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The implications of developments on the Atlantic Frontier for marine mammals

John Harwood*, Ben Wilson

NERC Sea Mammal Research Unit, Gatty Marine Laboratory, University of St Andrews, St Andrews KY16 8LB, UK

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Abstract

We review the available information on the distribution and abundance of marine mammals in the Atlantic Frontier area, and the literature on the potential effects of oil exploration and extraction on these species. Reliable estimates of seal abundance are only available for two species (grey and harbour seals). For grey seals and hooded seals there is also information from telemetry studies on their distribution at sea. Data on cetaceans comes from a variety of sources including whaling statistics, dedicated surveys, observers placed on vessels of opportunity, and from bottom-mounted hydrophone arrays. These indicate that the Atlantic Frontier region is of national, and possibly international, importance for a number of cetacean species. The most abundant small cetacean is likely to be the white-sided dolphin; however, smaller numbers of large whales, including endangered blue, right, fin and sei whales, and vulnerable humpback and sperm whales are also likely to be present in summer. There is growing evidence that a number of marine mammal species respond to the acoustic and physical disturbance associated with exploration for oil and gas resources, although the ecological impact of these responses is unclear. We describe how risk assessment frameworks, initially developed for evaluating the environmental impacts of hazardous chemicals, can be used to address this problem. © 2001 Published by Elsevier Science Ltd.

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1. Introduction

There has been considerable concern (e.g. Hughes et al., 1998) about the impact on marine mammals, particularly large whales, of oil and gas exploration and extraction on the Atlantic Frontier. In this paper, we will review the available information on the distribution and abundance of marine mammals in the Atlantic Frontier area, paying particular attention to the

*Corresponding author. Tel.: +44-01334-462629; fax: +44-01334-462632.
E-mail address: jh17@st-andrews.ac.uk (J. Harwood).

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nature of that information and the insight it provides into the area's importance for the species concerned. We also evaluate published data on the potential impacts of oil and gas exploration and extraction on marine mammals. Finally, we consider how the US Environmental Protection Agency's extension (EPA, 1992) of the risk assessment framework developed by the US National Research Council (National Research Council, 1983) may be used to assess the importance of these impacts and to evaluate the likely effectiveness of any mitigation measures.

2. Marine mammal species which may occur in the Atlantic Frontier area

The most reliable information on the distribution and abundance of cetaceans comes from sightings made by observers on ships or planes carrying out dedicated surveys, who record the location (relative to the survey platform) and behaviour of any surfacing cetaceans observed. Five such surveys in the Northeast Atlantic and adjacent waters have included all or part of the Atlantic Frontier. Three surveys (NASS-87, NASS-89 and NASS-1995) were carried out by coordinated multinational teams, one was carried out by the Norway in 1988, one (SCANS) by a multinational team in 1994, and one by Greenpeace and the Whale and Dolphin Conservation Society (WDCS) in 1998. Additional data are available from a collaboration between eight major organisations which regularly survey seabirds in European waters. The results of these latter surveys are held in a central database curated by the UK's Joint Nature Conservation Committee (JNCC). As part of this programme, observers are placed opportunistically on vessels carrying out tasks other than surveying. In addition, a number of surveys have been dedicated to counting seabirds. Observers in this programme also record the presence of any cetaceans observed within a fixed distance of the survey vessel. Survey tracks have been concentrated around the British Isles and North Sea. Similar sightings data have been collected from vessels carrying out seismic surveys (Stone, 1997, 1998). Records of cetacean sightings made by volunteer observers around the British Isles have been collated under the SeaWatch scheme (Evans, 1992). Most of the sightings in the 1970s and 1980s were made from coastal vantage points, but during the 1990 s the majority of observations were made from vessels at sea. Historical information on the distribution of whales killed during commercial whaling operations is available from a variety of sources, most of which were compiled in the twentieth century. Whilst this information is useful for documenting the presence of species in particular areas during the whaling season, it must be treated with caution because the current population sizes of many species are much reduced and their ranges may now be much more restricted. Furthermore, whaling effort itself was concentrated in areas adjacent to shore-based stations.

Information on the presence of cetaceans in particular areas can also be obtained from hydrophones. Low-frequency calls of blue, humpback, fin and minke whales have been recorded from the SOSUS network of seabed-mounted hydrophones originally designed to monitor submarine movements in the North Atlantic and Norwegian Sea (Clark, 1995). Limited information can also be derived from strandings of dead or dying whales on coastlines. A variety of national schemes have been established to record these events, which are generally better reported for the larger and more spectacular species.

Seals are not easily seen at sea, and so sightings survey techniques to study their distribution are usually inappropriate. Instead most information on seal distribution and abundance comes from surveys of their land- or ice-based haul-out locations and breeding sites. Information is poorest for species that are either dispersed when they breed or do so on mobile ice. The foraging movements of seals at sea are poorly known and patterns have frequently been inferred from the locations of seals which have hauled out to rest. More reliable information has been gained using transmitters attached to individual seals. These can provide accurate information on the location of animals at sea, as well as ancillary information on their diving behaviour. However, such studies have involved only a small number of animals from a few locations. Thus, whilst information on the movements and dive characteristics is of high quality, problems arise when generalising to entire populations. Furthermore, only a few of the species likely to use the Atlantic Frontier area have been studied using these sophisticated techniques.

The following sections review the available information on the distribution and occurrence of the 23 marine mammal species which are known to occur regularly on the Atlantic Frontier.

2.1. Northern right whale (Eubalaena glacialis)

Northern right whales were once abundant in the vicinity of major land masses in the temperate latitudes of the northern hemisphere. However, whaling on this species began as early as the 11th century and numbers started to decline before regular catches of other whale species even began. Most of the published information on the distribution of this species comes from the records of early twentieth century whaling and may not reflect its pristine distributions. It is generally assumed that right whales migrate between high-latitude summer feeding grounds and lower-latitude winter breeding grounds, but there is little direct evidence to support this. Furthermore, their migrations seems to be much less regular or coherent than those of other migratory baleen whales. Migrating right whales, for example, may stop off in particular areas for days or weeks at a time.

