid-frequency sonar.

The second hypothesized, non-auditory link between strandings and sonar exposure is acoustically mediated bubble growth (e.g. rectified diffusion) within tissues that is proposed to occur if tissues are supersaturated with dissolved nitrogen gas (Crum and Mao, 1996). Such bubble growth could result in gas emboli formation, tissue separation and increased, localised pressure in tissues, a similar scenario to decompression sickness (DCS) in human divers. Although the rectified diffusion model of Crum and Mao (1996) suggested that received sound levels of >200dB (re: 1μPa@1m) would be needed to drive significant bubble formation in marine mammal tissues, the model was run under relatively low levels of tissue nitrogen supersaturation (100-200%). A more recent study predicted that beaked whales, due

to the typical dive profile characteristics, may accumulate over 300% nitrogen tissue supersaturation at the end of a typical dive sequence (Houser *et al.*, 2001). This study, based on empirical observations of nitrogen tissue accumulation in bottlenose dolphins (Ridgway and Howard, 1979) and dive data from northern bottlenose whales *Hyperoodon ampullatus* (Hooker and Baird, 1999), suggested that beaked whales in particular may be more susceptible to acoustically mediated bubble formation than originally predicted by Crum and Mao (1996).

Box 1 Decompression sickness and acoustically-mediated bubble formation

Decompression sickness is the result of the supersaturation of body tissue with nitrogen and the subsequent release of bubbles of nitrogen gas. In human divers, decompression sickness is typically caused by rapid decompression following diving while using compressed air or repetitive, breath-hold dives. Unlike humans, the lungs of marine mammals collapse during a dive, limiting the nitrogen they carry to that which is absorbed into the blood stream within 60 m to 100 m of the surface, although some pinnipeds dive on expiration and lung collapse occurs at much shallower depths (e.g. 25-50m in Weddell seals) (Falke *et al.*, 1985). At greater depths, nitrogen is sequestered in non-exchanging airways. The amount of gas dissolved in specific tissues depends on dive depth, dive duration, descent and ascent rates, lipid content of the tissue, and surface intervals between successive dives. Progressive accumulation of nitrogen in tissues due to repetitive breath hold dives has been demonstrated empirically in bottlenose dolphins (Ridgway and Howard, 1979) and has been predicted to reach levels in excess of 300% supersaturation in northern bottlenose whales based on typical dive profiles (Houser *et al.*, 2001).

Although a number of anatomical, physiological, and behavioural adaptations that presumably guard against nitrogen bubble formation in marine mammals have been proposed (Ridgway 1972, 1997; Ridgway and Howard, 1979, 1982; Falke *et al.*, 1985; Kooyman and Ponganis, 1998, Ponganis *et al.*, 2003), it is possible that the gas emboli and associated lesions found in cetaceans in the Canary Islands and in the UK (Jepson *et al.*, 2003; Fernandez *et al.*, 2004, in press) could be caused by disruption of these evolutionary adaptations to deep diving. Anatomical and physiological adaptations to diving are unlikely to alter in the short course of acoustic exposure, but behavioural changes in response to sonar might. For example, in experiments northern right whales *Eubalaena glacialis* responded to novel acoustic stimuli by a combination of accelerated ascent rates and extended surface intervals at received sound levels as low as 133dB re 1μPa@1m (Nowacek *et al.*, 2004). If beaked whales respond similarly they could experience excessive nitrogen tissue supersaturation driving potentially damaging bubble formation in tissues via a similar mechanism to the human diver that incurs DCS due to too rapid an ascent. Alternatively, physical mechanisms (e.g. rectified diffusion) exist for acoustically-mediated bubble formation in tissues already supersaturated with nitrogen (Crum and Mao, 1996; Houser *et al.* 2001).

It is therefore theoretically possible that sonar transmissions (of low, mid or high frequency) could directly initiate or enhance bubble growth in tissues were sufficiently supersaturated with nitrogen and if the received sound pressure levels were of sufficient intensity. However, there is as yet no scientific evidence for any of the steps in these postulated chains of events. A (US) Marine Mammal Commission Workshop on beaked whales and anthropogenic noise considered it important to test the "bubble hypothesis", and prioritised a programme of research that incorporates both acoustically mediated bubble formation and bubble formation via a DCS-like mechanism, and includes the use of controlled exposure experiments (Cox *et al.*, in prep.).

Even more recently, the first evidence of gas and fat emboli and acute and chronic gas bubble lesions has been reported in a number of cetacean species stranded in Europe. In the UK, ten stranded cetaceans comprising four Risso's dolphins, four common dolphins, a Blainville's beaked whale and a harbour porpoise had acute and chronic lesions in liver, kidney and

lymphoid tissue (lymph nodes and spleen) associated with (predominantly) intravascular gas bubbles (emboli) (Jepson *et al*., 2003, in press; Fernández *et al*., 2004). These animals stranded singly and the etiology of these lesions (including whether or not they were exposed to any form of acoustic activity) is unknown. However, a suite of widely disseminated microvascular haemorrhages associated with gas and fat emboli, lesions highly consistent with DCS, were found in ten beaked whales that died as part of a mass stranding of 14 beaked whales in the Canary Islands linked to an international naval exercise (Neo Tapon) in September 2002 (see Section 4.2.4). The Canaries findings are important for understanding effects on tissues as they are the first to be based on fresh material. In other similar incidents, either tissues were not examined, or were examined much later. The gas bubble hypothesis is relatively new and has received much recent theoretical attention and evidence, however there has as yet been little scientific testing of it. Such testing is needed and necessary before a full judgement of the hypothesis can be made.

3.2.3 Masking and changes in vocal behaviour

Cetaceans use sound for a number of purposes including communication, searching for food and detecting predators. In all cases, a cetacean needs to hear a sound, either originating from itself (with an echo reflected from a target) or originating somewhere else and may not be very loud. In order to detect the sound, the sound has to be louder than (or be able to be differentiated from) the ambient sound level. The hearing mechanisms or auditory processing of the whale also has to be sensitive enough to detect this difference.

An increase in ambient noise could have a number of effects depending on the particular use of sound by the cetacean. If a sound is propagating with cylindrical spreading, a 10 dB increase in ambient sound could effectively reduce the maximum range at which a sound can be heard to a tenth of the original range (a 20 dB increase could reduce this to a hundredth of the range). It is likely that cetaceans can compensate to some extent to this increase in ambient noise. Belugas adjust their echolocation clicks to higher frequencies and higher source levels in the presence of increased background noise (Au *et al*., 1985). Long-finned pilot whales *Globicephala melaena* changed the type of vocalisation in the presence of military sonar signals (Rendell and Gordon, 1999). Belugas have been observed to increase call rates and shift to higher call frequencies in response to boat noise (Lesage *et al*., 1999). Some humpback whales lengthened their song cycles when exposed to the LFA source (Miller *et al*., 2000; Fristrup *et al*., 2003); increasing the redundancy of the song may improve communication in a noisier channel. Note that it is difficult to separate the two possible causes of these changes – masking by the sound and direct behavioural response to the sound.

Thus, one general effect of the increase in ambient ocean noise could be to affect several vocal characteristics or behaviours of cetaceans. The degree to which these changes significantly affect the animals is not known and will be case dependent. Sonar is a lesser contributor to the overall ocean noise budget than other sources of anthropogenic sound.

Surveys conducted by NOAA Fisheries showed that during the last 20 of the 33 years covered by the Andrew *et al*. (2002) study all cetaceans in west coast of the USA increased by an average of 8.2%. A mark-recapture study on humpback whales showed a 7.2% increase in this same area, which bolster's the survey estimates (Barlow, 1994; NOAA, unpublished data). The increases noted in section 2.3 in ambient noise level involved frequencies used for communication by blue, fin, and grey whales. If ambient noise has untoward effects on mysticete populations through masking, it is not apparent at the levels reported by Andrew *et al*. (2002).

3.2.4 Behavioural reactions

Besides the changes in vocal behaviour outlined above, many possible changes in behaviour could occur in the presence of additional noise. Behavioural responses may range from changes in surfacing rates and breathing patterns to active avoidance or escape from the region of highest sound levels. Several studies suggest that bowhead whales *Balaena mysticetus* follow a pattern of shorter surfacings, shorter dives, fewer blows per surfacing, and longer intervals between blows when exposed to anthropogenic noise, even at moderate received levels (114 dB re 1µPa).

Many now hypothesise that the mechanism(s) underpinning the phenomenon of beaked whale mass strandings linked to naval sonar are initially triggered by a behavioural response to acoustic exposure rather than a direct physical effect of acoustic exposure (Jepson *et al*., 2003; Fernández *et al*., 2004, in press; Cox *et al*., in prep.) (see section 3.2.2). The first potential pathway entails a simple behavioural response to sound that leads directly to stranding, such as swimming away from a sound into shallow water. An alternative scenario involves a behavioural response leading to tissue damage. Such responses may include a rapid ascent, staying at depth, or remaining at the surface, and these could lead to gas bubble formation, hypoxia, hyperthermia, cardiac arrhythmia, hypertensive hemorrhage, or other forms of trauma (Cox *et al*., in prep.). Of these, the hypothesis that a behavioural change could lead to gas bubble formation via a mechanism similar to decompression sickness (Jepson *et al*., 2003; Fernández *et al*., 2004, in press) is seen as a priority for future research (Cox *et al*., in prep.). Beaked whales might also experience tissue damage directly from sound exposure, such as acoustically mediated bubble formation and growth (Crum and Mao, 1996), vestibular response that leads to stranding, acoustic resonance, or hemorrhagic diathesis, and all of these could lead to behavioural alterations in beaked whales, stranding and death (Cox *et al*., in prep.).

Marine mammal responses also appear to be affected by the location, motion, and type of onset of a sound source. Bowheads are more responsive to overflights of aircraft when they are in shallow water (Richardson and Malme, 1993). Fin whales are more tolerant of a stationary than a moving source (Watkins, 1986). Humpback whales are less likely to react to a continuous source than to one with a sudden onset (Malme *et al*., 1985). In the St. Lawrence River, belugas are less likely to change their swimming and diving patterns in the presence of vessels moving at low speed than in the presence of fast-moving boats (Blane and Jaakson, 1994). In Alaska, belugas feeding on river salmon may stop and move downstream in response to noise from small boats, whereas they are relatively unresponsive to noise from fishing boats (Stewart *et al*., 1982). In Bristol Bay, belugas continue to feed even when surrounded by fishing vessels, and they may resist dispersal even when purposely harassed (Fish and Vania, 1971). This context-dependent response to sound and disturbance illustrates the difficulty of extrapolating results from captive animals to those in the wild.

Few studies have been designed to document long-term responses to anthropogenic noise by marine mammals. At Guerrero Negro Lagoon in Baja California, Mexico, shipping and dredging noise associated with a salt works may have induced grey whales to abandon the area through most of the 1960s (Bryant *et al*., 1984). After ship traffic declined, the lagoon was reoccupied, first by single whales and later by cow-calf pairs. Killer whales in the British Columbia region were displaced from Broughton Archipelago during 1993-1999, a period when acoustic harassment devices were in use at existing salmon farms (Morton and Symonds, 2002).

Displacement by sound from areas could have effects on individual animals and populations, probably depending on the distance and persistence of the displacement. These effects may not become immediately apparent and could be modified by habituation, sensitisation, hearing loss, physiological damage and stress. Noise would be biologically significant if it induced

long-term abandonment of an area important for feeding, breeding or rearing the young, as it may lead to reduced fecundity, carrying capacity, or both. Social disruption brought about by noise may be especially important if mother/calf pairs become separated.

The individual and population level effects of non-lethal disturbance are also likely to be dependent on body size and life history. Generally, larger whales need to balance their energy budgets over time-spans of months (up to a year) (Boyd, 2002). Many larger whales migrate to high latitudes to feed during the summer, storing energy in the form of blubber. These whales return to breed in warmer, less productive tropical waters during which time they may fast and rely on their blubber for energy. Smaller whales and dolphins are likely to balance their budgets over shorter (days to a month) periods. Smaller cetaceans may be more susceptible to shorter term disruption of foraging. The consequences of disturbance are thus time and space specific for each species.

4   Cetaceans and sonar

4.1   Marine mammals

There are globally around 120 species of marine mammal (the precise figure depending on the taxonomy used). Since ships of European countries operate globally, all of these species could potentially be affected by sonar from ships of European countries. In the waters of Member States of the European Union waters, there are about 30 species of cetacean and 10 species of seal. Each species of marine mammal has a unique geographical distribution though, with some distributions being better known than others are. Thus which species is affected by which sonar usage depends heavily on the location in which the sonar is used (and the local propagation characteristics of the particular frequency band being used by the sonar). Geographic distributions of cetaceans in north-west European waters have been described by Reid *et al.* (2003), while preliminary maps for Mediterranean Sea were assembled by Beaubrun *et al* (1995). The harbour porpoise is the only resident cetacean species in the Baltic, and here the species is rare and confined mostly to the south and west of the sea (ICES, 2003). The distribution of cetaceans in the Bay of Biscay, off Iberia and around the Macronesian Islands has not been mapped systematically. Although many species may live in a given area, sonar-related strandings and deaths typically involve mostly the beaked whales present. Few, if any, effects of sonar on other species have been observed in European waters. Consequently, rather than review the knowledge of distribution of all marine mammals in EU waters here, we focus on knowledge (and lack thereof) of beaked whale distribution and refer readers to the sources mentioned above for other species.

4.2   Beaked whales

There are some 20 species of beaked whale known globally at present, but given that two of these have only been discovered and described in the past twenty years, it would not be surprising if further species were found. One reason for this lack of taxonomic certainty is that all beaked whales appear to live in the deep ocean or on the margins of the continental shelves. All species appear capable of diving to great depth, staying underwater for many minutes (more than an hour in some cases) and then only being at the surface for a relatively short time before diving again. Surfacing behaviour is frequently relatively inconspicuous. Many of these species are shy and respond to the presence of ships by prolonged diving. Not surprisingly, this group of comparatively large mammals is one of the least known on the planet and much remains to be discovered about all aspects of their biology. Six/seven species have been recorded in European waters (Table 4.2.1), but many sightings of the group are not identified to species level.

Table 4.2.1   **Beaked whales recorded in European waters**

Cuvier's beaked whale *Ziphius cavirostris*
Northern bottlenose whale *Hyperoodon ampullatus*
Sowerby's beaked whale *Mesoplodon bidens*
(Gray's beaked whale *Mesoplodon grayi* – one stranding record (1927) only)
True's beaked whale *Mesoplodon mirus*
Gervais' beaked whale *Mesoplodon europaeus*
Blainville's beaked whale *Mesoplodon densirostris*

Most records of beaked whales in European waters come from deep waters at or beyond the shelf break. Reid *et al.* (2003) mapped a group of sightings to the north and west of Scotland (Figure 4.2.1), but this was one of the few areas where considerable survey effort had been expended in deeper water by those contributing to their atlas. It was however noticeable that the deeper cold-water area north of the Wyville Thomson ridge appeared to be less important than the area south of the ridge. Northern bottlenose whales were less tied to the areas near shelf breaks, but occurred throughout deeper water (Figure 4.2.2) in the survey reported by Reid *et al.* (2003).

Further south, surveys from ferries running from the UK across the Bay of Biscay have shown that the deep-water area and the surrounding shelf slope/canyons are important for Cuvier's beaked whale (Cresswell and Walker, 2001; Coles *et al.*, 2003), and other beaked whales have been recorded in this deep water area, but not in shallower waters.

Cuvier's beaked whale is the only beaked whale regularly present in the Mediterranean Sea (Notarbartolo di Sciara, 2002). Beaubrun *et al.* (1995) records seven sightings of live Cuvier's beaked whale – all from shelf break areas. The depressions and the deep trenches that surround the coasts of Greece appear to be good habitat for this species. Strandings and sightings during the last decade show the importance of Greek Seas for this species (Frantzis *et al.*, 2003). The yearly average of Cuvier's beaked whale strandings in Greece was 5.6 individuals (C.L.95%=2.78) for the decade 1990-1999 (the mass stranding of May 1996 (see Section 4.2.2 below) excluded). Although underestimated (because no official stranding network was established in Greece before 1992), this number is significantly higher than the respective average for each of the three northern countries of the west and central Mediterranean (Spain 1.9, France 0.2, Italy 2.6), and higher (although not significantly) than their sum. Most of the strandings that occurred in Greece were recorded along the Hellenic Trench, which runs all around the west and south Greece, and marks the limits of the European continental shelf. Surveys conducted along the Hellenic Trench confirmed that Cuvier's beaked whales are abundant (Frantzis *et al.*, 2003).

It is reasonable to assume that all suitable shelf break areas in European Seas are likely to form habitat for beaked whales, with some distributions extending to deeper water. It is not known how resident any individual or group of beaked whale might be to any particular area off Europe.
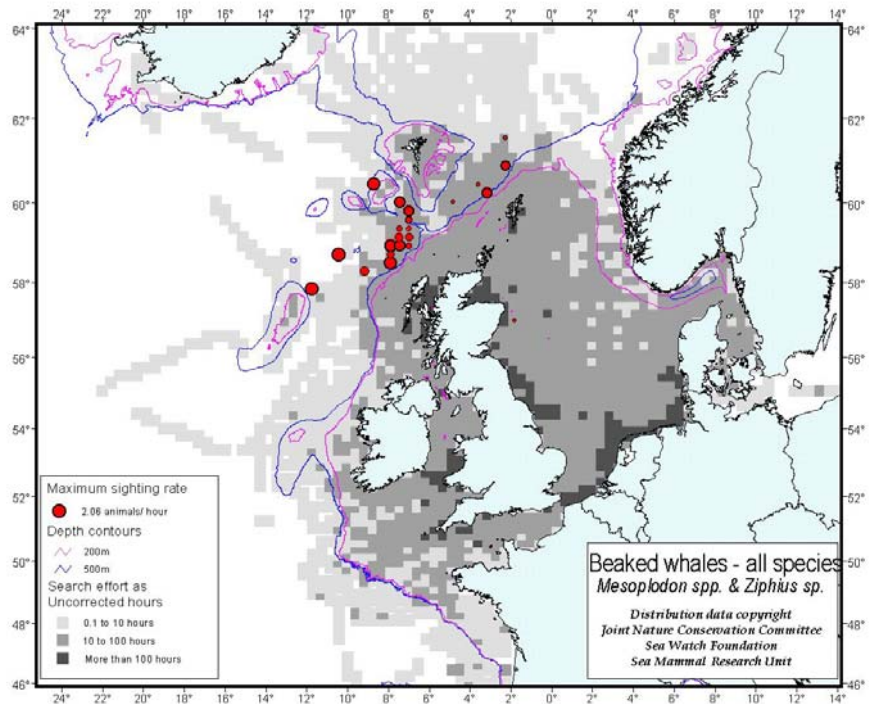
Figure 4.2.1 Distribution of effort-based sightings of beaked whales recorded by Reid *et al.* (2003). The background grey shading indicates hours of searching for each quarter ICES rectangle. The 200 and 500m depth contours are shown, indicating the area of the continental shelf break. Red circular dots indicate sightings rates per hour of searching.

