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Cetacean Stock Assessments in Relation to Exploration and Production Industry Activity and Other Human Pressures: Review and Data Needs

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Overview

The impacts of manmade underwater sound on cetaceans have become an important environmental issue. A number of studies have documented effects on individuals such as behavioural response; masking of biologically relevant signals; and hearing loss, either temporary or permanent (reviews by Richardson et al., 1995; Southall et al., 2007). Little is known, however, about the population-level consequences of acoustic impacts. Methodologies addressing this issue, such as risk-based and cumulative impact assessments, are still in their infancy (e.g., National Research Council [NRC], 2005; Boyd et al., 2008; Wright, 2009). There is also limited information on levels of human activities generating sound and uncertainties in cetacean stock assessments that hamper quantitative investigations. Yet, sound generating industries are active in many parts of the world's oceans and, therefore, qualitative assessments could provide a first step in managing potential conflicts between industry sectors generating sound and cetacean conservation.

The Exploration and Production industry (E&P industry) generates underwater sound potentially affecting individual cetaceans, with most concerns expressed about the effects of seismic surveys (review by OSPAR, 2009). However, the relationship between E&P industry activities and trends in cetacean stocks has rarely been investigated. We provide a global overview of E&P industries and cetacean stock data in order to identify hot spots for more detailed investigations. Thus, in four case studies, we quantified the E&P industry activity in a specific region, investigated the status and trends of seven cetacean stocks therein, and assessed other factors presumably influencing the populations in question.

A. Global E&P Industry Activity and Cetacean Stock Assessments

Approximately 6,200 E&P installations are presently operating in the marine environment, 65% of these are located off the coast of North America, with the Gulf of Mexico area comprising almost all of them. This is followed by the Asian Pacific region, the coasts of northwest Europe, the west coast of Africa, and South America. Data on the occurrence, effort, and type of surveys undertaken in seismic explorations is difficult to obtain in most cases, but the level of activities mostly follows the distribution of production facilities. Apart from some areas in North America and Europe, for many regions with a high proportion of platforms, there are huge knowledge gaps regarding cetacean stocks in the area. In the case studies, therefore, we focused on a representative sample of well-studied species, including (1) sperm whales (*Physeter macrocephalus*) in the Gulf of Mexico; (2) humpback whales (*Megaptera novaeangliae*), blue whales (*Balaenoptera musculus*), and fin whales (*B. physalus*) off the coast of California; (3) northern bottlenose whales (*Hyperoodon ampullatus*) off Nova Scotia; and (4) harbour porpoises (*Phocoena phocoena*) and minke whales (*B. acutorostrata*) off the east coast of the United Kingdom.

B. Case Studies: Gulf of Mexico, California, Nova Scotia, and UK East Coast

The case studies revealed some details of the number of E&P platforms and the amount of seismic surveys (2D and 3D)—in some cases, for extended periods of time. In the Gulf of Mexico, production platform locations overlap sperm whale distribution, most notably in the Mississippi Canyon where the density of sperm whales is highest (Jochens et al., 2006; Minerals Management Service [MMS], 2008). Seismic survey data has been recorded since 1968 in the Gulf, with activities ranging between 8,306 and 167,991 km/y for 2D surveys, and since 1993 with the steadily increasing 3D surveys, which peaked in 2002 with 119,526 km^2 surveyed (data 1968 to 2002; Dellagiarino et al., 2002). Abundance estimates for sperm whales for the period 1996 to 2001 and 2003 to 2004 did not differ significantly, but due to the very low precision of the estimates, the power to detect a difference is low (Waring et al., 2006). Data on reactions of individual sperm whales to sound from airguns is equivocal, with both presence and absence of avoidance behaviour (Mate et al., 1994; Madsen et al., 2002; Miller et al., 2009). There are several other human activities leading to pressures that could potentially impact sperm whales in the Gulf of Mexico, including fisheries, shipping, tourism, pollution, and environmental changes. In most cases, the uncertainty over the potential effects is high.

E&P industry activity on the U.S. Pacific Outer Continental Shelf (OCS) is predominantly concentrated off the coast of Southern California where 23 platforms are located. Data on seismic surveys are difficult to obtain but show that activity has occurred since 1968, with peaks in 2D survey activity pre-1977, 1982 to 1984, and 1988, and then an increase in 3D activity after a period of inactivity. A total of 157,420 km of 2D seismic surveys have been undertaken between 1968 and 2002 (Dellagiarino et al., 2002). Humpback whales have been increasing in numbers since the cessation of whaling, albeit with considerable statistical variance in their abundance estimates (e.g., Calambokidis et al., 1999; Carretta et al., 2009b). Blue whales have only inhabited Californian waters since the 1970s and have undergone shifts in distribution, probably due to shifts in prey abundance more than anything else (Carretta et al., 2009b). Fin whales are abundant off California, and results from line transect surveys indicate that numbers in that area have remained the same since the 1990s, although no statement regarding trends can be made due to uncertainty in the assessments (Carretta et al., 2009b). Data on effects of E&P industry sound on the three species are sparse; however, they indicate localised avoidance but no distributional changes in humpback whales during seismic surveys (McCauley et al., 2000) and cessation of vocalisation in fin whales during seismic surveys in one large area (Clark & Gagnon, 2006). There are several activities besides E&P industry sound that can potentially affect these three stocks such as fisheries, shipping (ship strikes and sound masking; Carretta et al., 2009b; Clark et al., 2009), and tourism, although the uncertainty about effects is high in all cases.

Offshore oil and gas production off Nova Scotia is relatively small, with only two offshore projects historically producing oil and gas. However, seismic exploration of the Scotian Shelf using 2D methods has been extensive, with 400,034 km surveyed between 1960 and 2004 (peaks during 1969 to 1972, 1981 to 1984, and 1998 to 1999). Seismic exploration using 3D methods did not begin until 1985, and around 30,000 km^2 had been covered by 2004 (peak between 1999 and 2001; Canada-Nova Scotia Offshore Petroleum Board [CNSOPB], 2000, 2003). Field studies using mark-recapture techniques indicate that the population of northern bottlenose whales in The Gully seems to have remained constant between 1988 and 2003, yet caution is urged when drawing conclusions about population trends for this group as confidence intervals (CIs) were very high (Gowans et al., 2000; Whitehead & Wimmer, 2005). Data on the effects of seismic surveys on northern bottlenose whales are lacking, although valuable information on sound levels was recorded at different distances from seismic survey vessels (see Lee et al., 2005). There are a limited number of human pressures that could lead to effects on the species such as fisheries, shipping, and pollution; however, these are impossible to assess currently.

E&P industry exploration began on the United Kingdom Continental Shelf (UKCS) in 1964, with 284 UKCS installations in production currently (data obtained from BERR, 2008). The first platform installations were predominantly in the southern North Sea, followed later by increased activity in the northern North Sea, the Moray Firth, and the Irish Sea (UK west coast). The largest increase in platform numbers occurred during the late 1980s; and most recently, activity has moved into the central North Sea and to the west of the Shetland Islands, with an increase in platform numbers between 1997 and 2007. Seismic surveys have been carried out in the North Sea since 1963; the majority have been 2D surveys, with 3D surveys being carried out since 1978. Effort between 1996 and 2004 was variable in seismic survey quadrants of the UK east coast, with 2000 being the least active year in terms of surveys (210 km and 463 km^2 of 2D and 3D seismic activity, respectively) and 1997 being the most active when 10,705 km (2D) and 6,441 km^2 (3D) of surveys were undertaken (data from www.ukdeal.co.uk; Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas [ASCOBANS], 2005). Large-scale surveys undertaken in 1994 and 2005 did not yield statistically significant results in the abundance of harbour porpoises in the whole North Sea and adjacent waters. However, the statistical error was very high, indicating that substantial positive or negative trends could have been masked (Hammond, 2006b). There appears to have been an increase in porpoise abundance in the southern North Sea, which might be due to a redistribution of the species as a consequence of prey availability (Hammond, 2006b; Thomsen et al., 2006a). Minke whales are found off the UK east coast, and there are indications that the overall stock in the Northeast Atlantic is increasing, although due to the high variability on the estimates, this trend is not significant (Hammond, 2006b; North Atlantic Marine Mammal Commission [NAMMCO], 2008). Harbour porpoises have been found to react to seismic surveys with short-term avoidance. A study undertaken on one individual indicates a lower threshold for TTS (temporary threshold shift) for airgun pulses compared to other cetaceans (Stone & Tasker, 2006; Lucke et al., 2009). Minke whales have not been found to react to seismic pulses (Stone & Tasker, 2006). For harbour porpoises, there are a variety of human activities that could lead to adverse impacts such as shipping; construction for offshore wind farms; marine aggregate dredging; pollution; and fisheries, although bycatch numbers have decreased recently, possibly as a result of declines in commercial fisheries (Stenson, 2003). For some of the pressures, information on effects on cetaceans is at least partly available—for example, the avoidance reaction due to pile driving has been documented and contaminants in cetacean tissue are well researched (Tougaard et al., 2006; Law et al., 2010b). However, a number of data gaps exist that hinder a comprehensive assessment. For minke whales, pressures are similar to those of harbour porpoises; yet, effects are largely unknown.

C. The Overall Picture

This study has provided new insights into the worldwide distribution of E&P industry activity and has also revealed striking data gaps in our understanding of cetacean population numbers and trends in areas of high E&P industry activity. Long-term cetacean data are only available for a limited number of populations located off the northwest European coast and off North America, but even here, comprehensive stock assessments come with huge uncertainties. Off Africa, Indonesia, and South America, there are significant data gaps. These areas are under increasing focus by the E&P industry for future exploitation, with likely differences in regulatory frameworks and mitigation measures from areas where the E&P industry is more established. Therefore, one important future research task should be a more comprehensive mapping of cetacean stocks worldwide, particularly off the west coast of Africa but also in Asia. This is also important if we consider that exposure to stresses/threats can vary greatly across regions, making extrapolations on effects of human activities from one area to another challenging.

D. A Closer Look

Our review of seven stocks found signs of an increase in numbers in one population (Californian humpback whales); for the remaining six (sperm whales off the Gulf of Mexico, blue and fin whales off California, northern bottlenose whales off Nova Scotia, and harbour porpoises and minke whales off the UK east coast), population trends could not be assessed due to the high variability in the abundance estimates. This emphasises the need for more intense survey programmes, although relatively high variation in cetacean abundance estimates is perhaps unavoidable (e.g., see Whitehead et al., 2000; Taylor et al., 2007). Combining visual surveys with passive acoustic monitoring and satellite telemetry can yield very important insights into the distributional patterns of individuals and could, together with the density estimates from visual surveys, aid in assessing habitat preferences of the target population (e.g., Skov & Thomsen, 2008). This information could then be used in management of cetacean populations and the human activities that could impact them. The positive trend in humpback whales in California points towards the possibility that in some cases populations may experience no measurable difference even when individuals are affected. This might be because the effects are either not severe enough or because individuals have learned to adapt to human pressures. Behavioural adaptations, however, likely come with costs to individuals that have to be incorporated into any comprehensive impact assessment (Bejder et al., 2009). It is of further importance to consider long-term impacts that are often indirect such as the potential consequences of climate change (e.g., see MacLeod et al., 2007b). It is likely that no single pressure is harmful enough to cause a decline in cetacean stocks on its own, but together, a number of pressures may create conditions which lead to reduced productivity and survival. Cumulative impact assessments for which methodologies are under discussion (see Wright, 2009) will further help in the understanding of human impacts on cetaceans.