In the eastern north Atlantic, the species used to range from the Azores and Madeira to the waters around Iceland, the Faroe Isands, Shetlands, and the Hebrides. The Bay of Biscay was an important wintering area and, along with Cintra Bay in north west Africa, probably represented their principle calving grounds. Animals probably left these southern areas in February or March and migrated north along the coast of Ireland and Britain, passing northern Scotland during May–July. They arrived in higher latitudes in July and August (Thompson, 1928). The numbers of right whales caught off the west of Scotland varied considerably between years; variations in the flow of the North Atlantic Drift may have caused animals to either stray further offshore or continue past Britain without lingering (Thompson, 1928). The route and timing of the return migration are unknown. There have been no strandings in western Europe during this century (Brown, 1986), but several right whales were killed near Madeira in the 1960s and a few sightings between Portugal and Norway have been reported (Brown, 1976, 1986; Gunnlaugsson and Sigurjónsson, 1990; Sigurjónsson et al., 1989, 1991; Martin and Walker, 1997). Although these animals may represent a relic of the eastern Atlantic population of this species, the recent sighting off Norway of a right whale previously photographed on the east coast of the US (P. Stevick, pers. comm.) suggests that they are more likely to be vagrants from the western Atlantic population.

Right whales are classed as endangered by Baillie and Groombridge (1996).

2.2. Blue whale (Balaenoptera musculus)

Blue whales are found throughout every ocean of the world from the equator to the polar regions. In the southern Hemisphere there appears to be an annual cycle of migration to polar waters in summer for feeding, with a return to low latitudes in winter for breeding. It is not clear whether this pattern applies in the northern Hemisphere. Our knowledge of blue whale migration habits in this region stems mainly from observations made during whaling operations around the turn of the 20th century. After wintering in southern latitudes, whales were thought to move northeast, either passing through the Denmark Strait or moving along the west of the British Isles and then between the Faroe Islands and Iceland to arrive north of Iceland in March and April. They were then thought to continue north to reach banks off Spitsbergen and Bear Island in May. Their migrations would then curve south eastward to the coast of Finnmark and north Norway, so that they spent June, July and August feeding on krill off Norway. Some whales may also have continued into the Barents Sea, rather than visiting the Norwegian coasts. The return migration in September was thought to take the reverse route (Ingebrigtsen (1929) in Christensen and Haug (1992)). Whilst there is agreement in the literature about the general direction of this movement, there is some variation in the times at which peak numbers were observed at each location. For example, Thompson (1928) reports peak catches around Iceland in June and August, whereas Christensen and Haug (1992) say they occurred in March and April. Peak catches to the north and west of Scotland occurred in July to September, the same months as those in north Norway (Thompson, 1928). This, along with the dissimilar way in which numbers declined as a response to whaling in different areas, suggests that the whales off Norway and Scotland may have followed different migration paths. The vast majority of whales caught off Scotland were taken to the west of the Hebrides.

Few data on the modern distribution of blue whales exist, but no blue whales were seen around the Faroe Islands and west of Britain and Ireland during NASS-87 (Sigurjónsson et al., 1989). No blue whales were seen during the SCANS survey which took place in the south east part of the Norwegian Sea area (Hammond et al., 1995); nor during the Greenpeace/WDCS surveys between the Faroe Islands and Shetland (Hughes et al., 1998). However, blue whales were seen during JNCC surveys on the Atlantic Frontier (Weir et al., 2001). Studies of calling whales using the SOSUS array showed that blue whales were present in an area around the Shetland and Faroe Islands between October and April (Clark and Charif, 1998). Peak levels of calling were detected in November. These times are precisely the reverse of dates of whale abundance derived from whaling statistics. However, no recordings were carried out during the times of year when whaling records suggested that blue whales were in peak abundance. In addition, little is known about when blue whales call and how many whales are represented by each call, so it is impossible to draw conclusions about abundance from these acoustic data. What is clear, however, is that blue whales are present in the area throughout the winter.

Blue whales are classed as endangered (Baillie and Groombridge, 1996). They were given total protection from whaling in the 1950s.

2.3. Fin whale (Balaenoptera physalus)

Fin whales are found in all oceans and most seas. They range from the tropics to the poles, although they are less likely to be found around the edges of sea-ice that have blue or minke whales and are usually replaced in the tropics by Bryde's whale. In the eastern North Atlantic, fin whales are found in winter from the Strait of Gibraltar to south western Norway. In summer their range extends as far as 80°N.

Today fin whales are primarily found in the open oceans. However, they appeared to make more use of coastal waters around Iceland in the past. Many of the fin whales caught at the beginning of the 20th century off Iceland were taken within the 250 m isobath, but between 1951 and 1975 almost all were in water deeper than 250 m (Sigurjónsson, 1995).

In Scottish waters, fin whales were taken from April to October, although catches off Shetland peaked in July and August (Thompson, 1928). Catches between the Faroe Islands and the Hebrides were largest at the beginning and end of the season, with few animals caught in June and July. The majority of catches were made beyond the 200 m isobath (Thompson, 1928).

Fin whales were the most abundant large whale species detected in the Icelandic and Faroese legs of the NASS-87 and NASS-89 surveys; they were seen in all parts of the survey areas. Densities varied from 0–0.1 whales nmile^{-2} (Buckland et al., 1992). The only sighting of a fin whale during the SCANS survey occurred off Shetland (Hammond et al., 1995). However, fin whales were regularly seen between Shetland and the Faroe Isands during the Greenpeace/WDCS cruise (Hughes et al., 1998). Analysis of recordings from the SOSUS array showed that fin whales were the most frequently heard whale species in the North Atlantic (Clark and Charif, 1998). Calling fin whales were present to the west and north of the British Isles in all months of the year. Detection rates were high from early October through mid-December, but fell gradually from January through April. Only a few calls were detected in May, June and July, but calling increased again in August and September. It should be noted that this technique can only detect calling whales. Because we do not know how often fin whales call at particular times of year, the absence of calls does not necessarily mean that no whales were present in an area.

This species is officially classified as endangered (Baillie and Groombridge, 1996). Around 75,000 were taken during whaling operations in the North Atlantic and current stocks are likely to be a fraction of this number. Despite this, fin whales are probably one of the most common large whales in the eastern North Atlantic (Evans and Scanlan, 1989).