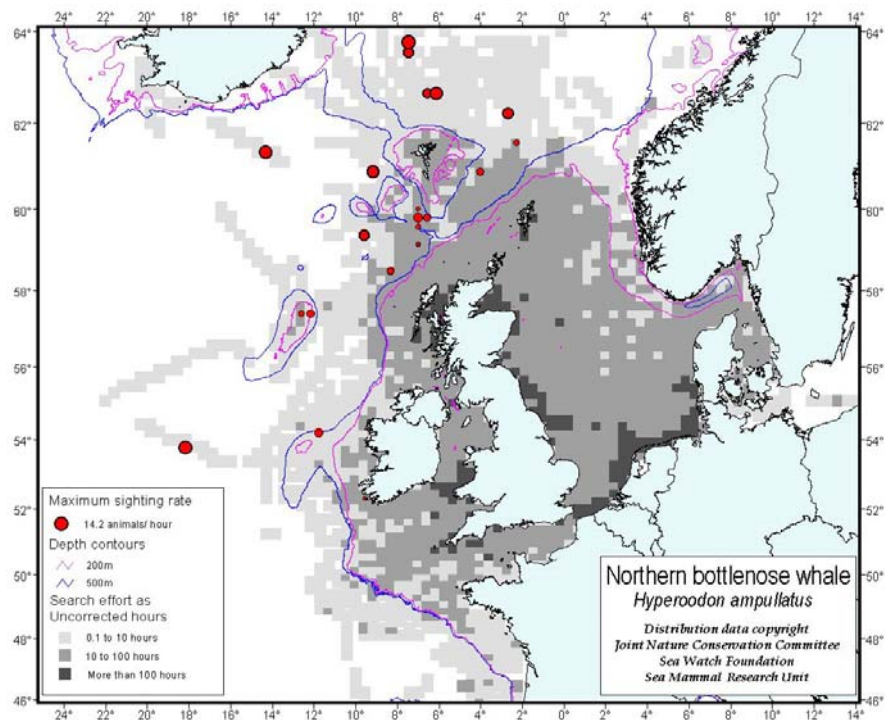**Figure 4.2.2 Distribution of effort-based sightings of northern bottlenose whales recorded by Reid *et al.* (2003). See Figure 4.2.1 for key to symbols used.**

4.2.1 Review of literature on effects of sonar on beaked whales

Cuvier's beaked whale is a deep-diving, pelagic cetacean that until recently was believed to rarely mass-strand (Heyning, 1989). Only seven strandings of more than four individuals were recorded by Frantzis (1998) from 1963 to 1996 worldwide, but more incidents in this period have come recently to light. On most of these occasions, mass strandings showed atypical characteristics unlike those that occur with other whales. This suggested that the cause had a large synchronous spatial extent and a sudden onset. Such characteristics are shown by sound in the ocean. Cetaceans and particularly the deep-diving whales were known to be especially affected by low and mid-frequency anthropogenic sound, even at quite low received levels (Watkins *et al.*, 1985; Finley *et al.*, 1990; Finley and Greene, 1993; Bowles *et al.*, 1994; Richardson and Würsig, 1997).

Research on LFAS began by NATO in 1981 (NATO-Saclantcen, 1993) and the US Navy's research on SURTASS LFA began about 1986 and a statement on its environmental impact was formally initiated in July 1996. It is worth noting that the first atypical mass stranding of Cuvier's beaked whale was in 1963 (Tortonese, 1963), shortly after the time that a new generation of powerful mid frequency tactical sonars became widely deployed (Balcomb and Claridge, 2001).

Hildebrand (2004) published a list (compiled by James Mead) of strandings of two or more Cuvier's beaked whales based on records at the Smithsonian Institution and recent literature (Table 4.2.1.1). This list is unlikely to be complete, but it represents all cases presently known. In only four of the cases, Greece 1996, Bahamas 2000, Madeira 2000 and Canary Islands 2002, is it documented that navy vessels were in the area, operating sonar at the time and place of the stranding, and partial or complete necropsies were undertaken. No necropsy results are available for any of the other events. It should be noted that it has proven very difficult to demonstrate whether or not military sonar was in use sufficiently near the stranding sites to be considered as a possible cause of the stranding. It is recommended that in future, systematic efforts be made to determine if any abnormal noise has been made near mass strandings. It is worth noting also that some other strandings, not categorised as mass strandings, could be caused by the same mechanism as behind the mass stranding. These records have not been reviewed for possible correlation with presence of naval vessels.

Since the stranding in the Kyparissiakos Gulf, Greece in 1996 (see Section 4.2.2 below), there has been increasing attention paid to the effects of sonar. Sections 4.2.2 – 4.2.4 illustrate some of the findings based on three case studies of incidents.

Table 4.2.1.1 Strandings involving at least 2 Cuvier's beaked whale *Ziphius cavirostris* (Zc) (after Hildebrand, 2004; Brownell *et al.*, 2004; Martín *et al.*, 2004; Litardi *et al.*, 2004). "Strandings" refers to individuals that became stranded on beaches and does not imply death (some were redirected out to sea and their fate is unknown). Items listed 'U.S. Fleet?' and 'Naval manoeuvres' represent mostly the word of locals that military ships might have been in the general area and cannot be taken as necessarily linked. These records also represent the only known multiple stranding events for Gervais' beaked whale *Mesoplodon europaeus* (Me) and Blainville's beaked whale *Mesoplodon densirostris* (Md).

Year	Location	Species (numbers)	Correlated activity, when available
1914	New York, United States	Zc (2)	
1960	Sagami Bay, Japan	Zc (2)	?US Fleet
1963	Gulf of Genoa, Italy	Zc (15+)	Naval manoeuvres
1963	Gulf of Genoa, Italy	Zc (15+)	Naval manoeuvres
1963	Sagami Bay, Japan	Zc (8-10)	?US Fleet
1964	Sagami Bay, Japan	Zc (2)	?US Fleet
1965	Puerto Rico	Zc (5)	
1966	Ligurian Sea, Italy	Zc (3)	Naval manoeuvres
1967	Sagami Bay	Zc (2)	?US Fleet
1968	Bahamas	Zc (4)	
1974	Corsica	Zc (3), Striped dolphin (1)	Naval patrol (?not sonar)
1974	Lesser Antilles	Zc (4)	Naval explosion
1975	Lesser Antilles	Zc (3)	
1978	Sagami Bay, Japan	Zc (9)	?US Fleet
1978	Sagami Bay, Japan	Zc (4)	?US Fleet
1979	Sagami Bay, Japan	Zc (13)	?US Fleet
1980	Bahamas	Zc (3)	
1981	Bermuda	Zc (4)	
1981	Alaska, United States	Zc (2)	
1983	Galapagos	Zc (6)	
1985	Canary Islands	Zc (12+), Me (1)	Naval manoeuvres
1986	Canary Islands	Zc (5), Me (1), *Ziphiid* sp. (1)	
1987	Canary Islands	Me (3)	
1987	Sagami Bay, Japan	Zc (2)	?US Fleet
1987	Italy	Zc (2)	
1987	Canary Islands	Zc (2)	
1988	Canary Islands	Zc (3), bottlenose whale (1), pygmy sperm whale (2)	Naval manoeuvres
1989	Sagami Bay, Japan	Zc (3)	?US Fleet
1989	Canary Islands	Zc (15+), Me (3), Md (2)	Naval manoeuvres
1990	Sagami Bay, Japan	Zc (6)	?US Fleet
1991	Canary Islands	Zc (2)	Naval manoeuvres
1991	Lesser Antilles	Zc (4)	
1993	Taiwan	Zc (2)	
1994	Taiwan	Zc (2)	
1996	Greece	Zc (12)	LFAS trials (see Section 4.2.2)
1997	Greece	Zc (3)	
1997	Greece	Zc (9+)	Naval manoeuvres
1998	Puerto Rico	Zc (5)	
2000	Bahamas	Zc (8), Md (3), *Ziphiid* sp. (2), minke whale (1), *Balaenoptera* sp. (2),	Naval mid-frequency sonar (see Section 4.2.3)

		Atlantic spotted dolphin (1)	
2000	Galapagos	Zc (3)	
2000	Madeira	Zc (3)	Naval mid-frequency sonar
2001	Solomon Islands	Zc (2)	
2002	Canary Islands	Zc, Me, Md (15-17 whales)	Naval mid-frequency sonar (see Section 4.2.4)
2002	Mexico	Zc (2)	RV Ewing seismic

Møhl (2004) points out that sperm whale clicks bear some resemblance to those of tactical sonars (Table 4.2.1.2). The main differences are the ping energy – a receiving animal would need to be 30-100 times closer to a sperm whale than a tactical sonar to receive the same sonic energy. The duty cycle (or proportion of overall time that the noise is made) is also much higher in tactical sonar and the directionality of each is different – sperm whales emitting a very narrow beam of sonic energy compared to the wide radiation pattern of the tactical sonars. Møhl (2004) felt that this similarity in properties between a natural noise source compared with the novel sources indicated that behavioural rather than physiological causes would be more likely to cause the multiple beaked whale strandings.

Table 4.2.1.2 Properties of sonar signals from sperm whales and tactical sonars (Møhl, 2004).

	Sperm whale	AN/SQS-56	AN/SQS-53C
Source level (dB re 1 µPa)	235	223	235+
Ping duration (ms)	0.1	500	500
Ping energy (dB re 1 µPa*s)	196	221	233
Repetition rate (pings/s)	1	0.125	0.125
Duty cycle (%)	0.01	6.2	4 – 8
Frequency (kHz)	5 – 20	6.8, 7.5, 8.2	2.6, 3.3
Spectrum type	Broad band	Narrow band	Narrow band
Directionality (half-power, half angle, degrees)	4	360x30	120x40

4.2.2 Case study: Greece

During the early hours of the morning of 12 May 1996, Cuvier's beaked whales started to strand alive in several locations along Kyparissiakos Gulf (a long sandy beach alongside the Hellenic Trench in the west coast of the Peloponnese (Frantzis, 1998, Figure 4.2.2.1). The strandings continued until the afternoon of 13 May 1996. A few more specimens (4-5) were reported as stranded and rescued, entangled and rescued, or swimming very close to the coasts during the next 3 days, however, only one of these reports could be confirmed. In total, 12 stranded whales were recorded on 12 and 13 May. They were spread along 38.2 kilometres of coast and were separated by a mean distance of 3.5 km (s.d. = 2.8, *n* = 11) (Fig. 4.2.2.1). Another whale stranded on 16 May and was driven back to the open sea. Two weeks later, one more animal was found decomposing on a remote beach of the neighbouring Zakynthos Island, 57 km away from the closest stranding on the mainland. Eleven of the whales were measured and sampled. Nine of them were immature males with no erupted teeth and two were females. The recorded spread of the stranded animals in location and time was atypical, as whales usually mass-strand at the same place and at the same time. The term "atypical mass stranding" has been proposed for the recorded strandings as opposite to typical mass strandings known mainly from pilot whales *Globicephala* sp. and false killer whales (Geraci and Lounsbury, 1993).
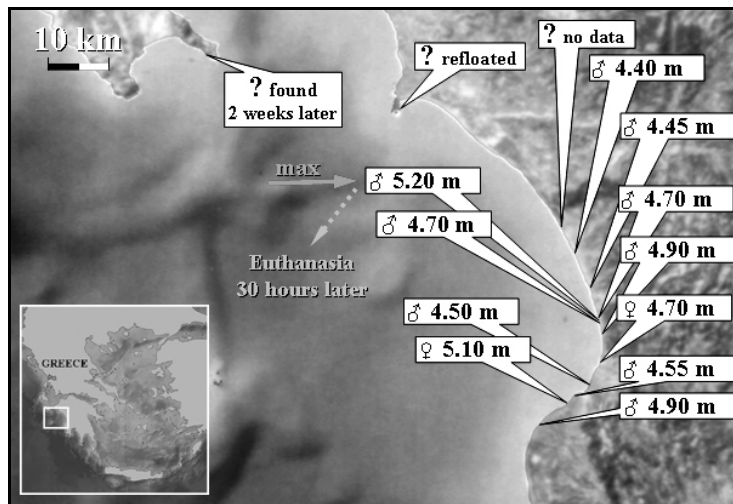
Figure 4.2.2.1 Position, sex and total length of the 14 Cuvier's beaked whales that were recorded during, or shortly after the mass stranding of 12 and 13 May 1996 in Kyparissiakos Gulf, Greece.

Necropsies of eight stranded animals were carried out, but no apparent abnormalities or wounds were found. These necropsies were limited to basic external examination and sampling of stomach contents, blood and skin. No ears were collected; no entire organs or histological samples were conserved because of many problems related to permits, lack of facilities and means, and lack of relevant knowledge and trained specialists. Stomach contents had variable quantities of squid remains (like beaks and ocular lenses) from three different squid species. Many of them contained cephalopod flesh, indicating that recent feeding had taken place.

All available information regarding the conditions associated with the mass stranding of May 1996 was gathered, and many potential causes were listed and examined. The most important of them were major pollution events, important tectonic activity, unusual geochemical/physical/meteorological events, magnetic anomalies in the area, epizootics and conventional military exercises. However, none of the potential causes listed above coincided in time with the mass stranding or could explain its characteristics (NATO-Saclantcen, 1998). Several months after the mass stranding a warning to mariners issued by the Greek Hydrographic Service was found by cetacean researchers that provided significant relevant information. This warning (586 of 1996) stated that 'sound-detecting system trials' were being performed by the NATO research vessel *Alliance* from 24:00 11 May to 24:00 15 May - a period that encompassed the mass stranding. The officially declared area where the sea trials had been carried out enclosed all the co-ordinates of the stranding points. The tests performed were for Low Frequency Active Sonar (LFAS; term used by NATO to describe their dual low- and mid-frequency active sonar), a system that introduces very high level of low and medium frequency sound into the marine environment to detect quiet diesel and nuclear submarines. Detailed information regarding the time schedule, the runs (Figure 4.2.2.2) and the specific sound characteristics of the transmissions became declassified and available through NATO-Saclantcen by the autumn of 1998 (NATO-Saclantcen, 1998). The *Alliance* was using high power active sonar, transmitting simultaneously to both low (450-700 Hz) and mid (2.8-3.3 kHz) frequencies, at a maximum output of 228 dB re 1 µPa @ 1 m, which enables long detection ranges.
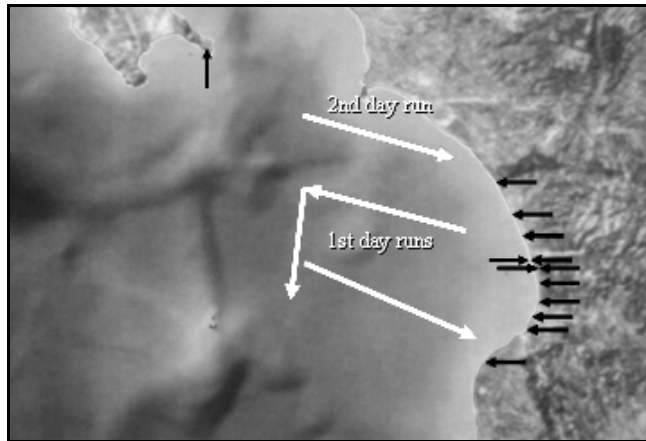
Figure 4.2.2.2. Routes of the first and second day of the LFAS tests (12 and 13 May 1996) according to NATO-Saclantcen (1998). The black arrows indicate the stranding positions of the whales during the same days, with the position of the whale found in Zakynthos Island.

Although the available data in 1996 could not directly prove that the use of active sonars caused the mass stranding in Kyparissiakos Gulf, the evidence clearly pointed to the LFAS tests. The main arguments and the supporting evidence are listed below:

- At least 12 of the 14 animals stranded alive in an atypical way.
- The condition of the stranded animals, along with the analyses of their stomach contents was not consistent with pathogenic causes (which anyway are not known to provoke atypical mass strandings).
- No unusual environmental events occurred before or during the stranding (e.g. tectonic activity, magnetic anomalies, geophysical or geochemical events, meteorological events etc.).
- The stranding characteristics suggested a cause with large synchronous spatial extent and sudden onset (i.e. those shown by sound in the ocean).
- Most importantly, the probability for the two events (i.e. the LFAS tests and the mass stranding) to coincide in time and location, while being independent, was extremely low. In other words if the 16.5-year period before the mass stranding is considered (1981 was chosen arbitrarily because this was the year that NATO started to experiment on LFAS, and we are sure that no mass stranding, nor other tests of LFAS had occurred in the area since that year), the probability of a mass stranding occurring for other reasons during the period of the LFAS tests (i.e. from 12 to 15 May 1996 instead of any other day) is less than 0.07%

Today, after three repeated mass strandings that followed the Greek case with similar characteristics and always in close association with naval exercises and use of mid-frequency active sonar in the Bahamas (see below), Madeira, and Canary Islands (see below), there is no dispute in the scientific community regarding the cause of the mass stranding in Kyparissiakos Gulf. If, after this case, more effort had been invested in mitigation, and military sonar had not been used in sea areas known to have many beaked whales, then the mass strandings that followed may have been avoided.