E. Future Studies

We recommend future studies that provide more comprehensive data on cetacean stocks, possibly combining visual methods with passive acoustic monitoring and satellite telemetry. We further encourage studies that help to transform activities into quantities of sound exposure by area ("noise budgets"). A further development of impact analysis methodology needs to be undertaken as well, including advances and testing of the PCAD (Population Consequences of Acoustic Disturbance) model (NRC, 2005), an application of risk assessments in underwater sound impact studies (see Boyd et al., 2008) and consideration of cumulative impacts (see Wright, 2009).

1. Introduction

A. Background

Concerns about potential adverse effects of anthropogenic sound[1] on cetaceans have been raised from within the scientific community since the 1970s, and research on the topic expanded in the 1980s and 1990s (e.g., Payne & Webb, 1971; Richardson et al., 1995). During the last decade, the topic has been investigated extensively by a number of scientific institutions, governmental agencies, and intergovernmental bodies, with major reviews dealing with behavioural and physiological responses of cetaceans to various anthropogenic sound sources. The results indicate that some of the sounds introduced into the marine environment, such as seismic pulses and sound from pile driving, can be detected by cetaceans over considerable distances. The emitted sound field of more continuous sounds, such as those emitted by ships, has the potential to mask communication signals and echolocation clicks. Loud sounds can induce behavioural reactions, and, in some cases and at very high received sound levels, high-intensity pressure waves might result in tissue damage or other injuries in individual cetaceans (reviews by Richardson et al., 1995; Würsig & Richardson, 2002; International Council for the Exploration of the Sea [ICES]-AGISC [Ad-Hoc Group on the Impact of Sonar on Cetaceans], 2005; NRC, 2003, 2005; Madsen et al., 2006a; Thomsen et al., 2006b; Marine Mammal Commission [MMC], 2007; Nowacek et al., 2007; Southall et al., 2007; Weilgart, 2007; OSPAR, 2009; Tasker et al., 2010).

Despite this progress in our understanding, there are still numerous uncertainties and data gaps in our knowledge of the effects of anthropogenic sounds on cetaceans. Depending on a variety of variables, individuals might behave quite differently to a given sound (review by Nowacek et al., 2007). Another major gap concerns whether and how anthropogenic sound may affect populations. This is an important issue since the goal of cetacean conservation is to prevent human activities from harming populations (NRC, 2005). In order to analyse population-level effects, links need to be established between sound exposure and changes in cetacean abundance or life history parameters—for example, recovery rates, mortality, and birth rates. Recently, the NRC (2005) developed a Population Consequence of Acoustic Disturbance (PCAD) model. The model involves different steps that are required to relate acoustic disturbance to effects on marine mammal populations, including (1) sound source characteristics, (2) behavioural changes, (3) life functions impacted, (4) effects on survival rates, and (5) the population consequences of acoustic disturbance. Most of the steps within the PCAD model comprise huge uncertainties and, thus, the model is currently difficult to apply. There are further reasons that hamper investigations on population-level consequences of sound effects, including uncertainties about the level of human activities generating underwater sound, data gaps in population estimates for several species and in various regions, and the difficulties in comparing sound against other pressures such as, by-catch in fisheries, contamination, predation, and decrease of prey numbers (see NRC, 2005, for a detailed discussion and Boyd et al., 2008, for methodology involving risk-based approaches). Before PCAD models or risk assessment frameworks are able to become common practice, more qualitative assessments have to be undertaken to manage impacts of underwater sound, particularly for those industries that are thought to be key contributors to underwater sound levels in some regions.

The offshore E&P industry is a particularly suitable candidate for closer evaluation with regards to effects on cetaceans. It has seen considerable expansion and growth since the 1960s. About 30% of the total world oil production and 50% of the world's production of natural gas is conducted offshore (NRC, 2003). There are currently approximately 6,200 offshore E&P installations worldwide. The E&P industry generates underwater sound at every stage of its process—for example, during (1) exploration (seismic surveys and side scan sonar), (2) construction (pile driving and vessel activity), (3) extraction (drilling, maintenance vessels), and (4) decommissioning. Each activity has the potential to affect the behaviour and physiology of individual cetaceans, with most concerns expressed towards seismic survey explorations (see reviews by Richardson

[1] The terms *sound* and *noise* are not clearly separated in the literature and are often used synonymously. The Advisory Committee on Acoustic Impacts on Marine Mammals (2006) defines *sound* as an all-encompassing term referring to any acoustic energy. *Noise* is defined as a subset of sound, referring to sound that is "unwanted" by a particular receiver. However, since it is almost impossible to define or outline what is meant by "unwanted," we use the neutral term *sound* throughout the document, except when referring to scientifically accepted terms such as *ambient noise* or *masking noise* (see Advisory Committee on Acoustic Impacts on Marine Mammals, 2006). *Noise* is also used if a term is explicitly used to describe stressors, effects, etc.

et al., 1995; McCauley et al., 2000; Gordon et al., 2004; Nowacek et al., 2007). Despite documented responses of individuals or groups of cetaceans, the relationship between offshore E&P industry activities and trends in local cetacean stocks have not been investigated to date. This is partly because information on E&P industry activities is in many cases not readily available. There has been little effort in documenting trends of E&P industry activity alongside cetacean population trends. There are also uncertainties about pressures resulting from other human activities such as shipping and marine industrial activities. Therefore, the effects of E&P sound on cetacean stocks are completely unknown, making environmental risk assessments with regards to the E&P industry challenging. As a consequence, mitigation measures that are protective of cetaceans, relatively cost-effective, and credible to outside stakeholders are very difficult to establish.

B. Objectives

This study provides a desk-based assessment of selected cetacean stocks in relation to E&P industry activity and other human pressures. We first conducted a global overview of E&P industry activity in relation to cetacean stocks with the aim of identifying case studies for more detailed analysis. We then investigated available cetacean stock data from scientific literature and published reports/papers by institutions that are regularly involved in cetacean stock assessments. In four case studies, we investigated oil and gas activity, trends in specific cetaceans stocks, and the presence of further human pressures in more detail. We analysed E&P industry activity with regards to the number of platforms and seismic surveys conducted to get a more detailed picture of potential impacts. We then examined the target cetacean stock in each region and documented its status (e.g., population size, birth and death rates) and attempted to discern trends (growth rate, current level of mortalities). For this analysis, we used published material on population/stock parameters. Next, we investigated other pressures that might impact the case study population with the aim of putting the potential impacts of the E&P industry sound in context with other pressures. We finally provide a comparative description of the different factors influencing the stocks in a qualitative overview. Based on the results of our study, we present a discussion on the potential relationships of human pressures and cetacean stock developments, including an outline of the limitations inherent in our approach. Finally, we provide detailed suggestions for future research into the effects of anthropogenic sounds on cetacean populations.

2. Methods

A. General Approach

Our desk-based assessment has two main parts: (1) a comprehensive overview of worldwide E&P industry activity and cetacean stock data, and (2) a case study stock assessment. Based on the worldwide overview and theoretical considerations, which are outlined further below, the target species for the case studies were chosen. All of our case studies follow the same structure. The review starts with a brief introduction to the region, followed by a detailed description of E&P industry activity. Then, the detailed stock assessment is undertaken. A review of documented effects of E&P sound on the case study species follows. The case studies then look into published accounts of other activities that could / are known to affect the target species. Finally, we provide an assessment of the human pressures on the case study species in the form of qualitative overview tables.

B. Selection of Target Species: E&P Industry Sound Profiles vs Cetacean Hearing

Our general approach in the assessment was to pick case study species based on the worldwide overview of E&P industry and cetacean stock data with emphasis on those species for which hearing sensitivity overlaps with E&P sound profiles. We therefore provide a brief overview of E&P sound profiles and points that have to be considered with regards to cetacean hearing systems and E&P sound.

There are excellent reviews on E&P industry sound available, including Richardson et al. (1995), NRC (2003), Hildebrand (2009), and OSPAR (2009) (see sources in Table 1). Sounds during exploration and geophysical surveying include ship echosounders (single and multibeam) that are usually mid to high frequency and short in duration. There are also side scan sonar systems in operation that are used to map the upper layers of the seabed.

Table 1. Overview of E&P industry-related sound profiles

Sound source	Source level at 1 m	Bandwidth	Main energy	Duration	Directionality	Source
		Exploration and geophysical surveying				
Echosounders	230-245 dB re 1 µPa (rms)	11.5-100 kHz	Various	0.01-2ms	Downwards	(1), (2)
Sparkers, boomers, chirp sonars	204-230 dB re 1 µPa (rms)	0.5-12 kHz	Various	0.2 ms	Downwards	(3)
Seismic airgun arrays	220 - 262 dB re 1 µPa (peak-to-peak)	5 Hz-100 kHz	10-120 Hz	10-100 ms	Downwards	(4), (5), (6), (7), (8), (9)
		Construction				
Construction and maintenance ships	150-180 dB 1 µPa (rms)	20 Hz-20 kHz	<1 kHz	Continuous	Omni-directional	(4)
Pile driving	220-257 dB re 1 µPa (peak to peak)	10 Hz->20 kHz	100-200 Hz	5-100 ms	Omni-directional	(10), (11), (12), (13), (14), (15)
		Operation				
Drilling	115-117 dB re 1 µPa (at 405 and 125 m)	10 Hz -~1 kHz	< 30-60 Hz	Continuous	Omni-directional	(4), (16)
		Decommissioning				
Explosives	272-287 dB re 1 µPa (zero to peak)	2 Hz-~1 kHz>	6-21 Hz	~1 ms	Omni-directional	(4)

Sources: (1) SCAR, 2005; (2) Hildebrand, 2009; (3) OSPAR, 2009; (4) Richardson et al., 1995; (5) Goold & Fish, 1998; (6) Gausland, 2000; (7) Madsen et al., 2006a; (8) Breitzke et al., 2008; (9) Goold & Coates, 2006; (10) Madsen et al., 2006b; (11) Thomsen et al., 2006b; (12) Würsig et al., 2000; (13) McKenzie-Maxon, 2000; (14) Caltrans, 2001; (15) Nedwell et al., 2007; (16) McCauley, 1998; for an overview, see also OSPAR, 2009