2.4. Sei whale (Balaenoptera borealis)

Sei whales are found in almost all oceans and seas, generally in sub-polar and temperate waters. Adults penetrate furthest into polar waters. This is a pelagic species, not generally found in inshore or coastal waters. Whalers off western Iceland found that sei whales preferred waters 800–1200 m deep (Martin, 1983). Their distribution in summer appears to be highly variable from year to year. The elevated numbers of sei whales observed in some years were referred to by whalers as "invasions". For example, catches from one Norwegian whaling station jumped from 6 to 659 in two consecutive years.

In the eastern North Atlantic, sei whales are thought to winter off Spain, Portugal, and north-west Africa. Whaling records suggest that they migrated north up the mid-Atlantic and eastern seaboard of Europe. They passed Ireland in spring and were abundant north of Shetland in April and May. Peak catches off Scotland occurred between May and July (Thompson, 1928) and around the Faroe Islands from June to August. Whales then migrated north to northern Norway, Bear Island and Novaya Zemlya, occasionally reach Spitsbergen.

The majority of sei whales sightings during the NASS-87 and NASS-89 surveys occurred to the west and southwest of Iceland. None were seen between Iceland and the Faroe Islands, or north of Shetland (Sigurjónsson et al., 1991; Cattanach et al., 1993). No sei whales were seen during the SCANS survey in 1994 (Hammond et al., 1995), but the Greenpeace/WDCS survey in July and August recorded a number of sightings of sei whales between Shetland and the Faroe Islands (Hughes et al., 1998).

This species is classified as endangered by Baillie and Groombridge (1996). The status of sei whale stocks in the North Atlantic is uncertain, although it is believed that the species was never as abundant in this region as the fin whale. Sei whales were given protection from whaling in most areas in 1979, although whaling continued in the Denmark Strait west of Iceland into the 1980s.

2.5. *Minke whale (Balaenoptera acutorostrata)*

Minke whales are found from the polar ice-edge to the tropics. They do not appear to perform the north–south migrations which have been observed in the southern Hemisphere. In some regions there appear to be shifts in latitudinal abundance with season whilst in others they are resident year round.

Minke whales were not a favoured quarry of whalers until the late-20th century, and there are few data on their occurrence from historical records. However, most whales taken in northern Scotland and the Faroe Isand were caught in July and August (Stephenson, 1951). There have been several large-scale sightings surveys in the North Atlantic specifically designed to determine the distribution and abundance of this species. Minke whales were frequently seen during the SCANS survey which took place in June and July 1994. The highest densities were recorded around northeast Scotland, Orkney and Shetland (Hammond et al., 1995). Only one possible minke whale was sighted during the Greenpeace/WDCS cruise between Shetland and the Faroe Isands (Hughes et al., 1998). JNCC data suggest that minke whales move into British waters from the north in spring and summer to use waters off northeast England and Scotland and the Hebrides (Northridge et al., 1995). In late autumn, numbers around the British Isles and the North Sea decline. Sightings by land-based observers around Shetland (Evans, 1992) peak from July to September. Minke whales have been detected off the British Isles using bottom-mounted hydrophone arrays (Clark and Charif, 1998).

2.6. *Humpback whale (Megaptera novaeangliae)*

Humpback whales are widely distributed, occurring seasonally in all oceans and from the Arctic to the Antarctic. Most populations undertake substantial migrations from summer feeding areas in cold waters, to tropical or subtropical winter breeding grounds. In the North Atlantic, the only remaining breeding ground appears to be off the West Indies. Following the winter breeding season, this whale population migrates north along the eastern seaboard of North America and then splits to use feeding areas in the North Atlantic from Cape Cod to the Barents Sea. There is evidence that there was an eastern Atlantic population which bred around the Cape Verde Islands and off north west Africa and migrated up the western edge of the European continental shelf to summer north of the British Isles. Recent evidence from photo-identification studies has confirmed movements of whales between the eastern Atlantic and the Caribbean (Stevick et al., 1998), and suggests that the West Indies is used as a breeding and calving ground by humpback whales that feed in Norwegian waters (Stevick et al., 1999). This conclusion is supported by genetic evidence that whales observed in the Northeast Atlantic are part of the western North Atlantic population (Larsen et al., 1996). Humpback whales (including mothers and calves) have been sighted around the Cape Verde Islands in recent years, and singing males have been recorded (Reiner et al., 1996). However, although 21 animals have been photographed around the Cape Verdes, none of these photographs has been matched with photographs taken on any of the North Atlantic feeding grounds (Carrillo et al., 1999). It is therefore possible that the whales observed around the Cape Verdes are from southern Hemisphere rather than northern Hemisphere feeding grounds but no evidence has been found of the presence of breeding whales, suggesting that a distinct eastern North Atlantic population no longer exists.

Only one humpback was seen during the SCANS survey, off Shetland (Hammond et al., 1995). No humpbacks were observed during the Greenpeace/WDCS survey between the Faroe Islands and Shetland (Hughes et al., 1998). Catches of humpbacks at Scottish whaling stations at the beginning of the twentieth century represented a far smaller proportion of the total catch of whales than they did in Norwegian whaling stations (Thompson, 1928). The bulk of captures off northern Scotland occurred in July and August (Thompson, 1928). In contrast, data from the SOSUS hydrophone array indicate that waters to the north and west of Scotland may be used more frequently and for longer periods than suggested by sightings surveys and whaling activities. Humpback whale vocalisations were heard from mid-November to early-March and showed a gradual pattern of southerly movement down the west coast of the British Isles, presumably as part of their migration to southerly breeding areas (Clark and Charif, 1998).

Humpback whales are listed on Appendix 1 of the UN Convention on Conservation of Migratory Species of Wild Animals and officially classed as "vulnerable to extinction" (Baillie and Groombridge, 1996). Commercial hunting in the North Atlantic ceased in 1956.

2.7. Sperm whale (Physeter macrocephalus)

Sperm whales have a world-wide distribution that includes most seas and all oceans. They are common from the tropics to semi-polar waters. However, females and calves are restricted to the tropics or sub-tropics, and are rarely observed north of about 45°N, whilst males feed in oceanic waters as far north as Bear Island (75°N) with rare sightings off Spitsbergen (77°N). Thus, only male sperm whales are likely to occur along the Atlantic Frontier.