The Cuvier's beaked whale stranding history of Kyparissiakos Gulf (Fig. 4.2.2.3) shows that although no mass strandings had been recorded before the 12 May 1996 the strandings of this species were not rare. The average stranding rate was 0.88 individual/half year (s.d. = 0.99, n = 8). After the mass stranding of May 1996, the stranding rate was reduced to less than one third of what it was before the mass stranding (0.25 individual/half year, s.d. = 0.45, n = 12). This alarming result indicates that the damage could be significantly higher than the death of the stranded whales. Many others may have left the area or may have died in the deep offshore waters.
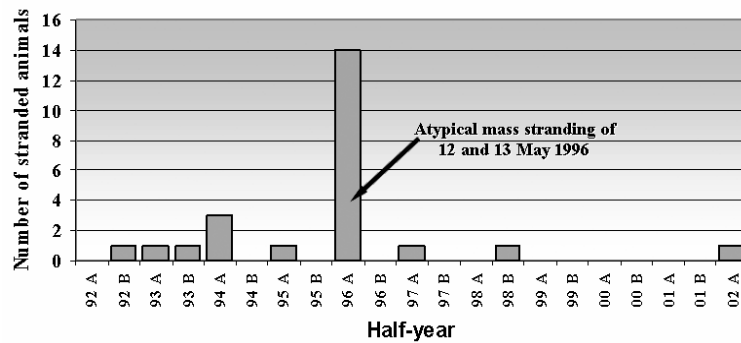
Fig. 4.2.2.3: The stranding history of Cuvier's beaked whales in Kyparissiakos Gulf from 1992 to 2002.

4.2.3 Case study: Bahamas

4.2.3.1 Introduction

On March 14 and 15, 2000, five U.S. Naval ships using mid frequency (2-10 kHz) sonar transited the Northeast and Northwest Providence Channels of the Bahamas Islands in an anti submarine warfare exercise lasting 16 hours. The ships were using two types of mid frequency sonar, designated AN/SQS-56 and AN/SQS-53C, that differed somewhat in their operating characteristics. The AN/SQS-56 closely resembles mid-frequency tactical sonars used by many other navies of the world. The ships operated in two loosely coordinated groups that passed through the channel six hours apart.

Beginning on March 15 only hours after the first group of ships passed, and continuing for the next 36 hours, 17 cetaceans were found stranded dead or alive, or in shallow water, along a 240 km stretch of the Northeast and Northwest Providence Channels on three islands (Figure 4.2.3.1.1). The Bahamas Marine Mammal Survey discovered the stranding, and they, Dr. Alan Bater, veterinarian for Bahamas Department of Fisheries, and members of the public pushed some of the stranded animals back into deeper water, and preserved for post mortem examinations tissues from those that died. The preserved specimens were shipped to the U.S. mainland and distributed among several pathologists for broad-based analysis of the cause of death.

The U.S. Navy was informed about the event and immediately started summarizing ship tracks and times, and modelling acoustic propagation from the sonars. The National Oceanic and Atmospheric Administration (NOAA) sent representatives of its stranding program to the Bahamas to assist in handling the biological specimens. It later sent specimens to a number of researchers for histological and toxin studies. Navy and NOAA each prepared verbal reports of their own findings, and in June 2000, the two agencies met for the first time and exchanged information. Subsequently, each agency prepared a written version of its report and submitted them to two editors (Cdr. Paul Stewart for Navy and Dr. Roger Gentry for NOAA) who compiled an interim report on progress to date. The report included the results of NOAA acoustic monitoring of the Bahamas region on the days of the sonar exercise and stranding (Evans and England, 2001).

4.2.3.2 Findings

The Navy sonar systems produced a sound approximately every 12 seconds. Except for one four hour period when one of the ships produced source levels that are classified, the source levels of all ships during the remainder of the exercise did not exceed 235 dB re 1 μPa. Complex propagation modelling showed that because of a surface duct, the sound was largely confined to the top 200 m of the water column, and that in many areas of the channel levels of

160 dB re 1 μPa would have occurred. Reverberation from the walls or floor of submarine canyons is not thought to have added much to these levels because of the surface duct. Whale locations at sea were unknown, so received levels cannot be estimated with confidence.

The animals that stranded included Cuvier's and Blainville's beaked whales, minke whales *Balaenoptera acutorostrata*, and an Atlantic spotted dolphin *Stenella frontalis*. An animation that plotted ship positions by time, and the time and place of each stranding showed a close temporal and spatial correlation for all but the spotted dolphin.

Seven of the stranded animals died, including five Cuvier's beaked whale, one Blainville's beaked whale, and a spotted dolphin. The latter may have died of causes not associated with acoustic exposure, and in a very different location than the beaked whales. Four of the beaked whales showed some evidence of auditory structural damage, including bloody effusions near and around the ears. The two freshest specimens showed subarachnoid haemorrhage and blood clots in the lateral brain ventricles. It is reasonable to assume the haemorrhages were acoustically induced. The immediate cause of death appeared to be cardiovascular collapse and physiological shock which together commonly result in death after stranding.

NOAA's investigation considered every possible cause of the stranding event, and eliminated all except sonar as the triggering event. Explosions were eliminated by NOAA's acoustic recordings. The evidence that most strongly suggested sonar as the triggering event was the close temporal and spatial match between sonar passage and the stranding events. The underlying mechanism by which sonar had this effect is still not known. It is possible but highly doubtful that direct acoustic exposure of tissues caused the lesions observed. All animals would have had to be very close to the vessels to receive such exposure, which seems unlikely. It is possible that sonar triggered some kind of unfavourable behavioural response which led to stranding and to subsequent tissue injury. It is also possible that some injury occurred before and some after stranding.
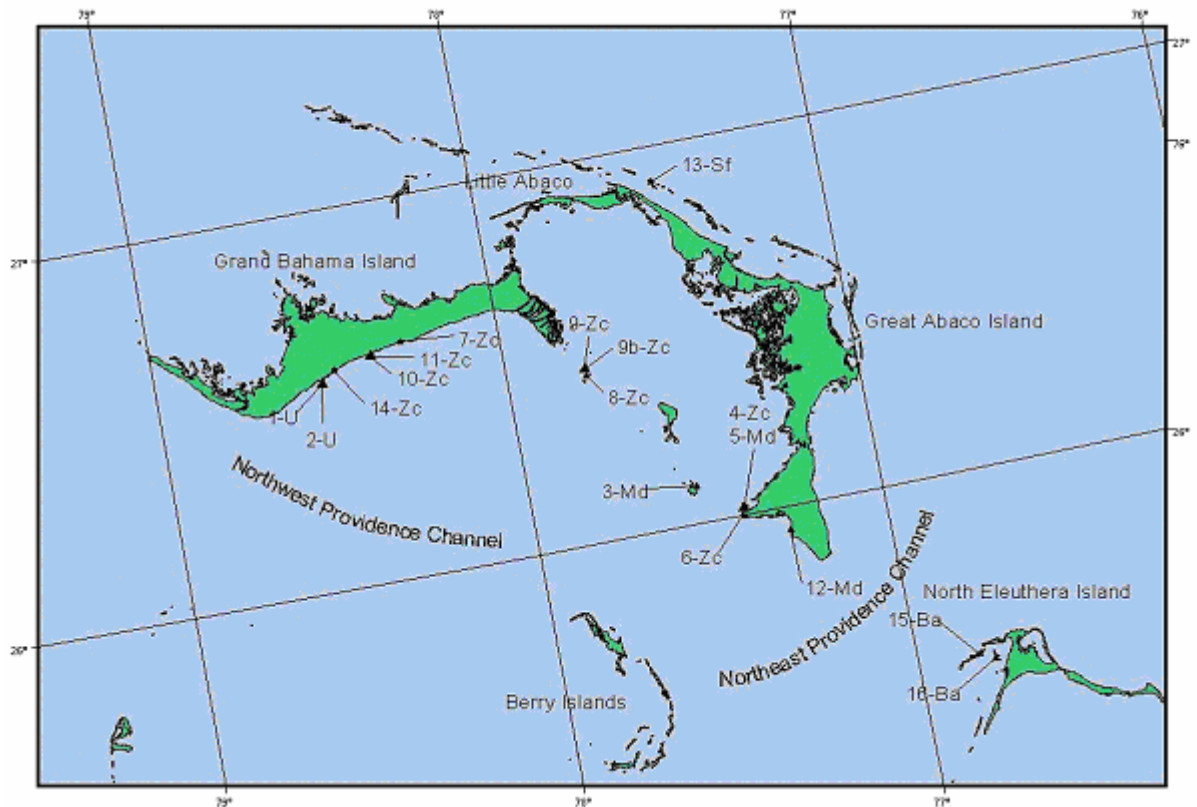
Figure 4.2.3.1.1. Locations of seventeen marine mammals that were stranded following anti-submarine exercises in the Northeast and Northwest Providence Channels, Bahamas Islands, on 14-16 March 2000. Initials indicate scientific names, numbers show specimen number. Zc = Cuvier's beaked whale *Ziphius cavirostris*, Md = Blainville's beaked whale *Mesoplodon densirostris*, Sf = Atlantic spotted dolphin *Stenella frontalis*, U = unidentified ziiphid, Ba = unidentified baleen whale.

4.2.3.3   Conclusions

The association of mid frequency sonar with this, the Madeira, and the Canary Islands strandings suggests that it was not the low frequency component of the NATO sonar that triggered the stranding in Greece in 1996, but rather the mid frequency component.

NOAA is arranging for a final report of the Bahamas event to be written after team members become more familiar with Canary Islands material and after they revisit all of the analyses that went into the Interim report.

4.2.4   Case study: Canary Islands

Mass strandings involving beaked whales had repeatedly coincided with the proximity of military manoeuvres from 1988 to 1991 in the Canary Islands (Vonk and Martin 1989; Simmonds and Lopez-Jurado 1991); however no data regarding the nature of the military activity and the possible use of active sonar that was taking place are available.

On 24 September 2002, fourteen beaked whales were stranded on Fuerteventura and Lanzarote Islands in the Canary Islands, close to the site of, and at the same time as, an international naval exercise code-named Neo-Tapon 2002. Strandings began about 4 hours after the onset of the use of mid-frequency sonar activity. Eight Cuvier's beaked whales, one Blainville's beaked whale and one Gervais' beaked whale were necropsied and studied histopathologically. A study of the lesions of these beaked whales provided evidence of the possible relationship between the sonar activities and the deaths of the whales.

Macroscopically, whales had severe, diffuse congestion and haemorrhage especially around the acoustic tissues in the jaw, ears, brain, and kidneys. Fat emboli and lesions consistent with *in vivo* bubble formation were observed in vessels and parenchyma of vital organs (Jepson *et al*., 2003; Fernandez *et al*., 2004, in press). This *in vivo* bubble formation associated with sonar exposure may have been caused by modified diving behaviour (in response to sonar) driving nitrogen super-saturation in excess of a threshold value normally tolerated by the tissues (as occurs in decompression sickness). Alternatively, a physical effect of sonar on *in vivo* bubble precursors (gas nuclei), the activation level of which may be lessened by nitrogen gas super- saturation of the tissues may explain the phenomenon (e.g. Crum and Mao, 1996). Exclusively or in combination, these mechanisms might initiate, augment and maintain bubble growth or initiate the embolic process. Severely injured whales died or became stranded and died due to a more severe cardiovascular collapse during beaching.

Martín *et al*. (2004) describe this incident as well as eight other cases that have occurred in the Canary Islands (see Table 4.2.1.1). These last cases include also a record of a single dead floating body of a Cuvier's beaked whale found at sea coincident with a naval exercise. Although no link can be demonstrated, as the carcass was not necropsied, this and other records at sea indicate that animals may be killed by sonar interactions and not just die on beaches following stranding.

4.3   Other cetaceans and sonar

As can be seen from Table 4.2.1.1, a number of other species have stranded coincident with strandings of beaked whales. These include dolphins (striped, Atlantic spotted), baleen whales (minke) and two pygmy sperm whales (these latter are also deep diving species). If these other strandings are linked to those of the beaked whales, the mechanisms are not known.

4.3.1   Research on LFA and cetaceans

In what became known as Phase I of LFA research, Croll *et al.* (2001) reported on the behaviour of foraging blue and fin whales exposed to loud low-frequency noise from the US Navy's SURTASS LFA. The behaviour of the whales was watched by observers who were unaware when the transmissions were occurring. During transmission, 12–30% of the estimated received levels from the LFA by the whales in the study area exceeded 140 dB re 1 μPa. However, whales continued to be seen foraging in the region. Overall, whale encounter rates and diving behaviour appeared to be more strongly linked to changes in prey abundance associated with oceanographic parameters than to LF sound transmissions. In some cases, whale vocal behaviour was significantly different between experimental and non-experimental periods. However, these differences were not consistent and did not appear to be related to LF sound transmissions. At the spatial and temporal scales examined, these authors found no obvious responses of whales to a loud, anthropogenic, LF sound. Croll *et al.* (2001) considered it perhaps likely that brief interruption of normal behaviour or short-term physiological responses to LF noise at RLs of approximately 140 dB re 1 μPa have few serious welfare implications and no serious effects on survival and reproductive success in cetacean populations. However they note that long-term impacts (e.g. displacement, masking of biologically important signals), while more difficult to identify and quantify, may be biologically significant through reductions in foraging efficiency, survival, or reproductive success.

In Phase II of the LFA research program, grey whales migrating south along the coast of California were exposed to a single LFA source suspended from a vessel moored in the narrow migratory corridor and producing a 42 second sound once every 6 minutes. Tyack and Clark (1998) reported that

- animals deviated out of their migratory pathway when received levels were about 140 dB re 1μPa,
- there was a steady increase in avoidance with received level, and
- higher levels were required to achieve the same avoidance when signals were of shorter duration and lower duty cycle (a reference to airgun work by Malme *et al.* 1985).

More significantly, when the LFA source was moved 1 km seaward of the migratory corridor, grey whale course deviations no longer occurred regardless of received level. This shows that whether course deviations will occur depends on the context (source in or out of the corridor) rather than on received level per se.

In Phase III of the LFA research program, humpback whales singing during the breeding season in Hawaii were exposed to an LFA source suspended from a moving ship. Miller *et al.* (2000) report results from 18 playback experiments in which a singing whale was followed and recorded from a small boat before, during, and after playback. Five of these singing whales may have responded to playbacks at received levels ranging from 120-150 dB (rms) re 1 μPa by stopping singing. Miller *et al.* (2000) also report a significant increase in song length by about 29% during playback. Fristrup *et al.* (2003) analysed 378 songs recorded from the focal whales, as well as any other that were audible. They also found an increase in song length, but they report that the peak of this response was delayed 1-2 hours after the playback ended and was correlated with the source level of the playback. They found no evidence of the cumulative effect of receiving multiple 'pings'.

No stranding, injury, or major behavioural change has yet been associated with the exclusive use of low frequency sonar.

5 Mitigation measures for cetaceans

5.1 Introduction

As described above, the only major effect noted on cetaceans from sonar comes from high intensity mid frequency military sources. This section therefore focuses on this usage, though the principles may be extended more widely.

In order for mitigation to be considered, it is necessary to know

1. the species that might be present,
2. their sensitivity to the noise and hence the area that might be affected;
3. the population density, such that the number of individuals that might be in this affected area can be calculated, and
4. the significance of the effect, or the risk of that effect, on those individuals or their stock.

If the environmental consequences are deemed too great, then use must be made of suitable mitigation measures to reduce the impact to an acceptable level. Note that decisions on whether or not an environmental consequence is too great are societal choices rather than a scientific fact. Examples where the effects of noise might not be acceptable include

1. where species are displaced away from a significant proportion of their feeding grounds;
2. where the species are endangered, and management is required to apply particularly risk-averse measures;
3. where the noise is in confined waters, on a migratory route, and is of sufficient duration that a significant proportion of a migratory period would be blocked;

4. where the effect of the noise on marine mammals itself has an economic impact, as for instance if whales were displaced from a whale watching area.

In many cases the noise may cause an effect which is of no environmental significance. For instance, a behavioural effect in which cetaceans are simply displaced from the area of the sonar operation to another area of similar habitat for a limited period may well be unimportant.

It is difficult to comment on the practicality of mitigation possibilities as the actual military requirement to use high intensity low- and mid-frequency sonar has not been defined in detail. From first principles though, there are three obvious mitigation possibilities, a) limit overall use, b) limit area of use and c) limit season of use. It is assumed that it would not be possible to reduce the source level, as it seems unlikely that this would not be as high as it is unless such power was needed for operational reasons. Limits on overall use would reduce risk to cetaceans, while limiting the area of use away from those known or thought to be important to beaked whales may be the most efficient way of reducing risk. The difficulty with this is that our knowledge of beaked whale biology and habitat needs is still fairly rudimentary and this species is comparatively difficult to detect in the wild. Acoustic detection may present a way forward, but even here, there is little knowledge of the acoustic behaviour of beaked whales. The calls of Cuvier's beaked whales have been recorded four times (Manghi *et al*. 1999, Frantzis *et al*. 2002; Aguilar de Soto *et al*. 2004; Johnson *et al*. 2004). While the first three recordings in the presence of Cuvier's beaked whale suggested that they may produce both whistles and pulsed sounds, Johnson *et al*. (2004) identified the vocalizing whale using an acoustic recording tag, and these data only recorded clicks with peak frequencies in the 40-50 kHz range, and little energy in the frequencies humans can hear. Whether these could be specifically separated from the other cetacean species is not known. Johnson et al. (2004) never recorded Cuvier's beaked whales clicking at depths <450 m, and they may therefore be more difficult to record at the surface than at depth. One recent solution for this problem would be to use autonomous submersible vehicles to 'sweep' an area, listening for beaked whales, for a period prior to the use of high intensity sonar. Plainly there is an area for great research and development here.