These are high-frequency devices (above 100 kHz) with very short signal times (300 to 600 μs; Markus Diesing, pers. comm., 2010). The source most often used in geophysical surveying is the seismic airgun. These are usually used in arrays and, when fired, the airgun releases a bubble of compressed air. Airgun pulses are typically of low frequency with the centre frequency between 10 and 120 Hz (Richardson et al., 1995; Goold & Fish, 1998; Gausland, 2000; Madsen et al., 2006b; Breitzke et al., 2008), albeit some acoustic energy has been measured up to about 100 kHz (Goold & Coates, 2006). The energy at these higher frequencies is low compared to the overall output of the airgun (see Table 1). The sound pulse is directed into the seabed and the reflected sound is detected by hydrophones placed inside a "streamer" (cable type device towed behind the vessel). In 2D operations, a single streamer is towed behind the survey vessel. In 3D operations, groups of streamers are used to increase accuracy of detection. Sparkers and boomers are higher in frequency than airguns and are used to determine shallow features in the sediment. These devices can also be towed behind the survey vessel. Chirp sonars produce sound in the mid-upper frequency range and can be used in a hull-mounted mode (for a detailed description, see OSPAR, 2009). Published accounts of pile-driving sound during E&P platform construction are sparse (see McHugh et al., 2005). The data presented here were gathered during various investigations of pile driving during construction of aviation fuel facilities, bridges, and offshore wind turbines. Pile driving can generate very high sound pressure levels (SPLs) with most energy below 1 kHz. Construction and maintenance ship sound levels can be inferred from measurements of vessels of comparable size. Operational drilling sound has only been very sparsely documented as being relatively low in energy and frequency. In summary, the information in Table 1 indicates that sound profiles vary greatly, with relatively high SPLs emitted during seismic surveys, during pile driving, and through the use of explosives during decommissioning. In general, the frequencies emitted during E&P industry operations are in the lower frequency ranges below 1 kHz.

Looking at the sound profiles from E&P industry, we should have selected cetacean stock for the case studies that are sensitive to sound at the lower end of the frequency scale. However, data on cetacean hearing is relatively sparse, with published audiograms for only a few of the ~77 species of cetaceans. No audiograms exist for baleen whales (overviews in Nedwell et al., 2004; Southall et al., 2007). Nonetheless, based on an analysis of comparative anatomy, modelling studies, and the investigation of sounds emitted, Southall et al. (2007) recommended species and subspecies of cetaceans to be assigned to one of three functional hearing groups (for mysticete hearing, see also Ketten, 1997; Clark & Ellison, 2004):

1. Low-frequency cetaceans (13 species/subspecies) with functional hearing between 7 Hz and 22 kHz comprising all mysticetes (baleen whales)

2. Mid-frequency cetaceans (57; hearing 150 Hz to 160 kHz), including 32 species of dolphins, six species of larger toothed whales, and 19 species of beaked whales

3. High-frequency cetaceans (21; hearing 200 Hz to 180 kHz), comprising eight species and subspecies of porpoises, six species and subspecies of river dolphins, plus the *franciscana*, the genus *Kogia*, and four species of Cephalorynchidae (for details, see Southall et al., 2007)

At first glance, we might conclude that an assessment of cetacean stocks with regard to potential impacts from E&P industry sound should focus on low-frequency and, perhaps to a much lesser extent, on mid-frequency cetaceans. Yet, looking at the issue in greater detail, there are further points to be made:

- E&P industry activities involve sound production in frequencies at least up to 15 kHz; and in the case of pile driving, at even higher frequencies, which could potentially affect all three hearing groups (see Madsen et al., 2006b; Thomsen et al., 2006b). In line with this, some observations in the field indicate that behavioural reactions to seismic surveys are not restricted to the low-frequency mysticetes, but can also occur in other groups, including, for example, bottlenose dolphins (*Tursiops truncatus*), common dolphins (*Delphinus delphis*), and harbour porpoises (Stone & Tasker, 2006).

- The auditory bandwidth estimated by Southall et al. (2007) is, in general, quite large, with a considerable overlap in areas of best hearing across groups. For example, audiograms obtained from harbour porpoises, a high-frequency cetacean according to Southall et al., indicate that their hearing threshold between 300 Hz and 1 kHz is at least as good, if not better at the same frequencies, than those found in mid-frequency species such as bottlenose dolphins, killer whales (*Orcinus orca*), and Risso's dolphins (*Grampus griseus*) (Johnson, 1967; Andersen, 1970; Nachtigall et al., 1995; Szymanski et al., 1999; Kastelein et al., 2002; Lucke et al., 2004, 2006, 2009). It is, therefore, important to consider the groups on the basis of the overall auditory bandwidth rather than on the range of their best hearing capability.

- It is possible that some odontocetes are able to detect low-frequency sounds using mechanisms other than conventional hearing, for example, by detecting particle velocity or a combination of pressure and velocity in the near-field (Turl, 1993).

- Injury is a concern for all functional hearing groups of cetaceans at close ranges to seismic airguns and pile driving (see Southall et al., 2007).

Following the points made above, an assessment of cetacean stocks in areas of high E&P industry activity should include low-frequency cetaceans as well as other species with a potentially higher frequency range of best hearing compared to mysticetes.

C. Methodology for Overview of Human Pressures

For each case study, a table summarises the pressures acting on the respective cetacean population. Due to the difficulties in quantitatively assessing pressures and potential impacts (e.g., see Miller et al., 2007; Boyd et al., 2008), we chose a qualitative approach. We first listed activities and their levels based on various parameters (e.g., number of platforms, kilometre transect/y) using the information available to us. It should be noted here that this comprises by no means an absolute assessment but merely a tool for the comparison of activities within regions. Pressures and potential effects were then listed according to knowledge from the literature (for overviews on sound, see Richardson et al., 1995; Southall et al., 2007; OSPAR, 2009; for other effects, refer to reviews in Perrin et al., 2002, 2008; Reynolds et al., 2005). The spatial scale of these potential effects was assessed on a two-fold scale as either being short-range, that is occurring in the immediate vicinity of the source only and/or within the area the activity is carried out (e.g., vicinity of a turbine and offshore wind farm area) or long-range—that is, occurring beyond that. It should be emphasised that this is a very preliminary and rather subjective measure that needs further refinement. It is appreciated that sound can have potential effects on a wide range of distances, up to several kilometres. Zones of noise influences are, however, so diverse and dependent on so many variables (see OSPAR, 2009) that a further split in spatial scales of effects was deemed unfeasible at this stage.

D. Definition of Sound-Related Effects

For the assessment of potential impacts as presented in the overview tables, the OSPAR (2009) paper was particularly relevant as it not only provides a background on underwater sound and its impacts on marine life, but it also covers documented impacts of the various sectors such as marine construction and industrial activities, shipping, sonar, seismic surveys, wave and tidal energy, and acoustic management devices. There are also reviews covering particular activities such as seismic surveys (Gordon et al., 2004), shipping (Southall, 2005), offshore renewable industries (Madsen et al., 2006a; Thomsen et al., 2006b; Bailey et al., 2010), and marine aggregate dredging (Thomsen et al., 2009). What follows is a short overview of the main issues that we considered when listing potential impacts of sound generated by these industries.

In the overview tables, effects were divided into *masking*, *behavioural disturbance*, *temporary threshold shift (TTS)*, and *injury*, either as *permanent threshold shift (PTS)* or *other injuries* (see Richardson et al., 1995; Southall et al., 2007).

Masking occurs when the sound is strong enough to interfere with detection of other sounds such as communication signals or echolocation clicks. It starts when the sound level of the masking sound—for example, sound from a nearby ship—equals the ambient noise at the frequency of the signal. Masking can shorten the range over which conspecifics are able to communicate—for example, mother and calf pairs of odontocetes. *Behavioural disturbances* are changes in activity in response to a sound. These effects can be very difficult to measure and depend on a wide variety of factors such as the physical characteristics of the signal; the behavioural state of the receiver; its age, sex, and social status; and many other factors. Therefore, the extent of behavioural disturbance for any given signal can vary, both within a population as well as within the same individual. Behavioural reactions can range from very subtle changes in behaviour to strong avoidance reactions. In some cetaceans, they can also be exhibited as changes in vocal activity (review by Richardson et al., 1995; Würsig & Richardson, 2002; Southall et al., 2007; Clark et al., 2009).

Both *TTS* and *PTS* represent changes in the ability of an animal to hear, usually at a particular frequency, with the difference that TTS is recoverable after hours or days and PTS is not (Southall et al., 2007). Further injuries to hearing organs and non-auditory tissues can happen at very high received sound levels and can be dependent on other sound characteristics as well (see Southall et al., 2007).

E. Use of Acoustic Terms

Sound pressure levels (SPLs) are provided as decibel (dB) measures of mean squared acoustic pressure where the reference pressure p_{ref} is equal to 1 µPa. Whenever possible, dB values are given in pressure metrics:

- *Peak pressure level* – The maximum absolute value of the instantaneous SPL (denoted as P_{max} in units of Pascal [Pa]). Peak SPLs are given as dB re 1 µPa (peak).

- *Peak-to-peak pressure level* – Difference between the maximum positive and maximum negative instantaneous peak pressure. Peak-to-peak SPLs are given in dB re 1 µPa (peak-to-peak).

- *Root mean square sound pressure level (rms)* – This is the root mean square of time series Pressure (time). RMS values are useful to describe continuous (i.e., nonpulsed) sounds such as those from shipping.

Source level is a measure of the acoustic output which is a characteristic of the source rather than the environment. It is often expressed as the SPL that would exist 1 m away from an equivalent point source radiating with the same acoustic power into the medium as the actual source. It is determined by measuring the SPL in the acoustic far-field and extrapolating back to determine the SPL that would exist 1 m away from the acoustic centre using an appropriate propagation model. Because of this definition, the units are often expressed as dB re 1 µPa at 1 m, but they sometimes may be seen stated as dB re 1 µPa•m (see Urick, 1983).

Sound exposure level (SEL) is the time integral of the squared pressure over a fixed time window (e.g., dB re 1 $\mu Pa^2 \cdot s$). It is useful as a measure of the sum of the acoustic energy over a measurement period (for this and the above definitions, see Urick, 1983; Southall et al., 2007; Ainslee, 2010).

3. E&P Industry and Cetacean Stocks: An Overview

Table 22 (see Appendix) provides an overview of the E&P industry worldwide and a rough assessment of cetacean stocks in each respective region. This table lists the number of platforms in different regions and provides an overview of seismic activity. For descriptive purposes, the numbers of platforms in different regions are shown in Figure 1.