Sperm whales are deep divers and can remain submerged for 90 min or more. They may reach depths of 3300 m but more typically dive to 300–600 m. Deep dives are followed by periods of rest at the surface lasting 5–15 min. Feeding occurs below 400 m in mid-water and sometimes on or near the bottom. Sperm whales only venture into waters less than 180 m on occasions.

Male sperm whales were seen during most sightings surveys which included the Atlantic Frontier. Sperm whales were seen during the SCANS survey in the southern Norwegian Sea and a sightings rate of 0.25 schools per 10^2 km was calculated for an area around the Shetland Isles (Hammond et al., 1995). Sperm whales were also seen on surveys between Shetland and the Faroe Islands. Sightings were generally in waters deeper than 500 m (Joyce et al., 1990; Hughes et al., 1998).

Sperm whales formed an important quarry for whalers off Scotland at the beginning of the twentieth century. Most were caught west of Scotland, although this may be more a result of the proximity to the continental shelf edge to the main whaling station than any biological factor. The whaling seasons ran from June to August. The beginning of the season probably reflected the arrival of whales off the west of Scotland, but the end was probably due to reduced effort rather than any changes in the abundance of sperm whales (Thompson, 1928).

Strandings around the British Isles have occurred for as long as records have been kept. They occur in all months, but peak between November and March. The overall number of strandings have increased in recent years and have been attributed to a variety of factors ranging from greater numbers of animals using areas off the British Isles, to changes in prey distribution and industrial activities (see papers in *Bulletin de L'Institut Royal des Sciences Naturelles de Belgique. Biologie* 67-(Suppl.) 79–87.)

2.8. Beaked whales (Mesoplodon/Ziphius spp.)

There are at least 18 recognised species of beaked whale, but they are rarely observed despite their abundance probably because they spend only short time at the surface between dives. In addition, many species are superficially similar and correct identification is difficult. As a result, little is known about the ecology or abundance of most beaked whales. One exception is the bottlenose whale. Sufficient data exist to devote a section to this species. Of the others, two (Sowerby's (*Mesoplodon bidens*), and Cuvier's beaked whales (*Ziphius cavirostris*)) are likely to occur on the Atlantic Frontier (Macleod, 2000). Cuvier's beaked whale has a world-wide distribution in tropical temperate or temperate waters whilst Sowerby's beaked whale occurs only in the temperate North Atlantic.

Beaked whales were either not seen or seen in very low numbers in the majority of sightings surveys, although large numbers of animals were seen on the southern legs of NASS-89 to the west of the British Isles (Sigurjónsson et al., 1991) and they have been observed on JNCC surveys (Weir et al., 2001). Sowerby's beaked whales are likely to be the most abundant beaked whale species in the North Atlantic. Two sightings have been recorded on the 100 m depth contour north of the Scottish mainland and west of Orkney (McBrearty et al., 1986). Strandings have occurred on most European coasts as far north as 64°N. Sightings of Cuvier's beaked whales are rare, but there have been several sightings of beaked whales in which the exact species remained unidentified. Strandings of Cuvier's beaked whales have occurred on the north and west mainland coasts of Scotland and in Shetland.

2.9. Northern bottlenose whale (Hyperoodon ampullatus)

Northern bottlenose whales are found only in the northern North Atlantic. In the eastern North Atlantic, they have been reported as far south as the Azores and Portugal and as far north as Spitsbergen. They occasionally enter the North Sea. There is little evidence of them having a continuous distribution across the central North Atlantic, but their distribution may be essentially continuous around the northern rim of the Atlantic basin. Total numbers are unknown but over 40,000 were taken from the eastern North Atlantic during whaling operations and so the original population size must have been somewhat larger. It is categorised as vulnerable by Baillie and Groombridge (1996).

Ratios of males to females and of age classes caught during whaling operations suggest that there may be some geographic separation within the populations. Whales caught off Scotland, for example, were predominantly female, whales stranded in Iceland were generally male, and whales of both sexes were caught or stranded around the Faroe Islands but the majority were juvenile. These whales are squid specialists, with a distribution that is strongly influenced by the distribution of one species: *Gonatus fabricii*. As well as squid, bottlenose whales are known to eat sea cucumbers, starfish, prawns, herring and deep-sea fish. The presence of stones and clay in their stomachs suggest that they forage at or near the bottom. Dives may last for over 70 min and reach depths up to 1400 m (Hooker and Baird, 1999). They are rarely observed on the continental shelf itself and do not become common until the water depth reaches 1000 m.

Based on the timing of strandings and captures, they are considered to migrate north early in the spring, for example arriving off the Faroe Islands in early March and becoming common between Iceland and Jan Mayen in late April, May and early June. After summering at high latitudes they appear to return southward, leaving northern areas in the end of June and Icelandic waters by the end of July. They pass the Faroe Islands in August and September and may be seen in British and European shores from July onwards (Bloch et al., 1996a; Thompson, 1928). The wintering grounds are unknown but they are presumably somewhere to the south (Thompson, 1928). However the year-round presence of some bottlenose whales off the Faroe Islands, suggests that some over-wintering occurs.

A principle hunting ground for Scottish and Norwegian boats in the nineteenth century lay between 64°N to 72°N and 2°W to 12°W in an area where these whales were said to congregate in July. Small scale whaling by Scottish boats in the twentieth century focused on areas further south, between Shetland, North Rona and the Faroe Islands. The main concentrations of bottlenose whales seen during the NASS-87 surveys were within the area targeted in the nineteenth century (Sigurjónsson and Gunnlaugsson, 1989). No bottlenose whales were seen during the SCANS or Greenpeace/WDCS surveys (Hammond et al., 1995). The only bottlenose whales seen during surveys associated with seismic operations in 1997 were north of Shetland (Stone, 1998).

2.10. Killer whale (Orcinus orca)

Killer whales are found in all oceans and most seas, from the equator to seas choked with ice. In the eastern North Atlantic, killer whales occur in most areas, from coastal fjords to oceanic waters. Killer whales are capable of dives to 200 m but more usually appear to dive to depths of 100 m or less.