The aim of mitigation is to control and minimise environmental impact, and comprises control of noise at source, mitigation by use of engineering and other methods, and monitoring. The most extreme form of mitigation is to avoid carrying out the activity. In the case of sonar use, the development of simulators might be an alternative to using the sonar for training. It can be assumed that sonar use is required at sea though.

5.2 Control at source

Of key importance is the use of the minimum source power to achieve an adequate resolution or range. Mitigation can take the form of reducing the total amount of sound produced, possibly by reducing power, duration and/or by reducing the number of times a system is transmits sound. Where the species of concern has a well-defined hearing sensitivity, it may be possible to operate at frequencies where the animal's hearing is relatively insensitive. We do not know the characteristic(s) of the mid frequency sonar that causes problems for beaked whales – determination of the characteristic(s) and of its precise effect on beaked whales might help in enabling a sonar to be designed that does not affect beaked whales.

5.3 Mitigation of death and injury caused by the direct effects of sound

The range at which death or injury due to the direct effect of sound levels (as opposed to behavioural alteration that may lead to death) can occur is limited. Hence the likelihood of a

marine mammal straying into the area prior to the commencement of a sonar transmission is relatively low unless there is a large degree of overlap between important or critical beaked whale habitat and areas of sonar usage. Since the range of the effect is small, there are several mitigation measures that might be effective in preventing injury through the direct effects of sound. A first mitigation measure might therefore be to avoid areas of known beaked whale abundance. Second, it might be possible to regulate the use of sound if marine mammals are detected close to the source. Such detection could occur in two main ways:

5.3.1 Marine Mammal Observers (MMOs)

MMOs are trained observers who aim to visually detect and identify marine mammals, at distances of up to 500 m during daylight hours. Their use is mandatory during UK and some other nation's offshore seismic surveys. It may be possible to watch for whales prior to commencing sonar operation and not start transmitting sound if whales are seen or to cease operations if whales enter the area during transmission. However, beaked whales in particular are very difficult to detect and spend a long time under water; in addition the approach does not work in poor visibility or at night. The efficiency of this mitigation measure is low under many conditions likely to be encountered in naval sonar operation.

5.3.2 Passive Acoustic Monitoring (PAM) or Active Acoustic Monitoring (AAM)

Both passive and active acoustic monitoring may be used to detect marine mammals. Passive acoustic monitoring is the term used for listening passively to sources of sound, while active acoustic monitoring is the term used for producing sounds and listening for echoes from nearby objects. Active acoustic monitoring is thus a form of sonar and offers several potential advantages compared to passive. Unlike passive acoustic monitoring, which can only detect animals when they vocalize, active acoustic monitoring can detect non-vocalizing animals such as marine mammals or fish. Active acoustic monitoring can estimate the range of targets more easily than can passive monitoring. In spite of these advantages, active acoustic monitoring is relatively undeveloped compared to passive acoustic monitoring for detecting marine mammals. Both systems might be installed on remotely operated or autonomous vehicles to provide a sweep of a wider area or a longer time period than would be possible from one ship at one time.

Passive or active acoustic monitoring offers one way that a wider area might be surveyed for beaked whales. If the lethal effects observed in beaked whales are due to behavioural alteration caused by sound and not to the direct effects of the sound, then such wider area surveys are needed if sonar deployment is to be avoided near beaked whales. This though would be challenging to accomplish, as little is known of beaked whale vocalisations and suitable technology has yet to be developed.

5.4 Other control methods

Two other measures can be taken that would reduce the risk of exposure of marine mammals to loud sound (though as noted earlier, not necessarily risk to behavioural change):

5.4.1 Scheduling

Sonar transmissions may be timed for periods when the species are not in the area, for instance by avoiding migratory periods or periods where local breeding or calf-rearing grounds are used. However, as noted in earlier sections, this information is largely absent for beaked whales, so it is difficult to apply this measure without further research on the use that beaked whales make of certain areas of the sea.

5.4.2 Warning signals

The National Research Council (1994) advocated the development of 'warning signals' for marine mammals – sounds that would make marine mammals move away from dangers such as explosions, fast ships, or intense sound sources such as sonars. There has been little development and testing of warning signals, but Nowacek *et al.* (2004) demonstrated that even though right whales do not respond to vessel noise, they do show strong responses to signals designed to alert them. In the absence of information on what sounds cause avoidance reactions, regulators have required some intense sound sources to be increased in level slowly. In principle, such a "soft start" might offer animals a chance to move out of the danger zone, but this seemingly reasonable technique is unproven. Soft start should be viewed as a type of warning signal, one selected because the sound source is already there, not because it is necessarily effective. In most cases, it is more likely that warning signals specially designed to elicit the appropriate avoidance safely would be more successful than soft start. Since it is not known what levels of sonar sounds are safe for beaked whales, warning signals other than sonar sounds would likely pose less risk as well. Nothing is known about behaviours at lower sonar power levels, or in response to sounds other than mid-frequency sonar. In other situations (e.g. salmon farms), noise is used to deter marine mammals and it might be that suitable noises exist that could achieve this for beaked whales. There may be value in studying sounds that might elicit avoidance responses in beaked whales that do not pose the risks of sonars.

5.5 Monitoring

It is plain that much still needs to be learned about the interaction of marine mammals and sonar. Knowledge can be gained and potential mitigation measures identified through good observation and monitoring. Monitoring can include:

5.5.1 Noise monitoring

Anthropogenic noise levels may usefully be recorded in order to be matched against any behavioural reactions by cetaceans. Such recordings also enable the sonar to be ranked against other local sources of noise.

5.5.2 Marine mammal observation

The monitoring of local cetaceans would help confirm whether there is any obvious effect of the noise. Monitoring the distribution of individuals around the noise source can be by tagging, by using passive acoustic monitoring to detect vocalisation, or by using active acoustic monitoring.

The latter monitoring strategies may serve two purposes, either of demonstrating that there is an effect, or, if an effect is observed, of identifying the level at which it occurs. While it may be argued that the monitoring itself has an effect on the species, this effect may be outweighed by the process providing information which may be used in the longer term to conserve stocks of the species. It should be noted that no monitoring program can demonstrate that there is no effect, for the range of potential effects is large, and many effects would be too subtle for a generic monitoring program to detect. A more scientific approach would test for specific hypotheses about effects, with experiments designed with strong statistical power.

5.6 Mitigation measures in use for military sonars with regard to marine mammals

5.6.1 Guidelines for sonar research testing by NATO and marine mammal risk mitigation research at the NATO Undersea Research Centre

Carron (2004) describes the current NATO SACLANTCEN (now called the NATO Undersea Research Centre) marine mammal mitigation programme that has developed following the Greek incident (see Section 4.2.2). The goal of the mitigation programme is to develop a predictive tool for the presence of cetaceans and to develop an on-site acoustic risk mitigation rules, procedures and tools. These goals are being met through the collection of cetacean presence data along with relevant hydrographic information. The programme has developed habitat models for Mediterranean Sea species and has developed a prototype Environmental Scoping Tool Kit for use by planners. The programme has, in cooperation with research groups from many nations, performed controlled exposure experiments on sperm whales as a proxy for beaked whales. Data from 5 years of at-sea experiments have been collected by trained visual observers, passive and active sonar and the use of acoustic and non-acoustic sensors attached to the whales (in cooperation with the Woods Hole Oceanographic Institute). Information about these experiments can be found at http://solmar.saclantc.nato.int. The programme has also developed, in cooperation with Mediterranean nations, a Sightings and Strandings database. Graphical representations from this data base will be available in autumn 2005 on the web page above. The programme has played an important role in the analysis of beaked whale vocalizations and has developed a series of passive sensors tuned to listen for these vocalizations. Testing of these sensors will begin in autumn 2005.

The risk mitigation policy has several stages. The first requires a scoping study that determines the possible negative effects of sonar operations on the environment. It then establishes an exposure level above which risk mitigation must be applied. This exposure level is likely to vary geographically depending which species are present. One method of reducing risk will derive from the predictive tool referred to above, hopefully enabling planners to chose the times and localities where there will be fewest marine mammals. The second method is the use of observers along with passive acoustic monitoring in the area of any sonar use. If, during the hour prior to tests starting, marine mammals are detected in the area, the test does not commence. If marine mammals are detected during the test, the test is immediately suspended. The amount of noise produced by the sonar is also progressively increased prior to a full-scale test in order to give mammals a chance to move away. It should be noted that these rules apply only to tests conducted by the NATO Undersea Research Centre and does not necessarily apply to use by individual NATO naval vessels outside those tests. NATO is developing rules for use by operational forces acting under the NATO command to minimize risk to marine mammals during noisy operations.

5.6.2 Mitigation on UK naval vessels or in UK sonar tests

The UK Ministry of Defence has a policy that any activity which may have a potentially harmful impact on the environment requires mitigating measures to reduce any adverse effects. To this end, guidance has been developed for sonar use.

The guidance applies worldwide outside harbours to all Royal Naval ships, submarines and aircraft operating in-service active sonars (not including mine-hunting sonar) not covered already by other Environmental Impact Assessments (EIA). The guidance is only applied when it is operationally safe to do so. The guidance covers three phases, planning, monitoring and taking action.

5.6.2.1 Planning

When planning active sonar operations, consideration is given to avoiding marine sensitive areas. For UK waters, a chart of relevant statutorily protected marine areas is provided, more general materials are provided for other parts of the world. A more complete Environmental Risk Management System is under development to help UK forces further in this respect. In addition, the guidelines ask that local geography should be examined. The guidelines note that in the case of three well-documented whale stranding events where sonar was implicated (Greece, Canaries and Bahamas (see Section 4.2)), there were three key environmental elements present at all events:

    i.   The presence of a shelf break close to the coast;
    ii.   A bay, all be it very shallow in one of the examples;
    iii.   The documented presence of a beaked whale species.

5.6.2.2 Monitoring

The guidelines ask that prior to transmitting sonar, every opportunity should be taken to monitor the local area and observe for cetaceans/marine mammals. This includes both visual monitoring (both from the sonar source ship or aircraft, and from any other nearby ships or aircraft), and acoustic monitoring. Forms are provide to note down any marine mammals (or other obvious marine life) seen.

5.6.2.3 Taking action

The guidelines require that if marine mammals are encountered during the conduct of active sonar operations then action should be taken, where safe to do so, to minimise the potential disturbance. Attention is drawn to the following possible courses of action:

a.   Cease Transmissions - where operationally practical and safe to do so, the sonar or other acoustic device should be turned off to avoid disturbance.

b.   Reduce Power - if the option of turning off the sound source is not operationally practical, then the sonar should be operated at a reduced power setting, commensurate with the scale of operation.

Other guidance is given to avoid marine mammal collisions and low over-flights by aircraft.

5.6.2.4 Mitigation during development and testing of UK Sonar 2087

Sonar 2087 is a new sonar being developed for anti-submarine warfare that combines both active and passive elements to attempt to localise submarines at medium range (40 km+). Details of the sonar and the associated environmental programme are available at http://www.mod.uk/dpa/projects/sonar2087.htm. The sonar is being tested in a series of about 11 sea trials due to end in 2007, and a specific environmental assessment has been developed for these trials. The environmental assessment is dynamic (in other words it can be modified in the light of new information on the environment of the effects of the sonar on the environment) and has been subject to peer review. Key features of the mitigation are similar to those outlined for UK sonar use generally – the local environment that each trial is planned in has been described and taken into account in the planning process. A full team of visual and acoustic monitoring specialists are employed on both the trials ship and an independent monitoring vessel. If marine mammals are detected in the area, the commonest response is to reduce power in the sonar.

5.6.3 Mitigation on Australian naval vessels

A full description of the Australian system of reducing risk to marine mammals (particularly larger whales) has recently been finalised (Polglaze, 2005, J. Polglaze, pers. comm..). The elements of planning, monitoring and taking action outlined above are also present in the Australian system. The objectives of the first risk-reduction stages are achieved by the use of Planning Guides and Planning Handbooks. These are augmented by Procedure cards focused at the operational level of activities. Monitoring and action procedures have been codified onto a series of easily accessible procedure cards, each of which covers a 'family' of sonar equipment. Families of equipment include:

> Hull-mounted anti-submarine sonar
> Active towed arrays
> Active sonobuoys
> Minehunting sonar
> Acoustic decoys
> Hydrographic survey sonar
> Mine and obstacle avoidance sonar

Most of the procedures are visually- based, and ships can augment this with opto-electronic and/or infrared sensors. Radar is also an option but is considered of limited utility in most circumstances. Passive acoustic equipment is considered not reliable enough and cumbersome in use for surface ships, but is used in submarines that are much better equipped in this regard. In addition, submarine sonar operators are better trained in the use and interpretation of passive acoustics.

The core objective of the Australian approach is to detect all whales within 4000 yards; whales detected within this range (based roughly on a likely received levels of 160 dB re 1 μPa) lead to systems not being started up, or to the system being turned off/decreased in power, or the ship altering course to open the range. For those systems where sound can be directed, guidance is given to blank out sectors containing whales at a range of 2000 to 4000 yards, with a requirement to turn the system off under this range. The stand-off range of 4000 yards is based upon conservative modelling using credible 'worst-case' scenarios. Lesser stand-off ranges are mandated for systems with lower radiated power output.

5.6.4 Mitigation on Italian naval vessels

The Italian Navy currently has rules to control sonar use within the northern Tyrrhenian Sea (cetacean sanctuary) only but these are in the process of being extended to cover operations by the Italian Navy in all seas around Italy and when operating elsewhere (Cerutti, 2005.). These new rules, that take account of the NURC guidelines (see Section 4.1), are due to be adopted in summer 2006 for testing during a transitional period. Any necessary adjustments will be made in the following year. Several rules apply to the planning phase of any sonar use. Sonar use should i) avoid areas with steep (>5%) slopes and a bottom depth of 1000m to 2000m; ii) avoid acoustic trapping situations (e.g. canyons, bays, gulfs) and iii) keep 5000m outside the boundaries of 'important' areas (e.g. whale sanctuaries) iv) standard conservative stand-off ranges (based on disturbance and damage receiving levels, including some relevant margins) apply for hull mounted and dipping sonars. A database, aimed to help populate NURC's one, is being developed to help ships know where such areas are.

Prior to the start of sonar use, a search of 30 minutes using both visual and passive acoustic methods is conducted, with the sonar system not being started if marine mammals are detected within 1500m. If no marine mammals are detected, then the system is bought slowly up (ramp-up) to full-power over 15-30 minutes. If the sonar is turned off for whatever reason, these procedures are repeated if the system is not restarted within 30 minutes.

The Italian Navy also has procedures for use with sonobuoys and helicopter-mounted sonars. These are similar to those used with vessel-mounted systems, but with considerably truncated time periods. The search period is reduced to 2 minutes, with a 5 minute ramp-up period to full power.

5.6.5 Mitigation on US naval vessels during training and during exercises

The US Navy has adopted a series of policies similar to those outlined above (Stone, 2005). There are variations in these policies depending on the type and location of the proposed activity. For activities where there is a choice of location, pre-planning requires consideration of deepwater areas with no significant bathymetric features that form preferred habitat for marine mammals. Areas with known critical habitat for marine mammals should be avoided (e.g. NW Providence Channel and Puget Sound). In areas where sonars will be used, a computer-based system provides information on what cetacean species may be present in an area is available to help plan operations. This system also provides information similar to that given by the Australian card system. Bridge crew are trained as cetacean look-outs as part of a 200 hour training programme. Passive acoustic monitoring systems are deployed where possible.

Other measures required include:

- Post lookouts with binoculars – lookouts survey for presence of protected species before, during, and following the exercise
- Conduct training during daylight when feasible
- Ensure sea state and weather conditions support visual survey capabilities
- Aerial survey when inherent to the exercise
- Range and ships/submarines conduct passive acoustic surveys before/during exercises
- Report stranded, injured, or dead sea turtles or marine mammals

Codes are also available for aircraft (helicopter) use of sonar.

5.6.6 Future mitigation development

Gentry (2004) considered that most current naval operations are conducted with minimal or no mitigation measures in place and he identifies whale-finding sonar as the mitigation measure of the future. These are high-frequency low-power sonars and therefore have a limited detection range (about 2 km). Their acoustic energy is also low. A difficulty is that ships carrying mid-frequency military sonar operate at relatively high speed and therefore detections may occur too late to take any action. This technique looks very promising though – and it might seem logical to examine the possibility of using the tuna finding sonar described in Section 2.5.3.

We have not found any reference to any attempts or proposals to evaluate or mitigate the environmental effects of any non-military sonars.

6   Summary of gaps in understanding for marine mammals

As can be seen from the foregoing, there is much more that could be learned about the interaction of sonar and cetaceans. Knowledge on the nature of sound in water is reasonable, but its transmission in and around the shelf break/canyon systems cannot be modelled well. Such modelling would aid the understanding of effects on cetaceans. There is basic information on the hearing capabilities of a few species of cetaceans. The variance in these capabilities is not known and audiometric data on multiple animals of different sexes and ages

within a given species would elucidate this. The sound exposure factors that produce temporary hearing loss in cetaceans are now fairly well known and predictable, although there is still uncertainty about factors that produce permanent hearing loss.

Further research is needed on behavioural and physiological responses of deep-diving cetaceans to low- and mid-frequency sonars. This could be aimed particularly at trying to understand the sphere of influence of sonar noise on cetaceans. The level of sound that is 'safe' for beaked whales is not known. However the problem may not be level alone but may also involve duration or some other parameter that triggers a behavioural response. Probably the most reliable way to address this would be through controlled exposure experiments where both received sound level and any change in whale behaviour can be monitored simultaneously. Similar work has been carried out on northern right *Eubalaena glacialis* (Nowacek *et al.* 2004) and sperm whales (Tyack and Johnson, 2004).

For mitigation purposes, further study of the distribution of beaked whales (in particular) and subsequent modelling of favoured habitats would help in understanding which areas to avoid and surveying these beforehand would be a benefit. Further development of more reliable methods of detecting beaked whales and determining if they are in an area that might be influenced would be particularly helpful.

7   Other relevant items

7.1   Noise pollution as a more serious problem?

This section briefly reviews other relevant topics that might justify further future consideration, but which are outside the current terms of reference of the study group.