Approximately 6,200 E&P installations are presently operating in the marine environment, with between 25 and 30% of global production of E&P industry estimated to come from offshore reservoirs (GESAMP [Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection], 2007). There are clear differences in the distribution of offshore E&P platforms in the world's coastal waters (see Figure 4 in Chapter 4; Table 22 in Appendix): over 3,800 (65.0%) of them are located off the coast of North America, with the Gulf of Mexico comprising almost all of them (95.0% of North American installations; 62.0% of total). The area with the second highest concentration of E&P platforms is the Asian Pacific region (15.0% of all platforms), with most facilities located off the coasts of Indonesia and Malaysia and with some activity off the west and north coasts of Australia. The third most active region in terms of platforms is located off the coasts of northwest Europe, notably off the east coast of the UK and the southwest coast of Norway (8.0% of overall). This is closely followed by the west coasts of Africa and South America (6.0 and 5.5%, respectively). Seismic survey data are difficult to obtain in most cases, but the level of activities mostly follows the above-mentioned trend.

Looking at the distribution of platforms, one might conclude that case studies—investigating cetacean stock assessments with regard to E&P industry sound—should concentrate on areas with the highest number of platforms and greatest seismic activity. The obvious candidate for a closer look is the Gulf of Mexico (see Table 22 in the Appendix). There are also a variety of cetacean species present in the Gulf of Mexico; and data for sperm whales, a mid-frequency cetacean (Southall et al., 2007), have been collected during various studies (e.g., Blaylock et al., 1995; Jochens et al., 2006; Waring et al., 2009; and summarised in many NOAA Stock Assessment Reports [SARs], 1995 to 2007). Based on the available data, the sperm whale activity in response to anthropogenic activity in the Gulf of Mexico represents the first case study.

It can be concluded that for many regions with a high proportion of E&P platforms (Figure 1; Table 22 in Appendix), there are huge gaps in our knowledge on cetacean stocks. We should bear in mind that in order to assess stocks, information on abundance and distribution of cetacean populations over several years, and some basic demographic

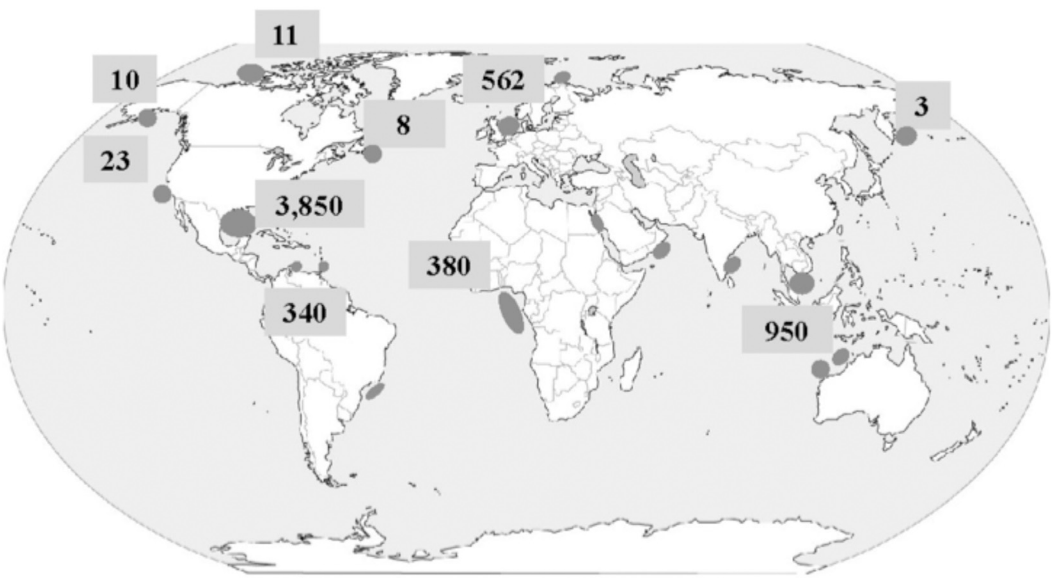


Figure 1. Schematic overview of the number of oil & gas platforms in different parts of the world (data from GESAMP, 2007; MMS, 2008; www.og.dti.gov.uk); grey: areas of high production.

data on mortality and productivity are absolute prerequisites. Ideally, further data on age and sex classes and genetic composition with which to postulate the presence of a stock should also be available. This information, however, is absent for the Asian Pacific region, with the exception of western and northern Australia, where field studies on humpback whales have been ongoing since the beginning of the 1990s (e.g., Jenner et al., 2001). This area off Australia was already under a similar investigation to our assessment by another group (W. J. Richardson, pers. comm., 2008) and, therefore, was not included in this study.

Information on West African cetaceans is only available in the form of presence/absence data or as lists of species encountered during more or less opportunistic surveys (see Table 22 in the Appendix). The situation off South America is similar; we were unable to include any cetaceans from either West Africa or South America in our assessment because of the lack of stock data. In fact, one of the first major trends made apparent by this study, with the notable exception of the Gulf of Mexico, is that the largest cetacean data gaps exist in those regions where there is a comparatively high level of E&P industry activity.

The picture looks much more promising for North America, with several established field studies off both the west and the east coasts. For example, for the coast of California, stocks of humpback, fin, and blue whales, all low-frequency cetaceans (Southall et al., 2007), have been monitored for at least a decade and shall therefore be presented in more detail in a second case study (see Carretta et al., 2009b). The relationship between E&P industry activity and the behaviour of bowhead whales (*Balaena mysticetus*) in the Beaufort Sea (Alaska) has been examined since the beginning of the 1980s (Richardson et al., 1985, 1986, 1990, 1995), with additional results under review in parallel to the present study as part of a similar investigation (W. J. Richardson, pers. comm., 2008). In order not to duplicate the effort, this area is omitted from the case studies included in this paper. Since 1988, the mid-frequency northern bottlenose whales have been studied off Nova Scotia in an area close to E&P industry activity; data on distribution and abundance are available for a period of almost two decades (Gowans et al., 2000; Hooker, 1999; Hooker & Baird, 1999; Hooker et al., 2002, 2008). The northern bottlenose whales off Nova Scotia, therefore, represent the third candidate for closer study.

For northwest Europe, data are available from large-scale surveys such as SCANS (Small Cetaceans in the European Atlantic and North Sea) I and II and opportunistic sighting schemes such as the one maintained by the Sea Watch Foundation in the UK. Much information is also provided by smaller-scale studies, with the most data available for the harbour porpoise (Hammond et al., 2002; Reid et al., 2003; Hammond, 2006a; Thomsen et al., 2006a, 2007). Harbour porpoises in the central and southern North Sea, where most E&P platforms are located and most seismic surveys have been undertaken, form one focus for the present assessment. To complement the picture, minke whales off the central and southern North Sea were also investigated (see Hammond, 2006b).

4. Case Study 1: Gulf of Mexico – Sperm Whales

A. Introduction to the Region

The Gulf of Mexico is the ninth largest body of water in the world and is bordered by the U.S. to the north, Mexico to the west, and Cuba to the southeast (Figure 2). As a consequence of its large coastal area, its shores are home to large human populations: in 1995, approximately 44.2 million people resided along the Gulf in the five U.S. Gulf states alone. This population size is predicted to rise to 61.4 million by 2025 (www.gulfbase.org). As such, the Gulf of Mexico is heavily utilised for pleasure and tourism as well as for its valuable natural resources.

B. E&P Industry Activity

Production

The Gulf of Mexico supports a large E&P industry: offshore operations in the Gulf produce a quarter of the U.S. domestic natural gas and one-eighth of its oil, according to the U.S. Minerals Management Service (MMS) (2008). Figures from the same source (MMS, 2008) reveal that the Gulf of Mexico is currently home to 3,855 active platforms and 7,169 active leases (Table 2). The Gulf of Mexico is split into three planning areas: (1) Western, (2) Eastern, and (3) Central. These planning areas are then subdivided into blocks, each approximately 16.7 km^2 in size.

Most of the exploration and production have been focused in the Central Planning Area and, to a lesser extent, the Western Planning Area. The Eastern Planning Area has seen far less activity to date (Figure 4).

Drilling activity has been closely recorded since 1959 (see http://investor.shareholder.com/bhi). These data show the average number of platforms (rigs) drilling/wk (see Figure 2). Three distinct peaks in drilling activity can be seen in 1966 (with an average of 107 rigs actively drilling/wk), 2001 (with an average of 148 rigs actively drilling/wk), with the period of highest activity during the late 1970s to the early 1980s, peaking in 1981 with 231 rigs actively drilling/wk (see http://investor.shareholder.com/bhi).

The vast numbers of platforms and their wide distribution means that they will likely overlap with the distributions and movements of the resident and migratory sperm whales. Maps from sightings, tagging data, and acoustic recordings during the Sperm Whale Seismic Study (SWSS) in the Gulf of Mexico provide a good indication that such overlaps do occur. Aggregations of female and mixed juvenile/calf groups were commonly sighted around the Mississippi Canyon in summer 2004 (Mullin et al., 1991; Davis et al., 2000; Mullin & Fulling, 2004; Jochens et al., 2006, 2008), while bachelor groups were commonly seen around the DeSoto Canyon and Florida slope