Sightings from a variety of platforms suggest that whales are distributed almost continuously from the Faroe Islands to Scotland and Norway (Hammond and Lockyer, 1988; Joyce et al., 1990; Hughes et al., 1998; Hammond et al., 1995; JNCC/ESAS, 1995; Couperus, 1994). Changes in the peak sightings in different areas suggest that there may be some seasonal movements of whales. Peaks occurred in the northern North Sea in February; and off Shetland in March–September; off Møre in February–March; off Lofoten in April–May and late autumn/winter; along Finnmark from February to May; in the Barents Sea in May–June; and in the Norwegian Sea, Iceland and East Greenland in summer (Øien, 1988; Hammond and Lockyer, 1988). Coastal sightings off Scotland and the Faroe Islands are rare in winter and suggest offshore movements in these areas (Evans, 1988).

2.11. Long-finned pilot whale (*Globicephala melas*)

Long-finned pilot whales occur in both hemispheres; in the northern Hemisphere, they are only present in the North Atlantic and western Mediterranean from approximately 30°N to the northern tip of Norway. Pilot whales are principally squid eaters with *Todarodes sagittatus* and *Gonatus sp*. probably being their primary prey in the eastern North Atlantic. The diving abilities of these animals are unknown, but judging by their prey, probably extend to hundreds of meters. Dives are usually shorter than 10 min.

Pilot whales are primarily animals of deep oceanic waters, but they do occasionally enter shallow bays and coasts. They frequently mass strand and so may be less adept at navigation in coastal waters than other species. Their range in the North Atlantic appears to be bounded by sea surface temperatures of 0–25°C.

During surveys conducted in the summers of 1986, 1987, 1988 and 1989 throughout the eastern North Atlantic, pilot whales were seen frequently in waters around the Faroe Islands and in all areas further south (Buckland et al., 1993). The highest densities were recorded around the Faroe Islands. Few data are available on the distribution of whales during the winter, although catches in the Faroe Islands and sightings during seabird surveys suggest that they are present in the Atlantic Frontier area throughout the year.

2.12. White-beaked and Atlantic white-sided dolphins (*Lagenorhynchus albirostris* and *Lagenorhynchus acutus*)

These two species are confined to the North Atlantic. Their distribution is difficult to disentangle because the two are often not distinguished in cruise reports. However, where identifications have been made, it is clear that white-beaked dolphins outnumber white-sided dolphins in the inshore waters of the eastern North Atlantic, whereas the opposite is the case in the western North Atlantic (Northridge et al., 1997). The white-sided dolphin is probably the most abundant cetacean in the Atlantic Frontier area. In the eastern North Atlantic, the range of both species extends from the British Isles to Spitsbergen and follows the rim of the ocean basin west to southern Greenland and the US coast. The isolated nature of white-beaked dolphin sightings around the British Isles and North Sea suggests that animals in this area may represent a single stock. No obvious seasonal changes in range are apparent in the Atlantic Frontier area (Northridge et al., 1995). McBrearty et al. (1986) report sightings off the Scottish mainland year round, but sightings north of 60°N were confined to July and August. Bloor et al. (1996) report that white-beaked dolphins were most often sighted around Shetland between June and September. The locations of sightings during the SCANS survey (Hammond et al., 1995) and seismic surveys (Stone, 1997, 1998) were very similar to those made during the seabird surveys.

2.13. Common dolphin (*Delphinus delphis*)

This species is usually found in oceanic and shelf-edge waters, but it is occasionally seen in coastal areas. Temperature appears to limit its range, and tropical and temperate waters are preferred. In summer, groups migrate into higher latitudes in association with increased water temperatures and the movements of schooling fish. In most areas their distribution in summer extends only as far as 40°N but in the eastern North Atlantic they occur much further north than this (McBrearty et al., 1986; Evans, 1992). Reports of sightings of common dolphins around the UK have increased since 1986 (Evans, 1992). Common dolphins are highly social, forming schools of tens or hundreds of individuals. They also associate with other cetacean species and frequently approach shipping.

2.14. Bottlenose dolphin (Tursiops truncatus)

These dolphins have a world-wide range and are found in virtually all seas and every ocean. They occupy most marine habitats from open ocean waters to shallow coastal lagoons. Bottlenose dolphins appear to be temperature limited and year-round resident coastal populations in the eastern North Atlantic extend only as far north as Scotland. However, individuals from oceanic populations, of which little is known, have been recorded as far north as Spitsbergen, and they are regularly caught in the Faroese drive fishery.

2.15. Striped dolphin (Stenella coeruleoalba)

Striped dolphins have a world-wide range; they are primarily oceanic animals but do enter shelf waters. Their distribution is similar to that of common dolphins although they tend to favour slightly warmer water. The first records in Scotland are from the 1990 s (Reid et al., 1993), but it is now known to be a regular visitor to Scottish waters, and it has been sighted off Iceland and the Faroe Islands (Bloch et al., 1996b; Stone, 1997).

2.16. Risso's dolphin (Grampus griseus)

Risso's dolphins are thought to be squid specialists and therefore deep divers. In most parts of their range they are found in oceanic waters, but in the eastern North Atlantic populations also occur in coastal waters where the bottom topography is steep, and a resident population in the Minches off the west coast of Scotland has been identified (Evans, 1992).

2.17. Harbour porpoise (Phocoena phocoena)

Harbour porpoises are confined to temperate and sub-arctic waters on the continental shelf in the Northern Hemisphere. They are able to reach depths of at least 220 m and to stay submerged for over 5 min. During the SCANS survey, porpoises were sighted westwards from the Norwegian coast to Shetland, but they were not seen in offshore waters between Shetland and the Faroe Isands (Hammond et al., 1995). Sightings during opportunistic, seabird and seismic surveys show a similar pattern (Northridge et al., 1995), in addition they indicate that porpoises are present in most months off the Shetland and the Faroe Islands (Evans, 1992; Northridge et al., 1995; Bloor et al., 1996; Stone, 1997, 1998). The numbers of porpoises using Faroese waters are unknown, but sightings are most common between May and August and around the north-eastern islands (Larsen, 1995).

In addition to the above species, two Arctic cetaceans, the beluga (*Delphinapterus leucas*) and the narwhal (*Monodon monoceros*), probably occur in the Atlantic Frontier area as vagrants.