Croll *et al.* (2001), while finding no major indication of effect of LFA SURTASS noise on blue and fin whales at received levels of 140 dB re 1 µPa, noted that their study was of a relatively short duration and a small spatial scale to that used by these whales. They noted that anthropogenic low frequency noises in the ocean that mask sounds associated with foraging can decrease an animal's ability to find and capture food. This can decrease population growth rates if: (1) population growth is limited by food rather than predation or disease; (2) the species in question does not regulate the population size of its prey. In addition, many marine animals use sound to maintain contact between group members (e.g. females and their offspring), or for other forms of communication, particularly for reproduction. Again, anthropogenic noise in the ocean that masks these communication sounds can decrease the ability of individuals to establish or maintain contact with group members or potential mates.

For example, Payne and Webb (1971) estimated that low frequency noise pollution from shipping may have reduced the area over which blue and fin whales could communicate by several orders of magnitude. They estimated reductions from *c.* 2.1 million km^2 under pre-shipping conditions to *c.* 21,000 km^2 under 1970's shipping conditions, equivalent to a reduction in the effective range for communication from 2100 km to 210 km. Examples of the potential effects of such reductions could include: increased calf mortality, changes in group spacing from optimal or inability to locate and maintain mates.

Consequently, the most serious potential impact of anthropogenic low-frequency noise may be its potential contribution to a long-term decrease in a marine animal's efficiency in foraging, navigating or communicating. Some cetaceans (e.g. sperm whales, northern bottlenose whales) have extremely low potential population growth rates, are poorly known and difficult to study, consequently any small decreases in their reproductive rate could have serious impacts on population size. These would not be detected by any known monitoring system. In addition, recovery of endangered populations of the baleen whales (e.g. blue, fin, sei

Balaenoptera borealis and humpback whales) that were severely reduced by commercial whaling may be hampered if anthropogenic low frequency noise affects long-term reproductive success or survival in these species. As stated in section 3.2.3, large whale populations in California increased by 8.2% (Barlow, 1994) as noise was increasing by 10 dB over 33 years. It is not clear whether this trend will continue if anthropogenic sound levels continue to increase.

Noise from commercial vessel traffic, by far the most dominant source of anthropogenic noise in the ocean, is continuous, ubiquitous and shows no sign of decreasing. The intense signals generated by various military sonars and seismic operations, although typically operated only for periods of weeks in limited areas, are being used increasingly throughout the world's oceans. There is increasing use of high intensity acoustic sound sources in oceanographic research projects. While none of these individual sound sources has been shown to cause prolonged disturbance to a biologically important behaviour, they could have cumulative effects.

8   General conclusion for marine mammals

The full effects of sonar on cetaceans are not well known, mostly due to the difficulty of studying the interaction, and to a lesser extent because details of sonar equipment and usage are not easy to obtain.

There appear to have been no dire consequences of using high frequency, low or medium intensity sonar on cetaceans over the period that such navigation and surveying sonars have been in use. Nevertheless, there have been very few studies of the effects of sonar at these frequencies. The propagation properties of these frequencies in water will mean that any sphere of influence of a single source is comparatively small. The use of multiple sources in a wider area, such as in a location where many vessels are using navigational sonar will have a greater effect, and the possibility of this affecting the distribution of some cetaceans in these areas cannot be discounted.

The use of high-intensity mid frequency sonar has led to the deaths of a number of cetaceans in some places. From our very limited knowledge, it appears that beaked whales are the most affected species, in particular Cuvier's beaked whale. A characteristic of most of the known mortality incidents is that they have been on shores near to the shelf break and deep water habitat favoured by these species. It is unclear therefore if further undetected mortality is occurring where these habitats are further offshore. We do not know the precise mechanism causing the animals to beach themselves – many arrive ashore alive, but obviously distressed. It is unknown whether animals that are affected further out to sea can survive and not strand. The possibilities and consequences of these effects are summarised in Table 8.1.

Table 8.1. Summary of likely effects of sonar on beaked whales

Type of effect	Extent of effect	Severity of effect	Individuals affected	State of knowledge
Direct death and lethal injury	Very local	Severe	Few/none	Adequate for current purposes
Gas embolism	Medium scale	Severe	Small numbers?	Moderate
Sublethal injury	Medium scale	Unknown	Small numbers?	Poor
Behavioural (avoidance)	Widescale	Mild/long term	Large numbers	Poor

The magnitude of the problem involving beaked whales and sonar presently verifiable by science is as follows. We know of about 40 sonar-related deaths among cetaceans (mostly, if not all, beaked whales) over the last 9 years. A recent IWC report (Read *et al*., 2003) indicates that worldwide, fisheries kill several hundred thousand cetaceans as bycatch each year. We do

not know of the scale of beaked whale bycatches but 35 fishery-related beaked whale mortalities were observed in the pelagic drift gillnet fishery off the east coast of the USA between 1989 and 1995 and between 1991 and 1995 the total average estimated annual fishery-related mortality of beaked whales in the U.S. EEZ was 9.7 (CV = 0.08). Even accepting that some beaked whales affected by sonar may die uncounted at sea, nevertheless it seems likely that the fishery-related mortality of beaked whales alone is several times higher than that caused by sonar.

Many fishery managers and fishers are attempting to address bycatch through research and use of mitigation measures. Some fisheries have been closed due to the lack of suitable known mitigation measures. It is worth noting that initially strandings have often been the only indicator of by-catch as a potential threat (with relatively small numbers compared to estimated population size of cetacean populations of interest). It was often not until after specifically-targeted studies had quantified numbers caught and killed that it was found that bycatch for some cetacean populations was unsustainable. There are still major uncertainties, difficulties and unknowns in relation to estimating impacts of sonar and noise generally on marine mammals. Those using the environment have a responsibility to minimise environmental impact under many international agreements – this applies equally to those using high intensity low- and mid-frequency sonar. Some mitigation measures are possible already and others need further development. The use and development of these measures should be encouraged.

As outlined above, sonars also contribute to the global ocean noise budget and overall levels of noise in the ocean are increasing, at least in some areas. The potential effects of this increase, if communication vital to the life history and reproduction of some cetaceans is badly affected, could be worse than direct killing. It seems likely that if these effects are occurring, the large baleen whales would be the most affected by increases in low frequency noise; many stocks of these whales are already in a threatened or endangered state due to over-hunting in the past. Their recovery in California was apparently not stopped by a 10 dB increase in shipping noise, but clearly a further reduction in ocean noise is desirable as a precaution.

However, according to a noise budget for the oceans that will be published soon, shipping accounts for more than 75% of all human sound in the sea, and sonar amounts to no more than 10% or so. Sonar will probably never exceed 10% because it is driven by electricity which is difficult to produce, unlike air pressure (airguns) or the burning of oil (shipping). Shipping's contribution to ocean noise has been projected to increase greatly, especially in coastal areas, in the next 20 years.

It appears that sonar is not a major current threat to marine mammal populations generally, nor will it ever be likely to form a major part of ocean noise. Sonar can place individual whales at risk, and has affected the local abundance of beaked whales. Sonar deployment seems likely to increase in the future. The need to research ways of mitigating the effects of sonar is a priority for future research and development.

9 Fish

9.1 Biological background

9.1.1 Hearing in fish

9.1.1.1 Hearing abilities

It has long been evident that fish can hear and that they use sound to communicate with one another, locate prey organisms and detect threats from predators (Hawkins, 1992). The inner ear of fish is similar to that of other vertebrates. Indeed, the sensory hair cells in the fish ear are almost the same as those found in the mammalian ear (Popper *et al.*, 2003).

Experimentally, the sensitivity of fish to sounds is often determined by measuring thresholds to pure tones of different frequency. A plot of the minimum sound pressure detectable by the fish against frequency is called an audiogram. The thresholds themselves are usually determined by conditioning the fish to respond to sounds in return for a reward or mild punishment. Once the fish is trained the sound level is reduced until the fish no longer responds. By alternately raising and lowering the sound pressure the threshold may be determined with some precision. An alternative method is to measure the amplitude of some physiological response of the fish (microphonics from the ear or the Auditory Brainstem Response – ABR) and then to reduce the sound level until no response is detectable.

Examples of audiograms determined by conditioning methods are shown in Figure 9.1.1.1. It can be seen that the auditory capabilities of fish vary widely. This variation reflects the great diversity of structure found in fishes – the most numerous of vertebrates both in terms of biomass and number of species.
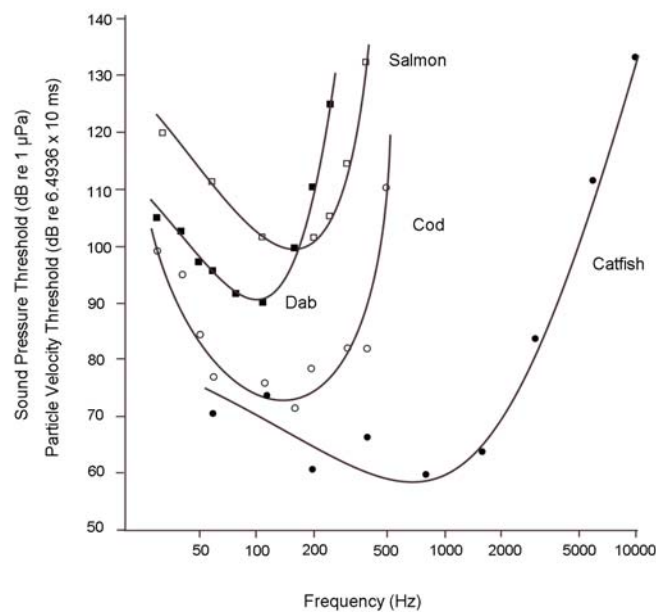
Figure 9.1.1.1. Audiograms for four species of teleost fish, showing the auditory thresholds or minimum sound levels detected by the fish at a range of different frequencies by means of conditioning experiments. The thresholds for the Atlantic cod _Gadus morhua_, (Chapman and Hawkins, 1973) and freshwater catfish _Ictalurus nebulosus_, (Poggendorf, 1952) are given in terms of sound pressure; those for the Atlantic salmon _Salmo salar_ (Hawkins and Johnstone, 1978) and dab _Limanda limanda_, (Chapman and Sand, 1974) are given in terms of particle velocity.

Auditory experiments require good acoustic conditions, where undistorted sounds can be accurately measured. Most hydrophones (underwater microphones) measure sound pressure (as particle velocities are generally very small) and most audiograms are expressed in terms of sound pressure. In a free sound field, a measurement of the sound pressure can be used to calculate the particle velocity. Most aquarium tanks are deficient in this respect as the walls reflect sound. In a small tank, or in the presence of reflecting surfaces, the relationship between sound pressure and particle velocity is difficult to estimate. Some fish are sensitive to particle velocity rather than sound pressure, and to examine the sensitivity of these fish it is necessary either to build a special tank in which the particle velocity can be estimated, or to conduct the experiments in the field, where good acoustic conditions prevail. Many published audiograms for fish are flawed, because they were measured under poor acoustic conditions, without ascertaining whether the fish were sensitive to particle velocity or sound pressure.

Several general conclusions can be drawn from the audiograms available from fish. Firstly, fish are sensitive to a rather restricted range of frequencies compared with terrestrial vertebrates. Even the most sensitive fish have poor hearing above 2-3kHz (in contrast humans are sensitive to frequencies up to and even above 15 kHz). There are one or two exceptions; some fishes do appear to be sensitive to ultrasonic frequencies. Studies have shown that some clupeid species, including alewife _Alosa pseudoharengus_, American shad _Alosa sapidissima_ and gulf menhaden _Brevoortia patronus_, actively avoid ultrasonic sources and can detect sounds at frequencies higher than 20 kHz (Dunning _et al._ 1992; Nestler _et al._ 1992; Ross _et al._ 1995, 1996; Mann _et al._ 1997, 1998, 2001). Other clupeids, including bay anchovy _Anchoa mitchilli_, scaled sardine _Harengula jaguana_, Spanish sardine _Sardinella aurita_ and Atlantic herring _Clupea harengus_ do not detect ultrasound (Mann _et al._ 2001, 2005). However, the majority of fish are sensitive to relatively low frequencies, in some cases extending into the infrasonic range (Sand _et al._, 2000).

Within their restricted frequency range, many fish are acutely sensitive to sound. At some frequencies, some species, including the cod, are not limited by their absolute sensitivity but by their inability to detect sounds against a background of ambient noise, even under relatively quiet sea conditions (Hawkins and Chapman, 1975). Any increase in the level of sea noise results in a decline in sensitivity. Indeed for these species, any differences seen in their audiograms may result from different levels of ambient noise during the conduct of the experiments. In contrast, other species like the Atlantic salmon show an absolute limit to their sensitivity and are only limited by sea noise at higher sea states

Impairment of the detection of a sound in the presence of background noise is known as masking. However, it has been established that not all frequencies contained within the background noise are equally effective at masking. Experiments with Atlantic cod (Hawkins and Chapman, 1975) and Atlantic salmon (Hawkins and Johnstone, 1978) have shown that only the frequencies in a narrow band on either side of a masked tone (the critical band) contribute to masking. Thus, both Atlantic cod and Atlantic salmon employ an auditory filter to remove the masking effect of frequencies away from the sound being listened to. The filter in the cod is rather narrower than the filter in the salmon. The bandwidth of this filter is frequency-dependent. The filters may not be static but can vary depending on the detection task (e.g. the band width of the signal; see Swets 1964 for a discussion on this topic). This makes the interpretation of the critical band concept difficult. Nevertheless, studies have shown that integrating the noise over a certain bandwidth in signal detection tasks is useful for modelling the signal detection abilities by most, if not all, vertebrates (Fay 1991).

In practical terms, to determine the range over which a sound can be detected by a fish it is necessary to know the source level and frequency characteristics of the sound, the threshold of the fish to those frequencies, the prevailing level of ambient noise, and the width of the critical band for the fish. The temporal characteristics of the sound may also be important, for example, the longer a sound the more likely it is to be detected. Some authors have ignored the importance of the critical band and have suggested that the audiogram itself can be used to determine the detection range. In contrast, those working with cetaceans have recognised the need to take account of the critical band (see for example Southall *et al.*, 2000).

9.1.1.2 Hearing mechanisms

The main sound receptors in fish are the otolith organs of the inner ears (Figure 9.1.2.1). The ears are paired structures embedded in the cranium on either side of the head close to the midbrain. There are no obvious external structures to indicate their presence, although at least in the clupeoid fishes there is indirect connection to the exterior via the lateral line system. Each ear is a complex structure of canals, sacs and ducts filled with endolymph. In elasmobranches and teleosts the ear has three semicircular canals which detect angular accelerations of the head. Three expanded sacs within the ear are linked with one another and with the semicircular canals. One of them, the utriculus, communicates directly with the lumen of the semicircular canals and with them forms the pars superior. The sacculus and lagena together constitute the pars inferior. In teleosts each of these sacs contains an otolith, a dense mass or stone of calcium carbonate and other inorganic salts within a protein matrix, sitting upon a sensory membrane or macula containing many mechano-receptive hair cells. Hair cells are directional in their response to mechanical stimulation, and there are particular patterns in the arrangement of the polarised hair cells in the various maculae Figure 9.1.2.1). Moreover, the various sacs with their otoliths vary in size, orientation and shape from one species to another, reflecting the great diversity of fishes.
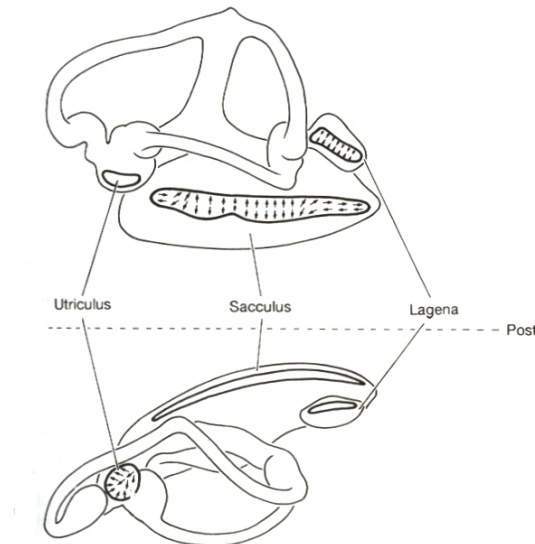
Figure 9.1.2.1. The main parts of the Atlantic cod ear. The sensory membranes or maculae of the three otolith organs are shown, with the orientation of the hair cells indicated by arrows. (a) Lateral view of the left ear, (b) Dorsal view of the left ear.

In many fishes, the inner ears are simple with no ancillary structures or attachments. In others there are well defined structural linkages with gas-filled cavities. Best known are fish from a group known as the Otophysi. All members of this group, which includes carp and catfish have the anterior end of their swim bladder coupled to the ear by a chain of moveable bones. However, there is a wide range of different couplings between the swim bladder and ear found in different fishes.

The simple otolith organs serve several functions. They serve as gravity receptors, enabling the fish to determine its orientation. The heavy otolith shifts as the head of the fish tilts, deflecting the sensory processes of the hair cells. The organ is also sensitive to linear acceleration, with the otolith tending to lag behind the accelerating fish, again deflecting the sensory processes of the hair cells. With three otolith organs on each side of the head, and with a complex pattern of orientation of the polarised hair cells, there is scope for detecting changes in the direction of tilt or angular acceleration.

The otolith organ also plays a major part in sound reception. There is evidence, reviewed by Hawkins (1992), that the otolith organ is essentially driven by the particle motion component of any sound. Thus, as the sound passes through the flesh of the head and the maculae themselves tend to move with the particle motion component of the sound, while the dense otolith lags behind, creating shearing forces at the sensory hair cells. However, the gas within the swim bladder also plays a major part in hearing in some fishes, including species like the Atlantic cod where there is no direct connection between the swim bladder and the ear. In these fishes the gas in the swim bladder is alternately compressed and expanded by the sound pressure wave, the pulsating movements being transmitted to the otolith organs by a variety of different mechanical mechanisms. The gas within the swim bladder is essentially acting as an acoustic transformer, converting sound pressure into particle motions that are much larger than those in the incident sound wave.