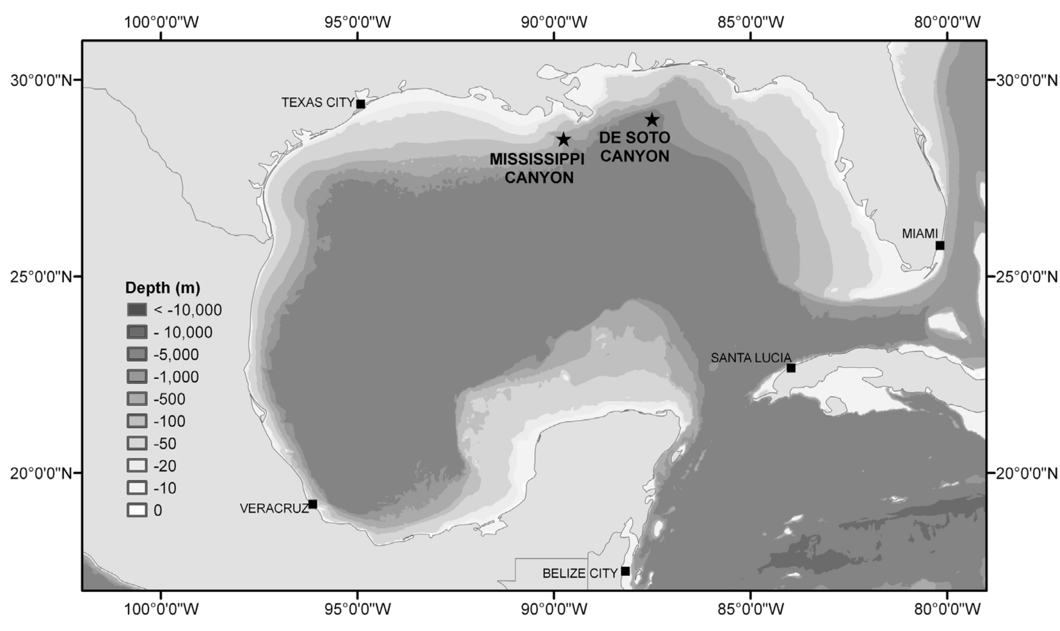
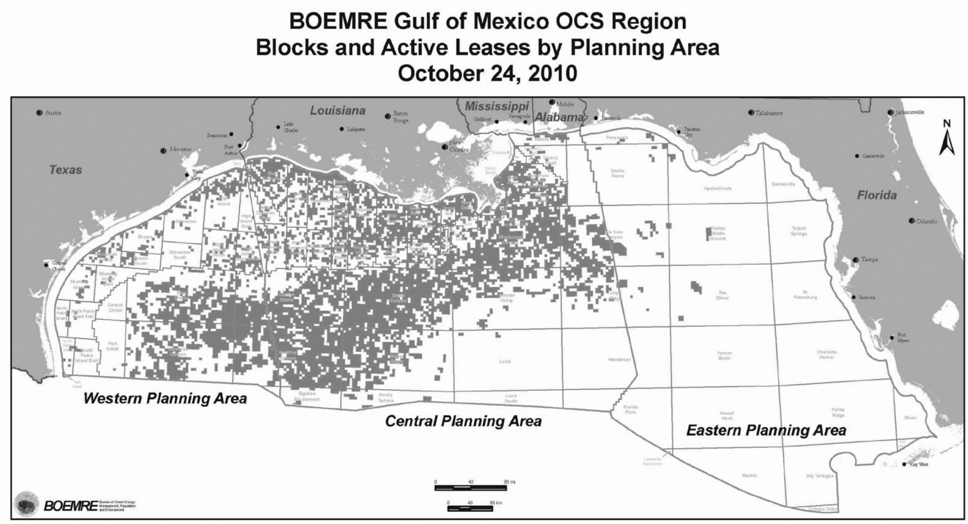


Figure 2. Overview of the Gulf of Mexico

Table 2. The number of platforms in the Gulf and the depths they occupy as of 11 February 2008

Water depth (m)	Active leases	Approved applications to drill	Active platforms
0 to 200	3,268	43,577	3,798
201 to 400	195	1,328	21
401 to 800	389	946	9
801 to 1,000	364	496	7
1,000 and above	2,953	1,387	20

Source: Minerals Management Service – Gulf of Mexico Region (https://www.gomr.mms.gov/homepg/fastfacts/WaterDepth/WaterDepth.html)



Planning Areas	Total Blocks	Total Acres	Number of Leases	Acres Leased
Western	5,240	28,576,583	1,518	8,539,801
Central	12,409	66,452,086	4,891	25,854,911
Eastern	11,526	64,556,650	122	659,264
Sub-Totals	29,175	159,585,319	6,531	35,053,976
CPA / EPA Shared Blocks*	(86)		(9)	
Totals	**29,089**	**159,585,319**	**6,522**	**35,053,976**

Active Leases
Planning Area Boundary

* CPA and EPA contain 86 shared blocks of which 9 are leased. These blocks are given both a CPA and EPA designation in the data which accounts for a higher block total.

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Figure 3. Planning areas within the Gulf of Mexico as defined by the U.S. Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), October 2010; the areas shaded are the locations of active leases. (*Source:* BOEMRE, U.S. Government; www.boemre.gov/disclaimer.htm; www.gomr.boemre.gov/homepg/lsesale/lsesale.html)

(Jochens et al., 2006, 2008). Conversely, the lone/bachelor males were found around the Mississippi Canyon during summer 2005 (Jochens et al., 2008).

Maps of sperm whale movement and residency, sightings, and tagging data (NOAA and SWSS studies; see description in more detail below) were examined for potential correlation with E&P industry leases and maps of rig locations. The areas in which sperm whales occur were related to the E&P field name; Table 3 depicts the fields (from east to west) and the associated numbers of rigs found in each.

The DeSoto Canyon is the favoured region for bachelor male sperm whales (Jochens et al., 2006). Although currently no platform structures are located in this region, 19 applications for permits to drill (APD) were approved from 2001 to 2007. Also, by 2007, approximately 63 blocks had received bids for lease sales. With these drilling permits being approved and technology advancements, it would appear that the deep offshore DeSoto Canyon could soon house E&P industry development.

Moving westward, the Main and South Pass fields also have some sightings around them, despite being located in shallower water. These regions are dense with structures (236 and 122, respectively). As already mentioned, the

Figure 4. Average active drilling rigs/wk between 1959 and 2007 within the Gulf of Mexico (http://investor.shareholder.com/bhi)

Mississippi Canyon is the region with the highest sperm whale numbers (Jochens et al., 2006, 2008). As of 2007, there were 23 rigs in the Mississippi Canyon area, at depths ranging from 105 to 2,438 m. The first three were installed on 1 January 1978 and the latest and deepest on 11 June 2007. It appears that deep rigs (i.e., placed farther into sperm whale deep diving habitat) are becoming more commonplace as technology allows. The remaining regions, farther west, are also in line with sperm whale movements, although the fields with highest rig densities (South Timbalier and Ship Shoal) are generally in shallower water and so would not likely be used by the animals with the same frequency with which they are seen in and around the canyons.

Proposals have been put forward to drill for deep gas in the Gulf of Mexico (https://www.gomr.mms.gov/homepg/offshore/deepgas.html). Despite being targeted toward shallow water rigs, the deeper drilling may have implications for sperm whales in the area, possibly through increased sound emissions. Another potential addition to waters of the Gulf of Mexico is the construction of Liquefied Natural Gas (LNG) terminals. As of 14 January 2008, one LNG terminal was already constructed in the Gulf (Gulf Gateway Energy Bridge), and two have been approved (offshore Louisiana and Port Pelican), with two more proposed (GOM and offshore Florida).

Exploration

During data collection for this review (2008), seismic surveys within the Gulf of Mexico were licensed in the form of permits issued by the U.S. Department of the Interior through the MMS. Under the conditions of the survey permits, industry was required to provide seismic data to the MMS. Only estimates of the amount of seismic activity undertaken can be made using the data readily available from public sources.

As is typical across the E&P industry, the first surveys were conducted using two-dimensional (2D) techniques. The 2D survey data has been recorded since 1968, averaging approximately 33,210 km of survey lines/y until 1975 (Figure 5). Following a drop in activity in 1977 (down to an estimated 8,306 km), 2D surveys increased at a relatively stable rate until 1990 when they reached a peak of an estimated 142,034 km. After a drop in the mid-1990s the km of 2D surveys peaked again in 1998 at an estimated 167,991 km. By 1993, technological advances allowed 3D surveys to become commonplace, with a steady increase in their use from an estimated 26,000 km^2 to an estimated 119,526 km^2 by the end of 2002.

There does not appear to be any readily available breakdown of the seismic data to the block level or even within regions of the Gulf of Mexico;

Table 3. O&G fields from the east to west distribution of sperm whales in the northern Gulf

Region	Number of structures	Shallowest (m)	Deepest (m)	First installation	Most recent installation
DeSoto Canyon	0	--	--	--	--
Main Pass	236	7.3	128.0	1 Jan 54	15 Aug 07
South Pass	122	4.3	152.4	1 Jan 58	23 Aug 04
Mississippi Canyon	23	104.5	2438.4	1 Jan 78	11 June 07
South Timbalier	347	7.9	147.5	1 Jan 56	23 Dec 07
Ship Shoal	436	2.4	141.4	1 Jan 50	12 June 07
Green Canyon	19	184.1	2148.8	1 Jan 86	16 Oct 07
Garden Banks	12	164.9	1615.4	1 Jan 80	5 Aug 04
East Breaks	6	201.2	1120.1	1 Jan 81	28 April 02
Corpus Christi	0				

Source: Minerals Management Service – Gulf of Mexico Region (https://www.gomr.mms.gov/homepg/fastfacts/platform/master.asp)

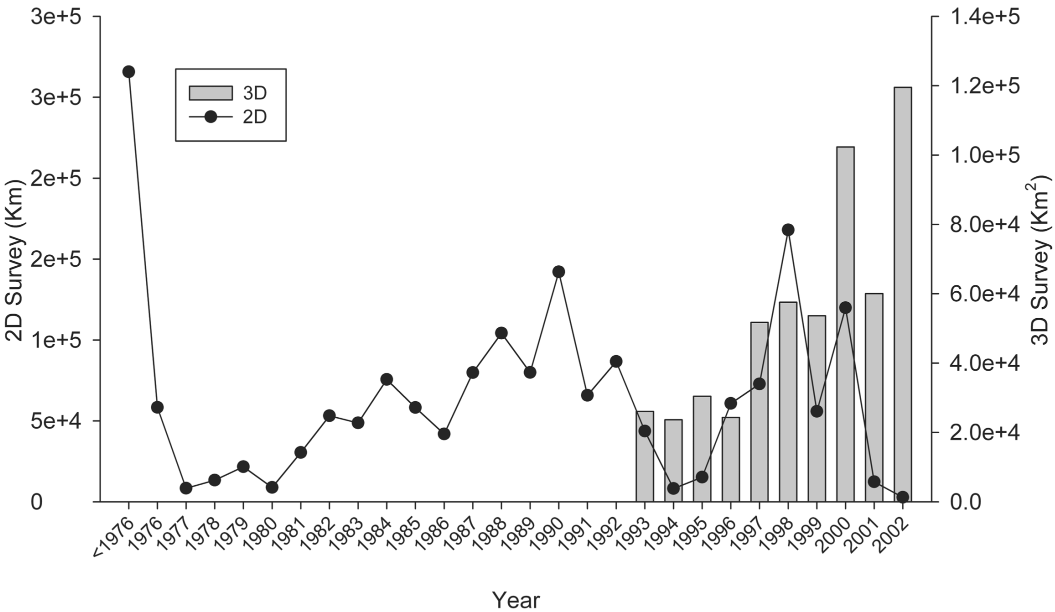

Figure 5. Total km of 2D surveys and total km² of 3D surveys carried out in the Gulf of Mexico between 1968 and 2002 (adapted from Dellagiarino et al., 2004)

however, the report by Dellagiarino et al. (2004) provides some detail of 2D data by planning area. While no information can be gained on the yearly distribution of 2D seismic activity, these data reinforce the concentration of activity within the Central and Western Planning Areas compared to the Eastern Planning Area. (It is worth noting that these planning areas refer to the planning areas as defined pre-July 2007 [Peterson et al., 2007], which are slightly different in distribution to the current planning areas.)

C. Sperm Whale Stock Assessment

The rich diversity of cetacean species residing in the Gulf of Mexico is a likely consequence of the diverse range of habitats found in the Gulf (Gore, 1992). Mullin & Fulling (2004) reported at least 19 different species during their 1996 to 1997 and 1999 to 2001 surveys of the northern Gulf of Mexico.