2.18. Harbour or common seal (Phoca vitulina)

Harbour seals are one of the most widespread (in terms of latitude and longitude) of the world's Pinnipeds. They have a circumpolar distribution, being found along the ice-free coasts of the northern Atlantic and Pacific from 30°N to 80°N. There are four sub-species, but only *P.v. vitulina* occurs in the eastern North Atlantic. The world population of harbour seals is estimated at between 300,000 and 400,000 with about 70,000 individuals of *P.v. vitulina*. The estimated size of the population associated with Orkney and Shetland is 14,000.

Foraging generally occurs within 60 km of the haul-out sites, usually in bouts lasting 1–5 d. When diving at sea, seals spend 80–90% of their time submerged and can dive to >400 m, although most dives are much shallower than this. Harbour seals haul out every few days on rocks or sandbanks and forage primarily in coastal waters. Haul-out sites usually occur on tidally exposed areas of rock, sand or mud. Areas where human presence is minimal are preferred. Foraging occurs in shallow waters over a variety of sediments from sandy gravel to rock and kelp beds. Haul-out sites occur right around the coastline of Shetland (Brown and Duck, 1997) and therefore seals are likely to be foraging year-round in almost all waters immediately around the islands.

2.19. Grey seal (Halichoerus grypus)

Grey seals occur only in the North Atlantic. Three stocks are recognised: the northwest Atlantic, Baltic and northeast Atlantic. The northeast Atlantic stock has been estimated to consist of 130,000–140,000 individuals with the majority breeding around the UK. The size of the Scottish population was estimated to be 104,000 in 1998 (SMRU unpublished data). Populations off the British Isles have been increasing in size since the 1960 s.

Grey seals are gregarious and haul-out on land together for breeding, moulting and between foraging trips. Breeding groups are formed on rocky islands, caves, sandy islands and beaches. Whilst at sea, grey seals range over a variety of habitats. Forays off the continental shelf margin are known, but rare. The movements of individuals, is indicated by telemetry studies, are highly variable and generalising is difficult. Some individuals virtually confine their foraging trips to specific areas of seabed, often where gravel or sand predominate, whilst others wander over large areas. Foraging trips generally last several days and may involve excursions of 50 km or more from land followed by return to the original haul-out site. However, individuals may move to a different haul-out site, which may be hundreds of kilometres away.

2.20. Hooded seal (Cystophora cristata)

Hooded seals are found throughout the northern part of the central and western North Atlantic. Three breeding aggregations are known: one to the north of Jan Mayen in the Greenland Sea, another off Newfoundland and in the Gulf of St Lawrence, and the third in the Davis Strait. Individuals from all of these aggregations probably moult in the Denmark Strait or between Jan Mayen and Greenland. Hooded seals are known for their wandering habits and stray individuals have been recorded as far south as Portugal.

Hooded seals are accomplished divers and spend more than 80% of their time at sea submerged. They can dive to 1000 m and can remain submerged for over 52 min. Even average dives last 5–15 min and are to 100–600 m. The depths that they dive to vary with both location and season. In waters off the Faroe Islands between August and November dives were generally to 100–300 m, between December and May they were to 300–600 m (Folkow and Blix, 1995; Folkow et al., 1996). They appear to forage in deep waters at and beyond the edge of the continental shelf, and have not been observed to haul out on land.

After breeding hooded seals may make long excursions (Folkow and Blix, 1995) to waters off the Faroe Islands and northern Ireland. These trips continue until June, when the seals head for moulting sites in the Greenland Sea, north of Jan Mayen and east of Greenland and in the Denmark Strait. Seals from the Jan Mayen moulting site have been tracked with satellite transmitters (Folkow et al., 1996). They made 3–7 week long excursions to distant areas, the most frequently visited area was the waters off the Faroe Islands. Hooded seals have been observed in the Atlantic Frontier area by the JNCC Seabirds at Sea Team (Tasker, pers. comm.).

Four other pinniped species (the bearded seal, *Erignathus barbatus*; the harp seal, *Phoca groenlandica*; the ringed seal, *Phoca hispida*; and the walrus, *Odobenus rosmarus*) are known to occur in the Atlantic Frontier area as vagrants.

3. Response of marine mammals to exploration and extraction

Most exploratory surveys for oil and gas are now carried out using seismic techniques, and the documented response of marine mammals to these, and to low-frequency noise in general, are described below. However, explosions are still used in some cases to obtain particular sorts of information, and data on the potential effects of these are also summarised.

3.1. Explosions

Underwater explosions generate a series of events in the water column which can cause disturbance, injury, or even death, to marine mammals at considerable distances from the source. These events are: a pressure pulse or shock wave which emanates radially from the source at the speed of sound in water; an after-flow of water following the shock wave with a velocity of about $7.5\,\mathrm{m\,s^{-1}}$; subsidiary pulses which are reflections from the surface and the bottom; a succession of bubble waves; and after-flow of water following the passage of each bubble pulse (Rawlins, 1988).

The shock wave can cause serious injury as it passes through the boundary between two media in which the speed of sound is different. The lungs and gastro-intestinal tracts of birds and mammals are obvious sites where this can occur. Seals usually empty their lungs before diving, and so their risk of damage from the shock wave is reduced. Many cetacean species, however, do not empty their lungs completely and are therefore at risk. The subsidiary pulses resulting from reflection can cause similar damage, particularly in shallow water where they arrive soon after the main pulse and often with a similar intensity. In deep water much of their energy is lost in transit to the bottom and then on reflection.

Bubble waves, generated by the gases produced by an explosion can also cause physical damage but, because they tend to rise to the surface, they have their greatest effect close to the explosion. Finally, the after-flow(s) of water can cause serious crushing type injuries to an animal which is completely immersed. Animals floating on the surface are much less likely to be injured because the force of the after flow is cushioned by the compressible air above them.

Data on the damage caused to large mammals by underwater explosions is limited. In fact most calculations of safe ranges for man and other mammals rely entirely on experiments carried out by the Lovelace Foundation for Medical Education and Research in the 1960 s and 1970 s (Yelverton et al., 1973). Yelverton and his colleagues suspended dogs, monkeys and sheep in underwater cages, exposed them to explosions at various distances in shallow water, and recorded the gross injuries that followed. They found that injuries occurred above some threshold impulse level, and that this level increased with increasing body size.