It has now been clearly demonstrated that those fish having a close association between the swim bladder and the ear are primarily sensitive to sound pressure, while those lacking gas-filled cavities are sensitive to particle motion. The former tend to be more sensitive to sound, and have a wider frequency range than the latter. Experiments have shown that in the former the deflation of the swim bladder results in a reduction in the sensitivity to sounds. Even more remarkably, placing a small balloon of gas close to the head of a fish lacking a swim bladder

may increase its sensitivity and extending its hearing range (see for example Chapman and Sand, 1974).

In performing auditory experiments on fish it is especially important to monitor the particle motion within the incident sounds, as well as the sound pressure. This may be achieved by means of specially designed hydrophones (which may be constructed using seismic accelerometers), or by measuring the pressure gradient with two or more pressure hydrophones. Particle velocity is a vector, and it is usually necessary to measure the particle velocity in 3 orthogonal directions.

Fishes from one subfamily of clupeids (the shads or Alosinae) have been shown to detect frequencies in the ultrasonic range (Mann *et al.*, 2001); it is reported that the American shad is able to detect frequencies to over 180 kHz (Mann *et al.*, 1997). This ability may help in the detection of the ultrasonic clicks of dolphins, possibly at ranges approaching 200m (Mann *et al.*, 1998; Plachta and Popper, 2003). It has also been reported that Atlantic cod can detect sound from an echo-sounder operating at a frequency of 38 kHz (Astrup and Møhl, 1993). It is important in carrying out such experiments to ensure that the fish is not detecting lower frequency cues which accompany the ultrasonic signal. Such cues may be generated by radiation pressure or by non-linearities within the water or the fish itself.

Within their relatively restricted frequency range, fish are capable of distinguishing between sounds of differing frequency. In addition, the masking experiments mentioned earlier show that fish can perform frequency filtering within the auditory system. Experiments have also shown that fish can distinguish sounds coming from different directions, although the auditory mechanisms that allow this to take place are poorly understood. It is conjectured that some fish may determine the axis of the sound source by comparing the responses of the differently oriented otolith organs to the particle motion components of the sound. However, such a vector weighing process yields a 180° ambiguity in the determination of direction. For the Atlantic cod, which appears to be able to detect both the sound pressure and the particle motion, it is evident that the discrimination of source direction depends upon the phase relationship between sound pressure and particle motion (Schuijf and Buwalda, 1975; Buwalda *et al.*, 1983).

9.1.1.3   Sound production and communication

Many teleost fishes produce sounds. They use a variety of different methods ranging from rubbing two bones together to more complex mechanisms involving the contraction of exceptionally fast muscles connected to the swim bladder. Sounds produced in this way usually have most of their energy below 1,000 Hz and are characterised by a pattern of amplitude modulation. Indeed, within a family of fishes the sounds of different species may often be distinguished by their different temporal patterns (Hawkins and Rasmussen, 1978). The great majority of sounds emitted by fish are produced in a social context and involve interactions between individuals (Myrberg, 1981). Sounds may be produced when an individual is disturbed by a predator or subjected to a noxious stimulus. They are also produced during aggressive displays between fish of the same species. Perhaps the most common context of sound production is during reproductive activity, where often the male fish is the dominant sound producer. Here, the sounds produced may serve to attract mates, drive away competing males, and synchronise spawning activities.

There is potential for intense low frequency sounds generated by ships, pile drivers, air-guns, low frequency sonars and other sources to interfere with communication by means of sound in fish, both through masking and through the generation of signals similar to those produced by the fish themselves. As sounds are used by fish during important activities such as spawning then there is potential for such sound sources to disrupt their lives significantly.

9.1.1.4 Behavioural responses of fish to sounds

Some direct evidence has been provided of the effects of exposure to man-made sounds on fish, including observations that sound from pile driving can injure and even kill fish that are very close to the source. Hastings and Popper (2005) recently reviewed the relatively few studies on the effects of sound on fish.

One particular area of concern has been whether fish are affected by the sounds of ships, and especially the noise generated by ships using sonar systems to examine the abundance and spatial distribution of fish. There are many anecdotal reports of fish responding to the passage of fishing vessels. In general, modern survey vessels are designed to radiate only low levels of noise but here is nevertheless concern that if fish do react to the sounds of the survey vessels then the results of the survey itself may be compromised. A number of studies have been carried out to investigate the impact of surface vessel noise (see for example Engås *et al,* 1995), but it has been difficult to draw definite conclusions.

Attention has also focussed on the effects upon fish of the high level, low frequency, impulsive sounds generated by the air-gun arrays deployed during seismic surveys. Engås *et al.* (1996) and Engås and Løkkeborg (2002) showed that there was a significant decline in catch rate of haddock and Atlantic cod that lasted for several days following a seismic survey, after which the catch rates returned to normal. The authors concluded that the sound caused the fish to leave the area. Similar effects upon catch rates have been observed in other studies. However, Wardle *et al.* (2001) observed the behaviour of fish on a rocky reef in response to emissions from seismic air guns and found no permanent changes in the behaviour of the fish. More recently, Popper *et al.* (2005) examined three species, including a salmonid (broad whitefish *Coregonus nasus*), after stimulation with five and twenty blasts of a seismic air gun. The broad whitefish showed no loss of hearing after exposure to the sounds, whereas northern pike *Esox lucius* and lake chub *Couesius plumbeus* showed 10-15 dB of hearing loss, but with complete recovery within 24 hours after exposure. Importantly, no animals died as a result of exposure and preliminary evidence indicates no damage whatsoever to other body tissues including the ear and the swim bladder.

There is a small but growing body of literature demonstrating that intense sounds can destroy the sensory cells in fish ears and that exposure to such sounds may cause temporary, and possibly permanent, loss of hearing (Enger, 1981; Hastings *et al.*, 1996; Scholik and Yan, 2001; Popper, 2003; Smith *et al.*, 2004; Popper *et al.* 2005). Sounds generated during seismic surveys, activities such as pile driving or even low frequency sonar systems may cause damage to the hearing of fish. McCauley *et al.* (2003) investigated the effects of exposure to sounds from a seismic air-gun on the pink snapper *Pagrus auratus*. Fish were placed in a large cage in a bay and exposed to air guns over several hours. The fish were allowed to survive for different intervals after exposure, and the ears were then examined for any damage resulting from exposure to the sound. The results clearly showed that there was extensive damage to the sensory cells of the ear and that the level of damage increased the longer the fish were allowed to survive post-exposure. Studies of the impact of exposure of fish to high levels of sound have been thoroughly reviewed by Hastings and Popper (2005).

9.1.2 Impact of sonar on fish

There have been few studies of the effects of sonar on fish. Ross *et al.* (1995, 1996) reported the use of high frequency sound to deter alewives from entering power station inlets. The alewife is from the shad family (Alosinae) which have been reported to be capable of detecting sounds at ultrasonic frequencies (Mann *et al.*, 2001). Turnpenny *et al.* (1994) reviewed the risks to marine life, including fish, of high intensity, low frequency sonar sources. Their review focused on the effects of pure tones (sine waves) at frequencies between 50-1000 Hz. Johnson (2001) evaluated the potential for environmental impacts of employing

the SURTASS LFA sonar system. While focusing on the potential effects on whales, the study did consider the potential effects on fish, including bony fish and sharks. It considered that the swim bladders of most fish are too small to resonate at low frequencies and that only large pelagic species such as tunas were considered to have swim bladders large enough to resonate in the low frequency range. This conclusion however overlooks the findings of Sand and Hawkins (1973) which examined the resonance frequencies of cod swim bladders and revealed resonance frequencies from 2kHz down to 100Hz. Many fish species are likely to show resonance frequencies in the range of 100-500Hz.

Jørgensen *et al.* (2005) carried out experiments examining the effects of mid-frequency (1 to 6.5 kHz) sound at 150-190 dB re 1 μPa at 1m on survival, development and behaviour of fish larvae and juveniles. Experiments were conducted on the larvae and juveniles of Atlantic herring, Atlantic cod, saithe *Pollachius virens* and spotted wolfish *Anarhichas minor*. Swim bladder resonance experiments were attempted on juvenile Atlantic herring, saithe and Atlantic cod.

Sound exposure was performed at 1.5 kHz, 4 kHz and 6.5 kHz with sound simulating Naval sonar-signals. These experiments did not cause any significant direct mortality among the fish larvae or juveniles exposed, except in two (of a total of 42) experiments repeated on juvenile herring where significant mortality (20-30%) was observed. Among fish kept in tanks one to four weeks after sound exposure, no significant differences in mortality or growth related parameters (length, weight and condition) between exposed groups and control groups were observed. Some incidents of behavioural reactions were observed during or after the sound exposure ('panic' swimming or confused and irregular swimming behaviour). The latter seemed to be related to exposure of Atlantic herring juveniles to the lowest frequency (1.5 kHz) or close to the assumed frequency interval of air space resonance in the swim bladder. Histological studies of organs and tissues from selected Atlantic herring experiments did not reveal obvious differences between control and exposed groups, neither did SEM-studies of neuromast organs of young Atlantic herring larvae.

The work of Jørgensen *et al.* (2005) was used in a study by Kvadsheim and Sevaldsen (in press) to examine the possible 'worse case' scenario of sonar use over a spawning ground. This found that normal sonar operations will affect less than 0.06% of the total stock of a juvenile fish of a species, which constitutes less than 1% of natural daily mortality. The effect of a sonar exercise on juvenile fish is thus considered negligible. However, these authors did find that the use of continuous-wave transmissions within the frequency band corresponding to swim bladder resonance will escalate this impact by an order of magnitude. The authors therefore suggested that modest restrictions on the use of continuous-wave transmissions at specific frequencies in areas and at time periods when there are high densities of Atlantic herring present would be appropriate.

Most recently, Popper *et al.* (2005) have been investigating the effects of US Navy SURTASS LFA sonar on hearing and on non-auditory tissues of several fish species. Fish were exposed in the far field of an LFA source to a received signal of 193 dB re 1 uPa for a period that would be considerable longer than from any actual LFA exposure. Preliminary results for three species showed no mortality whatsoever and no damage to any body tissues either at the gross or histological level. Several of the species showed some TTS, but this was not extensive and there appears to be recovery from TTS within several days of exposure. The initial conclusions are that SURTASS LFA sonar does not kill or damage fish that in a worst-case scenario situation (exposure was for far longer than fish would receive from a sonar on a moving ship). Significantly, the sound level used by Popper and his colleagues in these experiments was the equivalent of the sound as close as 100 meters from a ship producing LFA sounds.

9.1.3 Mitigation measures for fish

The body of data currently available on the response of fish to sounds is not yet sufficient for developing scientifically supportable guidance on exposure to sound that will not harm fish. Nor is it possible at present to propose detailed measures for mitigation of the impact of sound. However, where work is to be carried out using potentially damaging sound sources it is sensible to take precautions to minimize any damage. For example, it is sensible not to carry out pile driving in confined areas in close proximity to migrating fish (e.g. in a narrow river through which salmon are migrating). It may be possible to carry out the work by other methods (such as vibro-piling rather than percussive piling), or to carry out the work for a restricted period each day or to time it so that it does not coincide with a peak in migration. It is also a sensible precaution to avoid the deployment of high level sound sources at times of spawning, or where any impact is likely to be especially disruptive. Measures such as air-bubble curtains around noise sources have been proposed to minimize any injury to fish, but there are no published results demonstrating this effect.

In evaluating the impact of sounds upon fish it is important not just to consider the immediate impact upon individuals, but to look at long term effects upon individuals and upon populations. Sounds may deter individual fish from passing through a noisy location, may cause disruptions in their behaviour and may even damage their hearing, but it is when there is long lasting effect upon the whole population and its ability to sustain itself that there is a need for greatest concern. Deflection of migrating fish, displacement of fish from their feeding grounds or disruption of spawning activities, especially when large numbers of fish are affected, may prove especially damaging.

10 Recommendations

Owing to the source of the request for advice, these recommendations are drawn up for European waters. Some have a wider applicability and some research is sufficiently general that it could be carried out elsewhere. As this is an international problem, there may be benefits to an international research effort.

10.1 Future investigations and research for marine mammals

1. There is insufficient knowledge in European waters of the location and habitats of beaked whales. More reliable information on this topic would enable those wishing to use high intensity sound to avoid those areas. A survey of all shelf-break and adjacent waters of Europe is required, as is the collation of all current records. Habitat modelling may also improve predictability of beaked whale distribution and help identify critical habitat.

2. Techniques to detect beaked whales more reliably need to be developed with acoustic monitoring, and possibly high-resolution satellite surveillance being promising options for the future.

3. Increased research into the sound transmission properties in the waters near the shelf break may aid in choosing areas to avoid the use of high-intensity sonar.

4. Further research is needed on the apparently non-auditory responses of deep-diving marine mammals to low- and mid-frequency sonars. This could be aimed particularly at trying to understand the sphere of influence of sonar noise on cetaceans. Understanding the mechanisms behind the apparent formation of bubbles in body tissue might help in understanding the causes of death of beaked whales.

If a balanced judgement is needed between the requirements for use of high intensity mid frequency sonar and the need to protect beaked whales is required, then a report could be commissioned on the extent to which quiet diesel-electric submarines pose a threat to security in Europe. Since mid-frequency sonar is the only viable tool for finding them in complex coastal waters, the two reports would give a fair appraisal of both sides of the sonar issue.

10.2 Future research on fish and sonar

There is a need for well-controlled studies to enable investigators to provide clear direction in the future. There are insufficient data on the effects of exposure to sound for the vast majority of fishes, and particularly on the diversity of species having differences in ear structures, hearing capabilities, and/or acoustic behaviours. The data in the literature, both in relation to the detection and response to sound are limited and the data on vulnerability to injury are almost totally non-existent, only relevant to particular species, and because of the great diversity of fishes are not easily extrapolated to other species. There are significant differences in the hearing abilities of different species. There are also major differences in anatomy which may affect the degree of injury to fish from high level sounds.

1. As well as a need for hearing thresholds for a range of fish species, information is also required on temporary and permanent hearing loss associated with exposure to sounds. The use of sounds during spawning by some fish, and their potential vulnerability to masking by anthropogenic sound sources requires closer investigation.

2. In carrying out such investigations it must be remembered that the effects of sounds with differing characteristics, whether they are from air guns, blasts, sonar systems, pile drivers or pure tones, are likely to be very different.

3. The effects of sound may not only be species specific, but also depend on the mass of the fish (especially where any injuries are being considered) and life history phase (eggs and larvae may be more or less vulnerable to exposure than adult fish.)

4. None of the earlier studies have investigated effects of cumulative exposure of fish to any type of sound. Moreover, no studies have carefully examined effects on fishes that are distant from the source, or have considered whether there are subtle and long-term effects on behaviour or physiology that could have an impact upon survival of fish populations.

5. It is important to note that some fish are sensitive to the particle motion component of sound rather than the sound pressure and that even in fish that are sensitive to sound pressure the particle motion may be important for discriminating sounds from different directions. In determining the sensitivity of fish to sounds and the impact of sounds upon fish it is important to express the sound levels in terms of particle velocity or intensity as well as sound pressure. Different signal parameters (e.g. bandwidth, duration, temporal variation) are also important. Producing a controllable particle motion signal in a small tank is extremely difficult and care must be taken to choose a suitable acoustic environment.

11 References

Aguilar de Soto, N., Rogan, E., O Cadhla, O., Gordon, J. C. D., Mackey, M. and Connolly, N 2004. Cetaceans and seabirds of Ireland's Atlantic Margin. Volume III – Acoustic surveys for cetaceans. Report on research carried out under the Irish Infrastructure Programme (PIP): Rockall Studies Group (RSG) projects 98/6 and 00/13, Porcupine Studies Group project P00/15 and Offshore Support Group (OSG) project 99/38. 51pp.

Andersen, S. 1970. Auditory sensitivity of the harbour porpoise *Phocoena phocoena*. Investigations on Cetacea 2: 255–258.

Andrew, R. K., Howe, B. M., Mercer, J. A. and Dzieciuch, M. A. 2002. Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. Acoustic Research Letters Online 3(2): 65–70.

Astrup, J. and Møhl, B. 1993. Detection of intense ultrasound by the cod *Gadus morhua*, Journal of Experimental Biology, 182: 71–80.

Au, W. W., Carder, D. A., Penner, R. H. and Scronce, B. L. 1985. Demonstration of adaptation in beluga whale echolocation signals. Journal of the Acoustical Society of America 77: 726–730.

Au, W. W. L. and Moore, P. W. B. 1984. Receiving beam patterns and directivity indices of the Atlantic bottlenose dolphin (*Tursiops truncatus*). Journal of the Acoustical Society of America 75: 255–262.

Au, W. W. L. and Moore, P. W. B. 1990. Critical ratio and critical bandwidth for the Atlantic bottlenose dolphin. Journal of the Acoustical Society of America 88: 1635–1638.

Au, W. W. L., Moore, P. W. B. and Pawloski, D. A. 1988. Detection of complex echoes in noise by an echolocating dolphin. Journal of the Acoustical Society of America 83: 662–668.

Bacon, S. and Carter, D. J. T. 1993. A connection between mean wave height and atmospheric pressure gradient in the North Atlantic. International Journal of Climatology, 13: 423–436.

Balcomb, K. C. III and Claridge, D. E. 2001. A mass stranding of cetaceans caused by naval sonar in the Bahamas. Bahamas Journal of Science 5: 1–12.

Barlow, J. 1994. Abundance of large whales in California coastal waters: a comparison of ship surveys in 1979/80 and in 1991. Report of the International Whaling Commission 44: 399–406.

Beaubrun, P. C., Bayed, A., Bompar, J. M., Boutiba, Z., Forcada, J., Gannier, A., Giordano, A., Maigret, J., Notarbartolo di Sciara, G., Ozturk, B., Ripoll, Th., Di-Méglio, N. and Geniez, Ph. 1995. Atlas préliminaire de distribution des cétacés de Méditerranée. CIESM , Musée océanographique, Monaco. 87 pp.