Sperm whales have been sighted throughout most of the deeper waters of the Gulf of Mexico (Figure 6; see Waring et al., 2006, for Southeast Fisheries Science Center [SEFSC] survey results; Mullin et al., 1991). However, particularly high aggregations are often found near the Mississippi River Delta (Mullin et al., 1991; Davis et al., 2000; Mullin & Fulling, 2004; Jochens et al., 2006, 2008). This is probably a consequence of the very high primary productivity associated with the Mississippi River plume that is enhanced by nutrient upwelling (Mullin & Fulling, 2004). This is likely to be the foundation of large food sources for these whales in the form of squid. Mullin et al. (1991) suggest that shortfin squid (*Illex illecebrosus*) and the orange back squid (*Ommastrephes pteropus*), which are known to occur in the deep Gulf waters (Voss, 1956) and are a recognised part of the sperm whales' diet (Rice, 1989), are likely the species making up the bulk of sperm whales' food in this region.

Population Structure and Size

Obtaining estimates for the population size of this stock is not straightforward for a number of reasons:

- There is some uncertainty that these animals are actually from one discrete stock, although recent SWSS reports (Jochens et al., 2006, 2008) support the National Oceanic and Atmospheric Administration's (NOAA) reasoning in treating them as such through positive results from genetic analyses, coda vocalisations, and population structure.

- Their deep diving behaviour means that they stay submerged for long periods of time and are not as gregarious at the surface as some other species such as bottlenose dolphins. Hence, obtaining enough data from visual surveys is challenging.

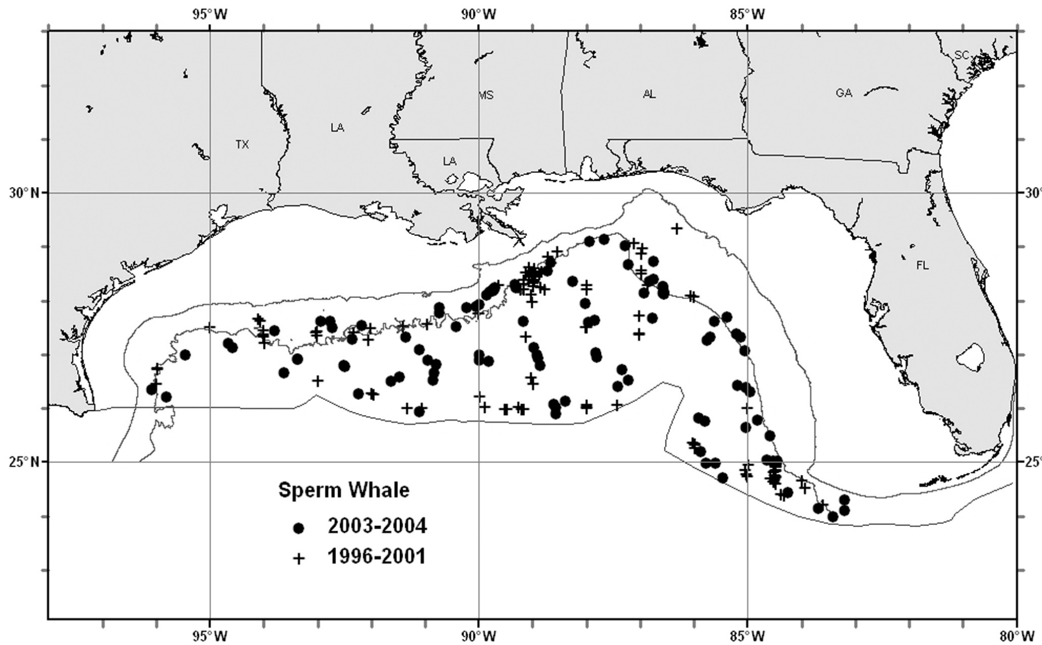

Figure 6. Distribution of sperm whale sightings from Southeast Fisheries Science Center (SEFSC) spring vessel surveys during 1996 to 2001 (taken from Waring et al., 2009) (*Source:* www.nefsc.noaa.gov/publications/tm/tm210)

- This species is normally sexually segregated; individuals only come together for mating. So, depending upon the time of year, males may or may not be present, which could skew the population numbers.

Still, the NOAA's National Marine Fisheries Service (NMFS) has undertaken five stock assessments (2003 and 2005 assessments used the same data and, thus, yielded the same abundance estimates) on the northern Gulf of Mexico sperm whale stock, initiated in 1995 (Table 4).[2]

Minimum population estimates were also calculated during NOAA's SARs and were 411 (1995), 1,114 (2003 and 2005), and 1,409 (2008 and 2009), respectively.

Demographic Variables

Information on age classes from the sperm whales occurring in the Gulf of Mexico is lacking. Observations indicate that the group composition consists of mixed-sex groups and bachelor male groups with spatial segregation between group types, with the former being mainly found in the region south and/or west of the Mississippi River Delta and Mississippi Canyon, while the latter were mainly found in the De Soto Canyon and along the Florida slope during the SWSS survey of 2004 (Jochens et al., 2006). It is still unclear whether adult breeding bulls inhabit the area; however, lone males (i.e., breeding bulls) were never/rarely sighted in this area, indicating that older males do not commonly make up part of this stock. It is likely that they move in and out of the area for breeding purposes, and they spend the rest of their time in colder-water feeding grounds at higher latitudes (Whitehead, 2002). The SWSS summary report (2002 to 2004) by Jochens et al. (2006) found that the proportion of calves to overall group size was 11.5%. This study also found that mean group sizes around Mississippi Canyon, where female and juvenile/calf mixed groups were most commonly sighted, included 9 to 11 animals.

These findings indicate that the population appears to consist of all age classes, if only at certain times of the year (as is likely for large breeding bulls). Sperm whale young are born following an equal sex ratio (Best et al., 1984; Whitehead, 2002) that does not remain equal into adulthood. It is assumed that modern whaling is responsible for the higher proportion of females to males. Whaling concentrated primarily on males,

[2] The values differ since the area covered varies: 1991 to 1994 covered the "area from approximately the 200 m isobath along the U.S. coast to the seaward extent of the U.S. Exclusive Economic Zone." The surveys in 1996 through 2001 covered "northern Gulf of Mexico oceanic waters," hence, a larger total area (see Table 4 for sources).

Table 4. Overview of abundance estimates of the Gulf of Mexico sperm whales (95% confidence intervals [CIs] calculated by the authors from coefficients of variation [CV])

Estimate of abundance	Coefficient of variation	95% CIs	Year	Source data	NOAA SAR year
143	0.58	0-309	1991	Hansen et al., 1995	1995
931	0.48	37-1825	1992	Hansen et al., 1995	1995
229	0.52	0-467	1993	Hansen et al., 1995	1995
771	0.42	123-1,419	1994	Hansen et al., 1995	1995
530	0.31	201-859	1995 (1991-1994 average)	Hansen et al., 1995	1995
805	0.27	370-1,240	1991-1994 (re-analysis of above)	Hansen et al., 1995	2003
1,349	0.23	728-1,970	1996-2001	Mullin & Fulling, 2004	2003/2005/2008
1,665	0.20	999-2,331	2003-2004	Mullin, 2007	2008/2009

partially because they are larger and more valuable, but also because of the view that, given the supposed "harem" system of the sperm whale, only one breeding male was needed per group of females (Whitehead, 2002).

The sex ratio of the northern Gulf of Mexico stock was found to be 2.54:1 females to males during the SWSS surveys (Jochens et al., 2008). Given the low latitude of the area and the prominence of female mixed groups, the authors expected this result. During the surveys, none of the males appeared to be physically and sexually mature, indicating that, in this area and at this snapshot in time (May to August), only female mixed groups and bachelor herds were present.[3] The GulfCet II study documented no large adult males in the area; it is unclear whether females leave the area to mate or whether lone adult bulls enter the Gulf periodically for breeding (Davis et al., 2000); still, it seems more likely that lone males would enter the area given the year-round presence of female mixed groups.

Female sperm whales can live into their 80s, and probably sometimes reach 100 y, but little is known about reproduction at these older ages (Whitehead, 2002). Sperm whale carcasses are not often washed ashore and, in a region like the Gulf of Mexico where they live in deep water, it is likely their bodies would sink rather than wash ashore. They are believed to have low mortality rates:

- Mortality of males over the age of 1 y was 6.6%/y.
- Mortality of females over the age of 1 y was 5.5%/y.
- Mortality between birth and age 1 was 9.3%/y.
- Birth rate of mature females was 20%/y.[4] (International Whaling Commission [IWC], 1982)

Migrations/Seasonality

Few animals are as widely distributed as the sperm whale, though the sexes have very different distributions (Whitehead, 2002). Females almost always inhabit latitudes less than 40°, and they are accompanied by juveniles and calves of both sexes until the young males leave the group between 4 and 21 y of age, gradually moving to higher latitudes: the larger and older the male, the higher the average latitude (Whitehead, 2002). In the Gulf, distinct migration patterns for sperm whales have

[3] Best (1979) calculated the proportion of sexually mature females to sexually mature males to be 2.6:1. Although coincidentally the same as discovered in the Gulf of Mexico during the SWSS survey, this value was not obtained from observed data but from calculations of age at sexual maturity against cumulative percent frequency. The ratio is thus biased as a result of only sexually mature males being included, with Best setting the age of male sexual maturity to be 26—obviously this comprises only a small percentage of a population. The ratio obtained from the SWSS survey is indiscriminate of age and maturity, and gives a more realistic ratio of the whales in the Gulf during May through August.

[4] However, Whitehead (2002) believes the figures used by the International Whaling Commission (IWC) (1982) for mortality rates were probably underestimated and concludes that it is more realistic to use the well-established mortality schedule of killer whales by Olesiuk et al. (1990) who estimated wild calf (neonate) mortality to be 43.0%. Bain (1990) estimated neonate mortality of resident killer whales off northern Vancouver Island to be 42.0%. Olesiuk et al. (1990) estimated a per capita death rate of 2.2%. Still, it is questionable whether data from one species can be utilised with any accuracy for another.

not been described; it appears that even individual stocks do not make clear movements between areas, even periodically. This may be a result of suitable temperatures and rich food sources being present in the regions in which they are found in abundance, thus, removing the need for migrations for breeding, food, or warm temperatures to rear young. In some mid-latitudes, there appears to be a general seasonal north-south migration, with whales moving pole-ward in summer; however, in equatorial and some temperate areas, there is no clear seasonal migration (Whitehead, 2002).