Yelverton et al.'s results were used by Goetner (1982) to calculate what distance various marine mammals would have to be from explosions of different sizes in order to sustain only slight lung and intestinal injuries. For each marine mammal, the calculated distance depends on the size of the explosive charge, at what depth in the water column it is exploded, and where in the water column the animal is. They must be interpreted with caution because Yelvertons work was carried out in shallow water, with terrestrial species and over a narrow range of body sizes which did not include the size of most marine mammals.

Goertner's calculations indicate that marine mammals are at greatest risk of injury when they are at the same depth as, or slightly above, the explosion. Risks drop off quite sharply above and below this depth. Thus any harbour porpoise which is within 750 m of an explosion of a 545 kg charge at 38 m is likely to suffer injury if it is at the same depth. But 30 m above, or 43 m below it, only animals within 500 m are likely to be injured. For a 4540 kg detonated at 61 m, the maximum "safe" range for a porpoise is 1750 m at 40 m. "Safe" distances for larger animals will be substantially less than this (for example, 750 m for a 17 m long whale in the above example). Young (1991) expanded on Goetner's results to calculate safe ranges for marine mammals of three different sizes and for human divers. However, the "safe" distances for humans are substantially larger than those for an equivalent sized marine mammal. Richardson et al. (1995) have suggested that a more precautionary approach would be to use the human value for all cetaceans. This would give a safe distance of 600 m for a 1 kg explosion, 900 m for a 10 kg explosion and 2 km for a 100 kg explosion.

Small explosive charges have been used to keep seals away from fishing gear, but seals seem to habituate rapidly to these. Similar charges have also been used to try to keep small whales away from certain fisheries, but with limited success. Humpback whales did not apparently move away from a construction site off the coast of Newfoundland where very large charges (200–2000 kg) were used in construction work (Lien et al., 1993). However, two whales with severely damaged ears were washed up dead during this work, and it seems very likely that the explosions were at least partly responsible for their deaths (Ketten et al., 1993).

3.2. Seismic surveys

Most seismic surveys are now carried out with airgun arrays which are fired once every few seconds. Most of the sound is concentrated around 100 Hz, although there may be leakage of sound at higher frequencies. Because of the relatively high source levels of sound produced by these arrays, they are often audible over many kilometres from source. The reaction of some baleen whales (bowhead, grey, humpback and fin) to airgun noise has been studied in the field.

Clear behavioural responses, in terms of changes in surfacing patterns and movement away from the source when it was within 5 km of the whales, have been observed on a number of occasions. Reactions have been most pronounced when the whales were to the side of the arrays long axis.

The hearing ability of toothed whales is relatively poor at low frequencies, nevertheless there is sufficient energy in the output of airgun arrays at frequencies of 200–500 Hz to make them audible at distances of 10–100 km. There have been a number of reports that dolphins are observed less frequently and cease vocalizing when seismic surveys are being conducted (e.g. Goold, 1996).

3.3. Vessel noise

Published literature on the response of marine mammals to vessel noise has been reviewed by Richardson et al. (1995). Many toothed whales appear to be tolerant of vessel noise and are regularly observed in areas where there is heavy traffic. Sperm whales have been reported to react to vessels with powerful outboard engines at distances of up to 2 km. Humpback whales and right whales are also reported to avoid large vessels in some areas. Right whales tend to swim directly away from such vessels but, because they can only swim slowly, they are sometime overtaken by the vessel and injured. Fin whales are reputed to ignore large vessels, but they respond to close (<100 m) approaches by whale-watching vessels by spending less time at the surface and by making shorter dives. In general, whales show very little response to slow approaches by vessels, but they may swim rapidly away from vessels producing sound which changes in intensity or head directly towards them. There is little or no data on the response of seals to vessel noise.

3.4. Low frequency sound in general

The response of marine mammals to low frequency sound will depend to a large extent on their hearing capabilities. Published information on this has been summarised by Richardson et al. (1995). Very little has been published on the hearing range of large whales because it is so difficult to carry out any direct studies. However, it is assumed that they have good sensitivity to sound of low and medium frequencies because most of their vocalisations are in this part of the sound spectrum. It is also assumed that their ability to determine the direction of a sound source is good because of the large physical distance between their ears.

Sperm whales, dolphins and porpoises appear to be most sensitive to sounds above 10 kHz, and they are capable of detecting frequencies as high as 200 kHz. This high-frequency sensitivity is required because of their dependence on sounds of this kind for echolocation. Bottlenose dolphins appear to be able to detect sound as low as 40–125 Hz but sensitivities in this part of the spectrum are low. Some pinnipeds, including harbour seals, can detect frequencies as high as 180 kHz, however sensitivities are low above 60 kHz. There is little variation in sensitivity between 1 and 50 kHz although, in general, sensitivity is less than in toothed whales in this part of the frequency spectrum.

A useful summary of the potential effects of low-frequency sound on marine mammals has recently been provided by the US Marine Mammal Commission (Anon, 1998). In decreasing order of severity they are:

1. Death from lung haemorrhage or other tissue trauma.
2. Permanent or temporary hearing loss or impairment.

3. Disruption of feeding, breeding, nursing, acoustic communication and sensing, or other vital behaviour. If severe, frequent or long lasting this could lead to a decrease in individual survival and productivity and a corresponding decrease in population size and productivity.
4. Abandonment or avoidance of traditional feeding, breeding or other biologically important habitats, again with possible effects on survival, productivity and population size.
5. Psychological and physiological stress making animals more vulnerable to disease, parasites and predators.
6. Changes in the distribution, abundance or productivity of important marine mammal prey species with consequent effects on individual survival, productivity and population size.

Recent experiments (e.g. Johnson and Spikes, 1997; Anon, 1998) have provided new information on effects 3, 4 and 6. These experiments were designed to document the response of a number of blue, fin, humpback and grey whales, northern elephant seals and their prey to low-frequency sonar. However, they did not provide any information on the consequences of these responses for individual survival and productivity, nor on effects 2 and 5. In order to better understand these effects it is necessary to have information on the sound intensities which individual animals are exposed to, and on their physiological responses to these intensities.