Blane, J. M. and Jaakson, R. 1994. The impact of ecotourism boats on the St. Lawrence beluga whales. Environmental Conservation 21: 267–269.

Boebel, O, Bornemann, H., Breitzke, Burkhardt, E., Kindemann, L., Klinck, H., Plötz, J., Ruholl, C. and Schenke, H-W. 2004. Risk assessment of Atlas Hydrosweep SDS-2 hydrographic deep sea multi-beam sweeping survey echo sounder. Poster at 'Policy on Sound and Marine Mammals: An International Workshop', London from 28th to 30th September 2004.

Bowles, A. E., Smultea, M., Würsig, B., DeMaster, D. P. and Palka, D. 1994. Relative abundance and behavior of marine mammals exposed to transmissions from the Heard Island feasibility test. Journal of the Acoustical Society of America 96: 2469–2484.

Boyd, I. 2002. Energetics: consequences for fitness. *In:* Marine mammal biology: an evolutionary approach, pp 247–277. Ed. by A. Rus Hoelzel, A. Blackwell Science, Oxford.

Brill, R. L., Moore, P. W. B. and Dankiewicz, L. A. 2001. Assessment of dolphin (*Tursiops truncatus*) auditory sensitivity and hearing loss using jaw phones. Journal of the Acoustical Society of America 109, 1717–1722.

Brownell, R. L., Yamada, T., Mead, J. G. and van Helden, A. L. 2004. Mass strandings of Cuvier's beaked whales in Japan: U.S. Naval acoustic link? Paper IWC/SC/56/E37 to 56th meeting of IWC Scientific Committee. 10 pp.

Bryant, P. J., Lafferty, C. M. and Lafferty, S. K. 1984. Reoccupation of Laguna Guerrero Negro, Baja California, Mexico, by gray whales. *In:* The gray whale *Eschrichtius robustus*, pp 375–386. Ed. by M. L. Jones. Academic Press, Orlando, Florida.

Buwalda, R. J. A., Schuijf, A. and Hawkins, A. D. 1983. Discrimination by the cod of sounds from opposing directions. Journal of Comparative Physiology, 150: 175–184.

Carder, D. A. and Ridgway, S. H. 1990. Auditory brainstem response in a neonatal sperm whale, (*Physeter* spp.). Journal of the Acoustical Society of America 88 (Supplement 1): S4.

Carron, M. 2004. NATO SACLANTCEN marine mammal risk mitigation programme (sound, ocean, and living marine resources). *In*: Proceedings of the workshop on active sonar and cetaceans, pp. 59–62. Ed. by Evans, P. G. H. and Miller, L. A. European Cetacean Society Newsletter No 42.

Cerchio, S. and Dahlheim, M. 2001. Variation in feeding vocalizations of humpback whales *Megaptera novaeangliae* from southeast Asia. Bioacoustics 11: 277–295.

Cerutti, F. 2005. Italian Navy's RIMPAM environmental impact reduction procedures for marine mammals. Presentation to intergovernmental conference on the effects of sound on marine mammals, Lerici, May 2005.

Chapman, C. J. and Hawkins, A. D. 1973. A field study of hearing in the cod, *Gadus morhua* L.. Journal of Comparative Physiology, 85: 147-167.

Chapman, C. J. and Sand, O. 1974. Field studies of hearing in two species of flatfish, *Pleuronectes platessa* (L.) and *Limanda limanda* (L.) (Family Pleuronectidae). Comparative Biochemistry and Physiology, Series A, 47: 371–385.

Coles, P., Diamond, J., Harrop, H., Macleod, K. and Mitchell, J. 2003. A report on the whales, dolphins and porpoises of the Bay of Biscay and English Channel 2000. Orca 2: 9–61.

Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K., Barlow, J. Caldwell, J., Cranford, T., Crum, L., D'Amico, A., D'Spain, G., Fernández, A. Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., Hullar, T., Jepson, P. D., Ketten, D., MacLeod, C. D., Miller, P., Moore, S., Mountain, D., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Mead, J., Lowry, L. and Benner, L. in prep. Why Beaked Whales? Report of Workshop to Understand the Impacts of Anthropogenic Sound. US Marine Mammal Commission.

Crane, N. L. and Lashkari, K. 1996. Sound production of gray whales, *Eschrichtius robustus*, along their migration route: a new approach to signal analysis. Journal of the Acoustical Society of America 100: 1878–1886.

Cresswell, G. and Walker, D. 2001. Whales and dolphins of the European Atlantic: the Bay of Biscay and the English Channel. Wildguides, Old Basing, Hampshire. 56 pp.

Croll, D. A., Clark, C. W., Calambokidis, J., Ellison, W. T. and Tershy B. R. 2001. Effect of anthropogenic low-frequency noise on the foraging ecology of Balaenoptera whales. Animal Conservation 4: 13–27.

Crum, L. and Mao, Y. 1996. Acoustically enhanced bubble growth at low frequencies and its implications for human diver and marine mammal safety. Journal of the Acoustical Society of America 99: 2898–2907.

Dubrovsky, N. A. 1990. On the two auditory subsystems in dolphins. *In:* Sensory abilities of cetaceans, pp. 233–54. Ed. by J. A. Thomas and R. A. Kastelein. Plenum, New York.

Dunning, D. J., Ross, Q. E., Geoghegan, P., Reichle, J. J., Menezes, J. K. and Watson, J. K. 1992. Alewives avoid high-frequency sound. North American Journal of Fisheries Management, 12: 407–416.

Edds, P. L. 1982. Vocalizations of the blue whale, *Balaenoptera musculus*, in the St. Lawrence River. Journal of Mammalogy 63: 345–347.

Edds, P. L. 1988. Characteristics of finback, *Balaenoptera physalus*, vocalizations in the St. Lawrence estuary. Bioacoustics 1: 131–149.

Engås, A. and Løkkeborg, S. 2002. Effects of seismic shooting and vessel-generated noise on fish behaviour and catch rates. Bioacoustics, 12: 313–315.

Engås, A., Løkkeborg, S., Ona, E. and Soldal, A. V. 1996. Effects of seismic shooting on local abundance and catch rates of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). Canadian Journal of Fisheries and Aquatic Science, 53: 2238–2249.

Engelhardt, F. R., Greene, C. R., Jr and Paterson, R. J. 1985. Explosives in the marine environment. Proceedings of the Northern Hydrocarbon Development Conference, Banff, Alberta, Canada, Sept. 24-26, 1985. 11pp.

Enger, P. S. 1981. Frequency discrimination in teleosts—central or peripheral? *In*: Hearing and Sound Communication in Fishes, pp. 243–255. Ed. by W. N. Tavolga, A. N. Popper and R. R. Fay. Springer-Verlag, New York.

Evans, D. L. and England, G. R. 2001. Joint Interim Report Bahamas Marine Mammal Stranding Event of 15-16 March 2000. Joint report of US Department of Commerce and US Navy. 59pp.

Evans, D. L., Lautenbacher, C. C., Jr. and Hogarth, W. T. 2002. Report of the Workshop on Acoustic Resonance as a Source of Tissue Trauma in Cetaceans. April 24 and 25, 2002, Silver Spring, MD. 19 pp.

Falke, K. J., Hill, J. R. D., Qvist, R. C., Schneider, M., Guppy, G. C., Liggins, P. W., Hochachka, P. W., Elliott, R. E. and Zapol, W. M. 1985. Seal lungs collapse during free diving: evidence from arterial nitrogen tensions. Science 229: 556–558.

Fay, R. R. 1991. Structure and function in sound discrimination among vertebrates. *In*: The evolutionary biology of hearing, pp 229–263. Ed. by A. N. Popper, R. R. Fay and D. B. Webster. Springer-Verlag, New York.

Fernández, A., Arbelo, M., Deaville, M. R., Patterson, I. A. P., Castro, P., Baker, J. R., Degollada, E., Ross, H. M., Herráez, P., Pocknell, A. M. Rodríguez, F., Howie, F. E., Espinosa, A., Reid, R. J., Jaber, J. R., Martin, V., Cunninghan, A. A. and Jepson, P. D. 2004. Pathology: Beaked whales, sonar and decompression sickness (reply). Nature 428: 1038.

Fernández, A., Edwards, J. F., Rodríguez, F., Espinosa de los Monteros, A., Herráez, P., Castro, P., Jaber, J. R., Martín, V. and Arbelo, A 2005. "Gas and fat embolic syndrome" involving a mass stranding of beaked whales (Family *Ziphiidae*) exposed to anthropogenic sonar signals. Veterinary Pathology Journal 42: 446–457.

Finley, K. J. and Greene, C. R. 1993. Long-range responses of belugas and narwhals to ice-breaking ships in the Northwest Passage. Abstracts of the 26th ASA Meeting, 4-8 October 1993, Denver. 4aAB4.

Finley, K. J., Miller, G. W., Davis, R. A. and Greene, C. R. 1990. Reactions of belugas, *Delphinapterus leucas*, and narwhals, *Monodon monoceros*, to ice-breaking ships in the Canadian high arctic. Canadian Bulletin of Fisheries and Aquatic Sciences 224: 97–117.

Finneran, J. J., Carder, D. and Ridgway, S. H. 2002a. Low-frequency acoustic pressure, velocity, and intensity thresholds in a bottlenose dolphin (*Tursiops truncatus*) and white whale (*Delphinapterus leucas*). Journal of the Acoustical Society of America 111: 447–456.

Finneran, J. J., Schlundt, C. E., Dear, R., Carder, D. A. and Ridgway, S. H. 2002b. Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. Journal of the Acoustical Society of America 111: 2929–2940.

Fish, J. F. and Vania, J. S. 1971. Killer whale, *Orcinus orca,* sounds repel white whales, *Delphinapterus leucas*. Fishery Bulletin 69: 531–535.

Francois, R. E. and Garrison, G. R. 1982. Sound absorption based on ocean measurements: boric acid contribution and equation for total absorption. Journal of the Acoustical Society of America, 72: 1879–1890.

Frantzis, A. 1998. Does acoustic testing strand whales? Nature (London) 392: 29.

Frantzis, A., Alexiadou, P., Paximadis, G., Politi, E., Gannier, A. and Corsini-Foka, M. 2003. Current knowledge on the cetacean fauna of the Greek Seas. Journal of Cetacean Research and Management 5: 219–232.

Frantzis, A., Goold, J. D., Skarsoulis, E. K., Taroudakis, M. I. and Kandia, V. 2002. Clicks from Cuvier's beaked whales, *Ziphius cavirostris* (L.). Journal of the Acoustical Society of America 112: 34–37.

Fristrup, K. M., Hatch, L. T. and Clark, C. W. 2003. Variation in humpback whale (*Megaptera novaengliae*) song length in relation to low-frequency sound broadcasts. Journal of the Acoustical Society of America 113: 3411–3424.

Gentry, R. L. 2004. Mitigation measures for use with military sonar. *In*: Proceedings of the workshop on active sonar and cetaceans, pp. 66–69. Ed. by P. G. H. Evans and L. A. Miller. European Cetacean Society Newsletter No 42.

Geraci, J. R. and Lounsbury, V. J. 1993. Marine mammals ashore. A field guide for strandings. Texas A&M Sea Grant Publication, Galveston, Texas. 305 pp.

Graham, N. E. and Diaz, H. F. 2001. Evidence for intensification of North Pacific winter cyclones since 1948. Bulletin of the American Meteorological Society, 82: 1869–1893.

Hastings, M. C., Popper, A. N., Finneran, J. J., and Lanford, P. J. 1996. Effect of low frequency underwater sound on hair cells of the inner ear and lateral line of the teleost fish *Astronotus ocellatus*. Journal of the Acoustical Society of America, 99: 1759–1766.

Hastings, M. C. and Popper, A. N. 2005. Effects of sound on fish. Report to Jones and Stokes for California Department of Transportation, January 2005. 82pp.

Hawkins, A. D. 1973. The sensitivity of fish to sounds. Oceanography and Marine Biology: An Annual Review, 11: 291-340.

Hawkins, A. D. 1992. Underwater sound and fish behaviour. *In:* Behaviour of Teleost Fishes, pp 129–166. Ed. by T. J. Pitcher. Chapman & Hall, London.

Hawkins, A. D. and Chapman, C. J. 1975. Masked auditory thresholds in the cod, *Gadus morhua* L. Journal of Comparative Physiology, Series A, 103: 209–226.

Hawkins, A. D. and Johnstone, A. D. F. 1978. The hearing of the Atlantic salmon, *Salmo salar*. Journal of Fisheries Biology, 13: 655–673.

Hawkins, A. D. and Rasmussen, K. J. 1978. The calls of gadoid fish. Journal of the Marine Biological Association of the United Kingdom, 58: 981–911.

Hemilä, S., Nummela, S. and Reuter, T. 1999. A model of the odontocete middle ear. Hearing Research 133: 82–97.

Heyning, J. E. 1989. Cuvier's beaked whale *Ziphius cavirostris* G. Cuvier, 1823. *In:* Handbook of marine mammals vol. 4, pp. 289–308. Ed. by S. H. Ridgway and R. J. Harrison. Academic Press, London.

Hooker, S. K. and Baird, R. W. 1999. Deep-diving behaviour of the northern bottlenose whale, *Hyperoodon ampullatus* (Cetacea: Ziphiidae). Proceedings of the Royal Society of London 266: 671–676.

Houser, D. S., Howard, R. and Ridgway, S. 2001. Can diving-induced tissue nitrogen supersaturation increase the chance of acoustically driven bubble growth in marine mammals? Journal of Theoretical Biology 213: 183–195.

Hildebrand, J. 2004. Impacts of anthropogenic sound on cetaceans. Paper IWC/SC/56/E13 to 56th meeting of IWC Scientific Committee. 32 pp.

ICES 2003. Report of the working group on marine mammal ecology. ICES CM 2003/ACE:03. 75 pp.

Jepson, P. D., Arbelo, M., Deaville, R., Patterson, I. A. P., Castro, P., Baker, J. R., Degollada, E., Ross, H. M., Herraez, P., Pocknell, A. M., Rodriguez, F., Howie, F. E., Espinosa, A., Reid, R. J., Jaber, J. R., Martin, V., Cunningham, A. A. and Fernández A. 2003. Gas-bubble lesions in stranded cetaceans. Nature 425: 575–576.

Jepson, P. D., Deaville, R., Patterson, I. A. P., Pocknell, A. M., Ross, H. M., Baker, J. R., Howie, F. E., Reid, R. J. and Cunningham, A. A. in press. Acute and chronic gas bubble lesions in cetaceans stranded in the United Kingdom. Veterinary Pathology.

Johnson, C. S. 1967. Sound detection thresholds in marine mammals. *In:* Marine Bioacoustics II, pp. 247–60. Ed. by W. N. Tavolga. Pergamon, Oxford.

Johnson, C. S., McManus, M. W. and Skaar, D. 1989. Masked tonal hearing thresholds in the beluga whale. Journal of the Acoustical Society of America 85: 2651–2654.

Johnson, J. S. 2001. Final overseas environmental impact statement and environmental impact statement for Surveillance Towed Array Sensor Low Frequency Active (SURTASS-LFA) Sonar. Volumes 1 and 2.

Johnson, M., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, M. and Tyack, P. L. 2004. Beaked whales echolocate on prey. Proceedings of the Royal Society of London, B (Supplement) 271: S383-S386 DOI 10.1098/rsbl.2004.0208.

Johnstone, D. W. 1985. An examination of Alaska's policy prohibiting the use of explosives in the marine environment. Division of Oil and Gas, Department of Natural Resources, Alaska, U.S.A. 64pp.

Jørgensen, R., Olsen, K. K., Falk-Petersen, I.-B. and Kanapthippilai, P. 2005. Investigations of potential effects of low frequency sonar signals on survival, development and behaviour of fish larvae and juveniles. Norwegian College of Fishery Science University of Tromsø. 49pp.

Kastelein, R. A., Bunskoek, P., Hagedoorn, M., Au, W. W. L. and Haan, D. d. 2002. Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency modulated signals. Journal of the Acoustical Society of America 112: 334–344.

Ketten, D. R. 2000. Cetacean ears. *In:* Hearing by whales and dolphins, pp. 43–108. Ed. by W. W. L. Au, A. N. Popper and R. R. Fay. Springer, New York.

Ketten, D. R., Lien, J. and Todd, S. 1993. Blast injury in humpback whale ears: evidence and implications. Journal of the Acoustical Society of America 94: 1849–1850.

Kooyman, G. L. and Ponganis, P. J. 1998. The physiological basis of diving to depth: birds and mammals. Annual Review of Physiology 60: 19–32.

Kvadsheim, P.H. and Sevaldsen, E.M. in press. The potential impact of mid frequency active sonar on stocks of juvenile fish during sonar intense operations. FFI/Rapport-2005/01027. Forsvarets Forskningsinstitutt, Kjeller, Norway. 19pp.

Larsen, T. and Johnsen, H. K. 1992. Recent experience on the impact of chemical explosives on penned Atlantic salmon and cod. Fisheries and Offshore Petroleum Exploitation, 2nd International Conference, Bergen, Norway, 6-8 April 1992.

Lesage, V. C. Barrette, M. Kingsley, C. S. and Sjare, B. 1999. The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River Estuary. Marine Mammal Science 15: 65–84.

Littardi, V., Rosso, M. and Wurtz, M. 2004. Enquêtes historiques (1900-1966) sur les échouages de *Ziphius cavirostris* G. Cuvier, en Mer Ligure. Rapport de la Commission Intérnationale pour l'Exploration Scientifique de la Mer Méditerranee 37: 388.

Malme, C. I., Miles, P. R., Tyack, P., Clark, C. W. and Bird, J. E. 1985. Investigation of the potential effects of underwater noise from petroleum industry activities on feeding humpback whale behavior. BBN Laboratories Inc., Cambridge, MA for U.S. Minerals Management Service, Anchorage, Alaska, BBN Report 5851, NTIS PB86-218385: var. pag.