Field studies suggest that there is no long-distance movement of sperm whales out of the Gulf given that no matches of identified individuals (185) have ever been made to individuals in the Atlantic catalogue (~2,500) (Jochens et al., 2006). DNA matrilineal evidence found that all sperm whales sampled in the northern Gulf contained one of five haplotypes (Jochens et al., 2006). This information, combined with different coda repertoires, also supports the hypothesis that they are a discrete stock with female mixed and possibly bachelor groups exhibiting residency, with no evidence for migrations into and out of the Gulf, given sightings year-round.[5]

Population Trends

No population trends from NOAA SARs have been established as yet. Blaylock et al. (1995) suggest that apparent changes in abundance may represent interannual variation in distribution rather than a real change. The pooled abundance estimates for 1996 to 2001 of 1,349, and that for 2003 to 2004 of 1,665 were not found to be significantly different ($p > 0.05$), but due to the very low precision of the estimates, the power to detect a difference is low (Waring et al., 2009). It is true that sighting rates in most cases are relatively stable, and no areas previously rich in sperm whale sightings have reported declines or seasonal absences. It is also likely that small-scale changes are identified relatively easily: Jochens et al. (2006) reported that, during early summer 2003, sperm whales moved out of their "hot spot" area of the Mississippi Canyon for a short period of time. However, how these small-scale changes translate into long-term trends is unclear.

D. Documented Effects of E&P Sound on Sperm Whales

Southall et al. (2007) places sperm whales in the mid-frequency hearing group (150 Hz to 160 KHz); thus, there is overlap between suspected hearing range and E&P sounds with a range of potential effects (see Tables 1 & 5). The behavioural reaction of sperm whales to airguns has been disputed in the literature. Mate et al. (1994) found that within the area of a seismic operation, the sighting rate changed significantly from 0.092 whales/km to 0.038 whales/km during the first 2 d and then to no sightings for the following 5 d, indicating that prolonged acoustic exposure forced them out of the area. Bowles et al. (1994) reported on the Heard Island Feasibility Test study (Indian Ocean) and documented that, although sperm whales were sighted during both the baseline and transmission periods, they stopped vocalising during times when seismic pulses were received from an airgun array > 300 km away. Sperm whales were heard in 23.0% of 1,181 min of baseline acoustic surveys, but in none of 1,939 min during the transmission period. However, they were heard again within 48 h after the end of the test. In another investigation, Norris et al. (2000) found that during the GulfCet surveys, the percentage of time seismic exploration sounds were recorded increased from 21.0% of the total time in GulfCet I to 34.1% in GulfCet II; and during the final cruise, up to 49.8%, a likely indication of the increased presence of the industry in this area. Norris et al. measured the average signal-to-noise ratio as 8.4 dB, with a maximum of 13.1 dB and a minimum of 4.3 dB[6]; the sperm whale sighting rate did not differ significantly between the different sound levels observed. Likewise Madsen et al. (2002) did not observe any avoidance or reduced vocalisations from adult male sperm whales in polar waters during exposure to pulses from a remote (> 20 km) seismic survey vessel and actually found that they stayed in the area for at least 13 d of exposure. The results of the SWSS (Jochens et al., 2006, 2008),

[5] Tagging studies (Mate & Ortega-Ortiz, 2006) involving 39 sperm whales as part of the SWSS survey found that during "tag transmitting life," only one whale moved out of the Gulf into the North Atlantic. This happened to be a large male, potentially sexually mature but not large enough to be considered a successful breeding bull. During the 610-d transmission, the male moved out of the Gulf for a period of 2 mo, providing evidence that movement such as this does occur, albeit possibly determined by variations in the individual's maturity. Despite more females being tagged than males, no movements were recorded out of the Gulf; and in general, the movements made by females remained around the upper slope edge, with far less movements made over deep water than exhibited by males (Jochens et al., 2006).

[6] The relative intensity of seismic signals was estimated from the signal-to-noise ratio (signal intensity in decibels above ambient). The signal-to-noise ratio was calculated by averaging the intensity of a 120-ms segment of recording, using a 180 dB bandwidth from 20 to 200 Hz, from both the background (ambient) and the seismic pulse (see Norris et al., 2000).

using three different approaches, found no apparent horizontal avoidance of sperm whales in the Gulf of Mexico to seismic survey activities. They also did not find any evidence that whales swam away from an airgun array during ramp-up procedures or when approaching at full speed (however, few exposures were above 160 dB re 1 μPa [peak-to-peak]). Limited data did suggest that there may have been some decrease in foraging effort for some individuals (Jochens et al., 2006, 2008). Recently, Miller et al. (2009) performed controlled exposure experiments on eight sperm whales in the Gulf of Mexico using airgun arrays. They found no indications of avoidance reactions to airguns, but they did notice subtle changes in foraging behaviour. The authors note the small sample size and recommend further studies on the topic.

The argument has been made that the number of sperm whales that may be exposed to high SPLs from airguns might be relatively small in the Gulf (MMS, 2004). Considering density estimates, a total of three sperm whales may potentially be exposed to levels of 180 dB re 1 μPa (peak-to-peak) or greater if they do not avoid exposure (i.e., one sperm whale per planning area; MMS, 2004). Yet, this argument appears to be problematic as animals might move between areas so that the total number of individuals exposed might be much higher. It is also clear that the sperm whale abundance estimates include high statistical errors so the number given by MMS is only a very rough estimate.

E. Other Factors Potentially Affecting the Stock

Fisheries

According to the NMFS, the commercial fish and shellfish harvest from the five U.S. Gulf states was estimated to be 0.65 billion kg valued at $689 million in 2006 (www.epa.gov/gmpo). Commercial fisheries are exceptionally important to the Gulf states in terms of economic value and fisheries landings by volume to U.S. markets (Figure 7). This industry is associated with highly utilised waterways and large amounts of vessel traffic. According to Adams et al. (2004), a total of 24,879 commercial fishing craft are registered within the Gulf region (excluding Texas), representing approximately one-third of the nation's entire commercial fishing fleet (Figure 8).

Recreational fishing is also lucrative, with a total weight of 49.4 million kg of fish taken from the Gulf of Mexico in 2006 (www.epa.gov). During 2001, the Gulf region had 8.3 million participants, who took 35.4 million trips (Adams et al., 2004). It must be considered that a large proportion of these trips operate in coastal locations and waters and, as such, the activities will not come into contact with the waters inhabited by sperm whales offshore in the Gulf of Mexico. The volume of commercial and perhaps some recreational fisheries poses several potential risks for the sperm whales in the Gulf—for example, disturbance due to sound, but also entanglement in fishing nets and gear. Although the NOAA SARs do not have any deaths formally attributed directly to the fishing industry, they do suggest that the extent of fishery-related mortality and serious injury to sperm whales is probably underestimated because not all carcasses that wash ashore are discovered, reported, or investigated and not all will show signs of entanglement or other fisheries interaction (Waring et al., 2009).

Food Depletion

The diet of sperm whales from the Gulf of Mexico was analysed by Barros (2003) from necropsy and

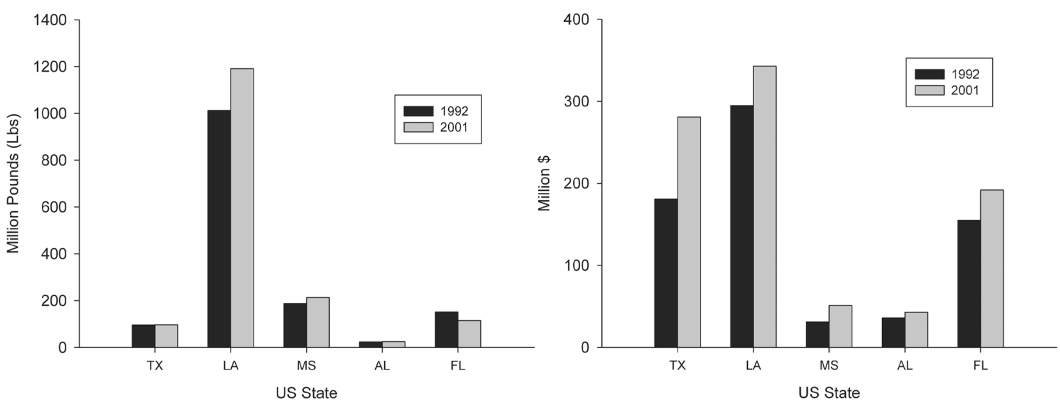

Figure 7. Fisheries activity in the Gulf of Mexico, 1992 and 2001; Left: commercial fisheries landings for the Gulf states, 1992 and 2001; Right: commercial fisheries dockside value for Gulf states, 1992 and 2001 (taken from Adams et al., 2004). TX = Texas, LA = Louisiana, MS = Mississippi, AL= Alabama, and FL = Florida.

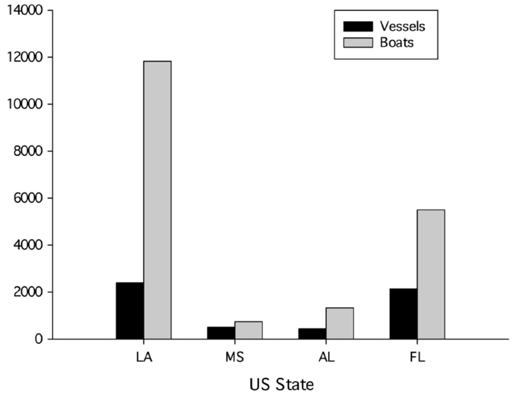

Figure 8. Commercial fishing vessels (> 5 net tons) and boats (< 5 net tons) in the Gulf states in 2001 (taken from Adams et al., 2004); LA = Louisiana, MS = Mississippi, AL = Alabama, and FL = Florida. Florida's figures include vessels from both coasts, and values for Texas are not available.

faecal samples. It was found that they only consumed cephalopods, with 13 species within ten families of cephalopods being identified as components of their diet. The most important prey species found was *Histioteuthis*, a mid-water squid important in the diet of sperm whales worldwide. *Histioteuthis corona* and *H. arcturi* are known to occur in the Gulf of Mexico (Voss, 1956; Barros, 2003), with the former being the most common and abundant, particularly off the mouth of the Mississippi River where sperm whales are frequent (Barros, 2003; Jochens et al., 2006).

Using the Food and Agriculture Organization (FAO) FishStat database, an extraction of all squid landings from the Western Central Atlantic between 1950 and 2005 reveals no decline in landings. In fact, 2005 had the highest landings recorded (618 tonnes of Northern shortfin squid alone). This would support conclusions that food is plentiful for sperm whales in the Gulf (see Jochens et al., 2006).

The diversity in diet found by Barros (2003) might indicate that the sperm whales in the Gulf of Mexico are capable of adapting to changes in the abundance of various squid species, and the risk of food depletion due to changes in the abundance of prey species in this area might, therefore, be relatively low. However, as Rodhouse (2001) points out, populations of squid are, in general, rather labile, and recruitment variability is driven partly by environmental parameters. Therefore, if conditions make the Gulf of Mexico unfavourable for several cephalopod species, there could be negative effects for sperm whales.