4. Risk assessment and mitigation

A well-defined methodology has been developed for assessing the risks to human populations associated with exposure to hazardous chemicals. Methods derived from environmental epidemiology and environmental health policy (Hertz-Picciotto, 1995) are used to estimate the risks of exposure and the likely response to exposure, taking account of the characteristics of humans who have been exposed and the environmental variables which are associated with exposure (Stallones,1988). In many cases, exposure probabilities and responses cannot be estimated directly because the potentially exposed population is too small, or there is a long latency period between exposure and response. As a result, estimates of risk are often based on the shape of dose–response curves derived from experimental studies of laboratory animals which are believed to be suitable surrogates for humans.

The assumptions made in this risk assessment process are often not directly testable, yet the needs of policy makers are usually so great that this approach is considered to be an acceptable way of evaluating the health costs of different actions. The US National Research Council developed a conceptual framework (National Research Council, 1983) for the process of risk assessment which has been widely accepted. This framework has been extended by the US Environmental Protection Council (EPA, 1992) so that it can be used to assess the risks to the environment from contaminant exposure, Monte Carlo techniques are then used to take account of uncertainties in assumptions about parameter values and processes (e.g. Cohen et al., 1996).

However, there is a fundamental difference between the two approaches. Human risk assessment is primarily concerned with the risk to *individuals* from exposure. Environmental risk assessment usually requires an additional step: an estimation of the consequences of the individuals' responses to exposure for the *dynamics* of their population, and ultimately of the consequences of these dynamic changes on ecosystem functions. The impacts of contaminants on individual animals or plants may, of course, be considered important when they involve species (like many marine mammals) which have enormous popular appeal, or endangered species (where the loss of even a few individuals could prejudice survival or recovery).

In this section we consider how the EPA risk assessment approach can be used to evaluate the potential impacts of exposure to the disturbance associated with exploration for oil and gas on marine mammal populations. In the previous section, we have identified the ways in which exposure may affect marine mammals, in this section we focus on exposure–response assessment, and on risk characterisation.

4.1. Exposure and exposure-response

The risk assessment process involves documenting the distribution of exposure — in this case the distribution of vessels carrying out surveys for oil and gas, and the nature of the sounds they will produce — and the extent to which this overlaps with the distribution of each marine mammal species in time and space. We have tried to document the latter in an earlier section. Nevertheless, considerable uncertainty remains about the precise distribution of animals, even where results from dedicated surveys are available. Recent refinements in the analysis of data from these surveys (Borchers et al., 1998; Cumberworth et al., 1996; Hedley et al., 1997) have, however, provided techniques for estimating the distribution of some species on the fine spatial scale which is necessary to assess the probability of encounters between marine mammals and survey vessels.

The next stage in the risk assessment procedure is to estimate the effect of a specific level of individual exposure on the probability of survival or fecundity for that individual — i.e. we need to know the form of the dose–response curve. As with humans, it is rarely practicable to estimate such curves directly. Instead, we must rely on analogy with related species to provide an insight into the form of the dose–response relationship.

4.2. Risk characterisation

In order to complete the risk characterisation we need some insight into the potential effects of contaminant exposure on the affected populations. This is where there is a complete lack of scientific understanding at present. Recent observational studies have indicated that, in general, marine mammals either do not respond to low-frequency sound (Costa et al., 1998; Thompson et al., 1998) or move away from high levels (Ridgeway et al., 1998; Thompson et al., 1998; Tyack, 1998). Based on studies of the anatomy of the inner ear, Ketten (1998) concluded that baleen whales and seals are more sensitive to low-frequency sound than other marine mammals, and thus are at greatest risk of permanent or temporary loss of hearing. But we do not know what the consequences of changes in behaviour or of loss of hearing are for survival or reproduction. As a result, it is difficult to assess the ecological impacts of exploration on marine mammal populations. Furthermore, an experimental approach is unlikely to be practicable and we will probably have to rely on theoretical models of energetics, migration and foraging to identify a feasible range of impacts. In the meantime, applying the precautionary principle, it would be sensible to try minimise the potentially harmful interactions between marine mammals and exploration vessels.

4.3. Risk mitigation

Some mitigation measures can be identified immediately without any further research. Exposure to all forms of risk can be reduced by avoiding areas where densities of marine mammals are known to be high. It is reasonable to assume that such areas are probably important for feeding, breeding or nursing, and that animals in them are likely to be more vulnerable to the effects of disturbance than those in neighbouring, low density areas. In addition, on average, the probability that marine mammals are in the vicinity of any device emitting low-frequency sound at start-up, will also be higher in these areas. However, reliable information on marine mammal densities are only available for a limited number of species, and even then only in certain well-studied regions at particular times of year. Thus the risks of death or major physical injury to marine mammals from exploratory surveys can be reduced by carrying out initial surveys for the presence of baleen whales and seals in the vicinity of the deployment. "Soft start" procedures may allow any animals that are present within a certain radius to move away without risk of injury.

However, evidence from the response of marine mammals to vessel noise indicates that they do not always move away from high intensity, low-frequency sound. This appears to be particularly the case when individuals are actively involved in feeding or mating. In such circumstances, animals may be exposed to sound levels which could cause permanent or temporary loss of hearing. It is possible to design suitable experiments to determine the circumstance under which some smaller marine mammals choose to remain in areas of high intensity, low-frequency sound. These experiments will have to be carried out under controlled conditions and there are only a few facilities in the world where this can be done.

There is considerable potential to incorporate additional information on marine mammal behaviour into seismic survey design and block licensing. For example, efforts to reduce output of high frequences from airguns could be increased (rather than onboard filtering after the sound is produced), arrays can be towed in paths that will not entrap animals wishing to escape the survey area, and surveys could be coordinated so that entire habitats or migration paths are not blocked. These areas of mitigation merit further research whilst the information and tools required to perform full risk assessments from an ecological perspective are developed.

5. Conclusions

The Atlantic Frontier area is regularly used by at least 23 species of marine mammal, some of which are officially classified as endangered or vulnerable. Anatomical evidence suggests that some species (particularly baleen whales and seals) may suffer permanent or temporary hearing loss if they are in the immediate vicinity of vessels conducting seismic surveys. Individuals of most species may move away from vessels conducting such surveys. However, the potential consequences of these changes in behaviour for survival, reproduction or growth of the species concerned cannot be quantified at present.

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