Manghi, M., Montesi, G., Fossati, C., Pavan, G., Priano, M. and Teloni, V. 1999. Cuvier's beaked whales in the Ionian Sea: first recording of their sound. European Research on Cetaceans 13: 39–42.

Mann, D. A., Higgs, D. M., Tavolga, W. N., Souza, M. J. and Popper A. N. 2001. Ultrasound detection by clupeiform fishes. Journal of the Acoustical Society of America, 109: 3048–3054.

Mann, D. A., Lu, Z., Hastings, M. C. and Popper, A. N. 1998. Detection of ultrasonic tones and simulated dolphin echolocation clicks by a teleost fish, the American shad (*Alosa sapidissima*). Journal of the Acoustical Society of America, 104: 562–568.

Mann, D. A., Lu, Z. and Popper, A. N. 1997. A clupeid fish can detect ultrasound. Nature, 389: 341.

Mann, D. A., Popper, A. N. and Wilson, B. 2005. Pacific herring hearing does not include ultrasound. Biology Letters, 1: 158–161.

Martín, V., Servidio, A. and García S. 2004. Mass strandings of beaked whales in the Canary Islands. *In:* Proceedings of the workshop on active sonar and cetaceans, pp. 33–36. Ed. by P.G.H. Evans and L. A. Miller. European Cetacean Society Newsletter No 42.

Mazzuca, L. L. 2001. Potential effects of low frequency sound (LFS) from commercial vessels on large whales. Master of Marine Affairs, University of Washington. 70pp.

McCarthy, E. and Miller, J. H. 2002. Is anthropogenic ambient noise in the ocean increasing? Journal of the Acoustical Society of America, 112: 2262.

McCauley, R. D., Fewtrell, J. and Popper. A. N. 2003. High intensity anthropogenic sound damages fish ears. Journal of the Acoustical Society of America, 113: 638–642.

Miller, P. J., Biassoni, N., Samuels, A. and Tyack, P. L. 2000. Whale songs lengthen in response to sonar. Nature 405: 903.

Møhl, B. 2004. Sperm whale sonar rivals tactical sonar with source levels at 235 dB. *In:* Proceedings of the workshop on active sonar and cetaceans, pp. 41–42. Ed. by P. G. H. Evans and L. A. Miller. European Cetacean Society Newsletter No 42.

Møhl, B., Au, W. W. L., Pawloski, D. A. and Nachtigall, P. E. 1999. Dolphin hearing: relative sensitivity as a function of point of application of a contact sound source in the jaw and head region. Journal of the Acoustical Society of America 105, 3421–3424.

Moore, P. W. B., Hall, R. W., Friedl, W. A. and Nachtigall, P. E. 1984. The critical interval in dolphin echolocation: what is it? Journal of the Acoustical Society of America 76: 314–317.

Morton, A. B. and Symonds, H. K. 2002. Displacement of *Orcinus orca* (L.) by high amplitude sound in British Columbia. ICES Journal of Marine Science 9: 1–9.

Myrberg, A. A. Jr. 1981. Sound communication and interception in fishes. *In:* Hearing and Sound Communication in Fishes, pp 395–452. Ed. by W. N. Tavolga, A. N. Popper and R. R. Fay, Springer-Verlag, New York.

Nachtigall, P. E., Pawloski, J. L. and Au, W. W. L. 2003. Temporary threshold shifts and recovery following noise exposure in the Atlantic bottlenosed dolphin (*Tursiops truncatus*). Journal of the Acoustical Society of America 113: 3425–3429.

National Research Council 1994. Low-frequency sound and marine mammals: current knowledge and research needs. National Academy Press, Washington, D. C. 92pp.

National Research Council 2003. Ocean noise and marine mammals. National Academy Press, Washington, D. C. 192pp.

NATO-Saclantcen 1993. Endeavour and Achievement. NATO–SACLANT Undersea Research Centre, La Spezia, Italy. 37 pp.

NATO-Saclantcen, 1998. Report of the SACLANTCEN Bioacoustic Panel and SACLANTCEN Marine Mammal Environmental Policy and Mitigation Procedures Panel, La Spezia, 15-19 June 1998. NATO-Saclantcen, La Spezia. 4 chapters + Annexes. Available at http://enterprise.spawar.navy.mil/nepa/whales/pressrel.cfm

Nestler, J. M., Ploskey, G. R., Pickens, J., Menezes, J. and Shilt, C. 1992. Responses of blueback herring to high frequency sound with implications for reducing entrainment at hydropower dams. Journal of North American Fisheries Management 12: 667–681.

Nieukirk, S. L., Stafford, K. M., Mellinger, D. K., Dziak, R. P. and Fox, C. G. 2004. Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. Journal of the Acoustical Society of America, 115: 1832–1843.

Norris, K. S. 1964. Some problems of echolocation in cetaceans. *In:* Marine bioacoustics, pp. 316–336. Ed. by W. N. Tavolga. Pergamon Press, New York.

Notarbartolo di Sciara, G. 2002. III – Cetacean species occurring in the Mediterranean and Black Seas, Pp. 6-26. *In:* Cetaceans of the Mediterranean and Black Seas: state of knowledge and conservation strategies. (Ed. G. Notarbartolo di Sciara). Document ACCOBAMS/MOP1/Inf.6, presented to the first meeting of ACCOBAMS partners, February 2002, Monaco. 219 pp.

Nowacek, D. P., Johnson, M. P. and Tyack, P. L. 2004. Right whales ignore ships but respond to alarm stimuli. Proceedings of the Royal Society B: Biological Sciences 271: 227–231.

Payne R. and Webb, D. 1971. Orientation by means of long range acoustic signaling in baleen whales. Annals of the New York Academy of Science 188: 110–141.

Pengelly, R. and Scott, R. 2004. Lower frequency ping the littoral ASW threat. Jane's Navy International - November 01, 2004.

Plachta, D. T. T., and Popper, A. N. 2003. Evasive responses of American shad *(Alosa sapidissima)* to ultrasonic stimuli. Acoustical Research Letters Online, 4: 25-30. doi:10.1121/1.1558376

Poggendorf, D. 1952. Die Absoluten Horschwellen des Zwergwelses (*Ameiurus nebulosus*) und beitrage zur Physik des Weberschen Apparate der Ostariophysen. Zeitschrift für Vergleichende Physiologie, 34: 222–257.

Polglaze, J. 2005. Marine mammals and sound: Australian risk mitigation procedures. Presentation to intergovernmental conference on the effects of sound on marine mammals, Lerici, May 2005.

Ponganis, P. J., Kooyman, G. L. and Ridway, S. H. 2003. Comparative diving physiology. *In:* Bennet and Elliott´s physiology and medicine of diving, 5th edition, pp. 221–226. Ed. by A. O. Brubakk and T. S. Neuman. Elsevier, New York.

Popper, A. N. 2003. Effects of anthropogenic sound on fishes. Fisheries, 28: 24–31.

Popper, A. N., Fay, R. R., Platt, C., and Sand, O. 2003. Sound detection mechanisms and capabilities of teleost fishes. *In*: Sensory Processing in Aquatic Environments, pp 3–38. Ed. by S. P. Collin and N. J. Marshall. Springer-Verlag, New York.

Popper, A. N., Halvorsen, M. B., Miller, D., Smith, M. E., Song, J., Wysocki, L. E., Hastings, M. C., Kane, A. S., and Stein, P. 2005. Effects of SURTASS Low Frequency Active sonar on fish. Journal of the Acoustical Society of America, 117: 2440.

Popper, A. N, Smith, M. E., Cott, P. A., Hanna, B. W., MacGillivray, A. O., Austin, M. E. and Mann, D. A. 2005. Effects of exposure to seismic airgun use on hearing of three fish species. Journal of the Acoustical Society of America, 117: 3958–3971.

Read, A. J., Drinker, P. and Northridge, S. 2003. By-catches of marine mammals in U.S. fisheries and a first attempt to estimate the magnitude of global marine mammal by-catch. IWC paper number SC/55/BC. 12 pp

Reid, J. B., Evans, P. G. H. and Northridge, S. P. 2003. Atlas of cetacean distribution in north-west European waters. Joint Nature Conservation Committee, Peterborough. 75 pp.

Rendell, L. and Gordon, J. C. D. 1999. Vocal response of long-finned pilot whales (*Globicephala melas*) to military sonar in the Ligurian Sea. Marine Mammal Science 15: 198–204.

Richardson, W. J., Greene, C. R., Malme, C. I. and Thomson, D. H. 1995. Marine mammals and noise. Academic Press, San Diego. 576 pp.

Richardson, W. J. and. Malme, C. 1993. Man-made noise and behavioral responses. *In:* The bowhead whale, pp. 631–700. Ed. by J. J. Burns, J. J. Montegue and C. J. Cowles. The Society for Marine Mammalogy, Special Publication No. 2, Lawrence, KN

Richardson, W. J. and Würsig, B. 1997. Influences of man-made noise and other human actions on cetacean behaviour. Marine and Freshwater Behaviour and Physiology 29: 183–209.

Ridgway, S. 1972. Mammals of the sea. Biology and medicine. Charles C. Thomas, Springfield, IL. 812 pp.

Ridgway, S. H. 1997. Who are the whales? Bioacoustics 8: 3–20.

Ridgway, S. H. and Carder, D. A. 1997. Hearing deficits measured in some *Tursiops truncatus* and the discovery of a deaf/mute dolphin. Journal of the Acoustical Society of America 101: 590–594.

Ridgway, S. H. and Howard, R. 1979. Dolphin lung collapse and intramuscular circulation during free diving: evidence from nitrogen washout. Science 206: 1182–1183.

Ridgway, S. H. and Howard, R. 1982. Cetaceans and the bends. Science 216: 651.

Ross, C. W., Hurley, G. V. and Parsons, J. 1985. The environmental impact of explosives on fish in nearshore waters near Sable Island, Nova Scotia. *In:* Effects of Explosives Use in the Marine Environment, Workshop Proceedings. pp 152–193. Ed. by G. D. Greene, F. R. Engelhardt and R. S. Paterson. Canada Oil and Gas Lands Administration, Environmental Protection Branch Technical Report, 5, Ottawa, Canada.

Ross, D. G. 1987. Mechanics of underwater noise. Peninsula Publishing, Los Altos, CA. 375pp.

Ross, D. G. 1993. On ocean underwater ambient noise. Acoustics Bulletin, January/February: 5–8.

Ross, Q. E., Dunning, D. J., Menezes, J. K., Kenna, M. J. and Tiller, G. W. 1995. Reducing impingement of alewives with high frequency sound at a power plant on Lake Ontario. North American Journal of Fisheries Management, 15: 378–388.

Ross, Q. E., Dunning, D. J., Thorne, R., Menezes, J. K., Tiller, G. W. and Watson, J. K. 1996. Responses of alewives to high-frequency sound at a power plant intake in Ontario, North American Journal of Fisheries Management, 16: 548–559.

Sand, O., Enger, P. S., Karlsen, H. E., Knudsen, F. R. and Kvernstuen, T. 2000. Avoidance responses to infrasound in downstream migrating European silver eels, *Anguilla anguilla*. Environmental Biology of Fishes, 57: 327–336.

Sand, O. and Hawkins, A. D. 1973. Acoustic properties of the cod swimbladder. Journal of Experimental Biology, 58: 797–820.

Schlundt, C. E., Finneran, J. J., Carder, D. A. and Ridgway, S. H. 2000. Temporary shift in masked hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, and white whales, *Delphinapterus leucas*, after exposure to intense tones. Journal of the Acoustical Society of America, 107: 3496–3508.

Scholik, A. R. and Yan, H. Y. 2001. Effects of underwater noise on auditory sensitivity of a cyprinid fish. Hearing Research, 152: 17–24.

Schuijf, A. and Buwalda, R. 1975. On the mechanism of directional hearing in cod (*Gadus morhua* L.). Journal of Comparative Physiology, 98: 333–343.

Simmonds, M. P. and Lopez-Jurado, L. F. 1991. Whales and the military. Nature 351: 448.

Smith, M. E., Kane, A. S. and Popper, A. N. 2004. Noise-induced stress response and hearing loss in goldfish (*Carassius auratus*). Journal of Experimental Biology, 207: 427–435.

Southall, B. L., Schusterman, R. J. and Kastak, D. 2000. Masking in three pinnipeds: underwater, low-frequency critical ratios. Journal of the Acoustical Society of America, 108: 1322–1326.

Stewart, B. S., Evans, W. E. and Awbrey, F. T. 1982. Effects of man-made waterborne noise on behaviour of belukha whales (*Delphinapterus leucas*) in Bristol Bay, Alaska. Hubbs/Sea World Research Institute for the U.S. National Oceanic and Atmospheric Administration, Juneau, AK, San Diego, CA,HSWRI Technical Report 82-145. 29 pp.

Stone, V. F. 2005. At sea policy: routine training and exercise protective measures. Presentation to intergovernmental conference on the effects of sound on marine mammals, Lerici, May 2005.

Swets, J. A. 1964. Signal detection and recognition by human observers. John Wiley & Sons, Inc, New York.

Szymanski, M. D., Bain, D. E., Kiehl, K., Pennington, S., Wong, S. and Henry, K. R. 1999. Killer whale (*Orcinus orca*) hearing: auditory brainstem response and behavioral audiograms. Journal of the Acoustical Society of America 106: 1134–1141.

Thewissen, J. G. M. 2002. Hearing. *In:* Encyclopaedia of marine mammals, pp. 570–574. Eds. W. F. Perrin, B. Würsig, and J. G. M. Thewissen. Academic Press, San Diego.

Thomas, J., Chun, N., Au, W. W. L. and Pugh, K. 1988. Underwater audiogram of a false killer whale (*Pseudorca crassidens*). Journal of the Acoustical Society of America 84: 936–940.

Thomas, J., Pawloski, J. L. and Au, W. W. L. 1990. Masked hearing abilities in a false killer whale (*Pseudorca crassidens*). *In:* Sensory abilities of cetaceans, pp. 395–404. Ed. by J. Thomas and R. Kastelein. Plenum Press, New York.

Tortonese, E. 1963. Insolita scomparsade cetacei (*Ziphius cavirostris* G. Cuv.) nel golfo di Genova. Natura 54: 120–122.

Turnpenny, A. W. H., Thatcher, K. P. and Nedwell, J. R. 1994. The effects on fish and other marine animals of high-level underwater sound. Report FRR 127/94, Fawley Aquatic Research Laboratories, Ltd., Southampton, UK.

Tyack, P. L. and Clark, C. W. 1998. Quick-look report: Playback of low-frequency sound to gray whales migrating past the central California coast. Unpublished report available at Woods Hole Oceanographic Inst., Woods Hole, MA.

Tyack, P. L. and Johnson, M. 2004. Can controlled exposure experiments be used to help determine safe exposure for beaked whales? – tools and techniques for quantifying the responses of whales to sound. *In:* Proceedings of the workshop on active sonar and cetaceans, pp. 43–51. Ed. by P. G. H. Evans and L. A. Miller. European Cetacean Society Newsletter No 42.

Urick, R. J. 1975. Principles of underwater sound. McGraw-Hill, New York, 384 pp.

Urick, R. J. 1986. Ambient noise in the sea. Peninsula Publishing Library of Congress, 85-063685. 205pp.

Vonk, R. and Martin, V. Goose beaked whales *Ziphius cavirostris* mass strandings in the Canary Islands. *In:* European Research on Cetaceans - 3, Proceedings of the 3rd Annual Conference of the European Cetacean Society, La Rochelle, 24-26 February, 1989, pp. 73–77. Ed. by P. G. H. Evans and C. Smeenk. European Cetacean Society, Lieden, Holland.

Wales, S. C. and Heitmeyer, R. M. 2002. An ensemble source spectra model for merchant ship-radiated noise. Journal of the Acoustical Society of America, 111: 1211–1231.

Wardle, C. S., Carter, T. J., Urquhart, G. G., Johnstone, A. D. F., Ziolkowski, A. M., Hampson, G. and Mackie, D. 2001. Effects of seismic air guns on marine fish. Continental Shelf Research, 21: 1005–1027.

Watkins, W. A. 1986. Whale reactions to human activities in Cape Cod waters. Marine Mammal Science 2: 251–262.

Watkins, W. A., Moore, K. E. and Tyack, P. 1985. Sperm whale acoustic behaviours in the Southeast Caribbean. Cetology, 49: 1–15.

Watkins, W. A., Tyack, P. L., Moore, K. E. and Bird, J. E. 1987. The 20Hz signals of finback whales, *Balaenoptera physalus*. Journal of the Acoustical Society of America 82: 1901–1912.

Wenz, G. M. 1962. Acoustic ambient noise in the ocean: spectra and sources. Journal of the Acoustical Society of America, 34: 1936–1956.

Wenz, G. M. 1969. Low-frequency deep-water ambient noise along the Pacific Coast of the United States. Journal of Underwater Acoustics, 19: 423–444.

Yelverton J. T., Richmond, D. R., Hicks, W., Sanders, K. and Fletcher, E. R. 1975. The relationship between fish size and their response to underwater blast. Report No.36777, Defense Nuclear Agency, Washington, D.C. 39pp.

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ANNEX 2: NAMES OF FISH SPECIES MENTIONED IN THE TEXT

English name	Scientific name
Alewife	*Alosa pseudoharengus*
American shad	*Alosa sapidissima*
Atlantic cod	*Gadus morhua*
Atlantic herring	*Clupea harengus*
Atlantic salmon	*Salmo salar*
Bay anchovy	*Anchoa mitchilli*
Broad whitefish	*Coregonus nasus*
Dab	*Limanda limanda*
Freshwater catfish	*Ictalurus nebulosus*
Gulf menhaden	*Brevoortia patronus*
Haddock	*Melanogrammus aeglefinus*
Lake chub	*Couesius plumbeus*
Northern pike	*Esox lucius*
Pink snapper	*Pagrus auratus*
Saithe	*Pollachius virens*
Scaled sardine	*Harengula jaguana*
shads	*Alosinae*
Spanish sardine	*Sardinella aurita*
Spotted wolfish	*Anarhichas minor*