Shipping

Two of the ten busiest ports in the world by cargo volume lie on the Gulf Coast: South Louisiana (New Orleans) and the Port of Houston; while seven of the top ten ports in the United States are located on the Gulf of Mexico (www.epa.gov/gmpo). A large volume of shipping operates in the waters of the Gulf, with a variety of import and export activities. There is also the petroleum and oil industry in the area. According to the U.S. port rankings by cargo volume in 2009 (American Association of Port Authorities [AAPA], 2009), the combined cargo volume being carried through Gulf waters is 1,185,200,458 short tons (Figure 9).

Obviously, the large volume of ships traversing the Gulf waters overlaps the areas occupied by sperm whales. In fact, Adams et al. (2004) notes that there is significant shipping activity occurring along the Mississippi River corridor into the Gulf, and 70.0% of all U.S. waterborne commerce ton-miles of shipping and 60.0% of all petroleum and petroleum products shipped via waterborne means occur in the Gulf of Mexico. Hence, much of this traffic through the Gulf waters is associated with the E&P industry.

Ship Strikes

In busy shipping lanes, sperm whales are in danger of injury or death resulting from collisions with vessels (Whitehead & Weilgart, 2000). Jensen & Silber (2003) detailed 17 reported sperm whale ship strikes around the world from the large whale ship strike database, one of which occurred off Grande Isle, Louisiana, in 1998, killing the whale. Despite this one incident, the problem of ship strikes does not appear to present a large risk to sperm whales in the Gulf of Mexico. From 1987 to 2003, 35 sperm whales were reported stranded

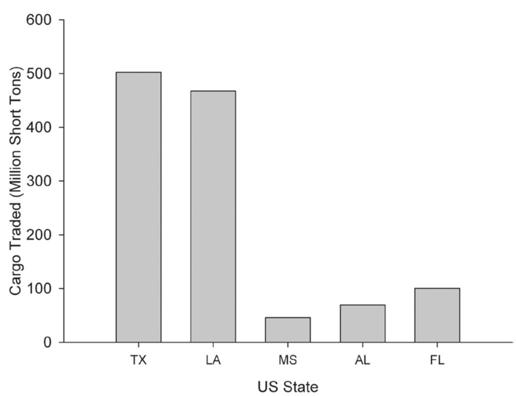

Figure 9. Volume of cargo traded by Gulf states in 2009; TX = Texas, LA = Louisiana, MS = Mississippi, AL = Alabama, and FL = Florida. (*Source:* American Association of Port Authorities)

in the northern Gulf of Mexico. Only two of these could be attributed to a vessel strike; and in one case, the carcass exhibited deep propeller cuts (Blaylock et al., 1995; Waring et al., 2004, 2006). However, this figure may not be a true representation of the full extent of ship strikes that occur in this region as carcasses are often not recovered, and in the case of recovery, their state of decomposition can make it difficult to assign the cause of death.

Tourism

Whale watching is not a large industry in the Gulf of Mexico, especially in areas inhabited by sperm whales. Their residency around the deep offshore continental shelf waters makes sperm whales inaccessible to potential day-trip whale-watching operations. According to Hoyt (2001), the overall impact of whale watching in the Gulf is modest at best.[7] Whale watching activities in other areas have been shown to cause disruption to natural movements of sperm whales (e.g., Richter et al., 2006).

Pollution

There have been a number of incidents involving oil spills in the Gulf. Between November 1979 and July 1984 alone, four incidents involving tankers resulted in the spilling of 16.3 million gallons of oil into the Gulf. A further 870,000 gallons of oil were spilled in Galveston Bay and its estuary alone between 1987 and 1991. In 1979, a major oil well blowout at the IXTOC-1 platform released an estimated 0.8 to 1.7 million gallons of oil/d for nearly 10 mo, leaving an estimated 140 million gallons of oil in the Gulf waters. A further blowout at the Ranger exploratory well in 1985 released 6.3 million gallons to the Gulf (for more details, see Gore, 1992). Despite these incidents, no cetacean deaths had been attributed to oil spills in the Gulf of Mexico up until spring 2010. The Deep Water Horizon blowup and subsequent spill of between 12,000 and 25,000 barrels of oil/d over a 3-mo period made this the biggest oil spill ever originated in U.S. waters (Lehr et al., 2010; McNutt, 2010). As of the time of revision of this document (November 2010), 110 cetaceans were found stranded (101 dead, 8 alive, 1 unknown) during the time after the spill. Species included bottlenose dolphins (83 dead, 4 alive, 1 unknown), spinner dolphin (*Stenella longirostris*; 3 dead, 3 alive), melon headed whale (*Peponocephala electra*) (2 dead), sperm whale (1 dead), one individuals of the genus *Kogia* (dead), and one unknown dead. From these, four were classified as visibly oiled (www.nmfs.noaa.gov/pr/health/oilspill.htm). Further research is underway to determine the effects of the oil spill on cetaceans in the Gulf (see daily updates information on consorted effort under www.nmfs.noaa.gov/pr/health/oilspill.htm and www.mmc.gov/oil_spill/welcome.html) (see Würsig, 1988, for an earlier review).

No evidence for high contaminant loads has been found for the Gulf of Mexico sperm whales thus far; however, this may be a consequence of limited studies. Given the recent oil spill disaster, it is likely that increased effort will be given to examining tissues in the future. Law et al. (1996) analysed blubber samples from seven sperm whales stranded around the North Sea for organochlorine pesticides and metabolites, and for a range of chlorobiphenyl (CB) congeners. The concentrations of these contaminants were lower or similar to those found in by-caught harbour porpoises and another sperm whale analysed previously.

Environmental Changes

Environmental changes caused a change in circulation patterns and the formation of a loop current eddy near the Mississippi Canyon in early summer 2003 (Jochen et al., 2006), which resulted in a loss of food temporarily, forcing whales away from this preferred region. Saunders & Lea (2008) found that a 0.5° C increase in tropical Atlantic sea surface temperatures (August to September) was associated with a ~40% increase in hurricane frequency and activity (1996 to 2005). However, any effect that hurricanes may have on sperm whales is unknown. Hurricanes could, however, pose more of an indirect threat due to materials being carried and deposited in the sperm whales' habitat. This could mean that not only solid materials, but also, and more importantly, liquids and chemicals, could be expelled into the water resulting in increased pollution.

In the Gulf of Mexico, one recurring environmental phenomenon is harmful algal bloom (HAB) outbreaks. These can have detrimental effects throughout the food chain. In one incident, 740 bottlenose dolphins stranded along the Atlantic coast between June 1987 and May 1988, wiping out approximately 50% of the coastal migratory stock between New Jersey and Florida. Brevetoxin was suspected as the proximate cause of mortality (Geraci, 1989). Red tides due to HAB outbreaks have also been responsible for the death of large whales. Saxitoxins were implicated in the death of 14 humpback whales over a 5-wk period in Cape Cod Bay, Massachusetts, in 1985 (Vos et al., 2003). In this region, there are at least two

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[7] The only specific interaction with the sperm whales of the Gulf comes from a Mississippi marine laboratory whose classes go out to meet cetaceans three days a year (Hoyt, 2001).

saxitoxin producing dinoflagellate (*Alexandrium tamarense*) blooms annually and, therefore, saxitoxins were investigated as the causative agent, transmitted into the whales from the mackerel on which they were feeding (Vos et al., 2003). To date, no sperm whale deaths in the Gulf of Mexico have been attributed to red tide outbreaks, and the risk they pose to the sperm whales is largely unknown.

F. Overview of Human Pressures

As can be seen in Table 5, there are a number of human activities that could affect sperm whales in the Gulf of Mexico, with E&P industry activities generating underwater sound as one of them. Exploration and production activity are high in the Gulf and so is shipping and fisheries. Various human activities could lead to pollution and environmental changes, but these pressures are very difficult to assess at present. The uncertainty over potential impacts are high in most cases.

Table 5. Overview of human pressures on the sperm whales in the Gulf of Mexico and an estimate on relative levels of activities and type and scale of potential effects on marine life

Activity	Activity level	Pressure	Potential effects	Comments	Uncertainty
E&P industry: Exploration	+++	Vessel sound Airgun array sound	Vessel: masking, behavioural response (long); Airgun: PTS (short), TTS (short), behavioural response (long)	Little evidence on disturbance from existing studies	High
E&P industry: Construction	+	Pile driving Vessel sound	Pile driving: PTS (short), TTS (short), behavioural response (long); Vessel: masking, behavioural response (long)	No studies	High
E&P industry: Production	+++	Drilling sound Drillship sound	Drilling and drillship: masking, behavioural response (short)	No studies on effects during production	High
Fisheries	+++	Vessel sound Fishing operations (nets), driftnets Competition	Vessel sound: masking, behavioural response (long): Fishing operations: death, injury due to entanglement (short); Food depletion (long)	Very little information; low competition with fisheries	High
Shipping	+++	Vessel sound Ship strikes	Ship: masking, behavioural response (long); Ship strikes: injury, death (short)	Little evidence for stranding due to ship strikes	High
Tourism	+	Whale watching Vessel sound Recreational boat sound, cruise ship sound	Masking, behavioural response (long)	Whale watching is only of minor importance with regards to sperm whales	Low
Various activities	*	Pollution	Physiological effects (long)	Contamination and severe effects due to large-scale oil spills are possible	High
Various activities	*	Environmental changes	Short- and long-term changes to habitat conditions with range of consequences (long)	Only due to harmful algae blooms; effects of hurricanes	High

+ = low level of activity, ++ = medium level of activity, +++ = high level of activity; spatial scale of effects: short = in close vicinity of the activity or area activity is carried out, long = beyond the activity area (depending on species and activity); * = insufficient data for a firm assessment

G. Conclusions

The volume of E&P industry activity in the Gulf of Mexico is large and, coupled with vast amounts of shipping, these waters are heavily utilised. Despite much research effort, no definitive population trends can be drawn for sperm whales in the Gulf, so it is impossible to assess the impacts of the various human pressures on this cetacean population at present. Results from one study indicate that no long-term displacements of individuals from certain areas have occurred. Furthermore, a relatively stable number of animals have been found yearly in a couple of hot spot regions, namely around the Mississippi Canyon. There are several other human activities leading to pressures that could potentially impact this population, including fisheries, shipping, tourism, pollution, and environmental changes. In most cases, the uncertainty over the potential effects is high.

5. Case Study 2: California – Humpback, Blue, and Fin Whales

A. Introduction to the Area

California is the third largest state in the United States by land area and the most heavily populated with ~37 million people, enclosing very large urban areas in and around Los Angeles and San Francisco, resulting in a variety of pressures on the marine environment (Figure 10). Biodiversity is high, especially with regards to cetaceans, and the area has been one of the focal points of cetacean research since the Second World War.

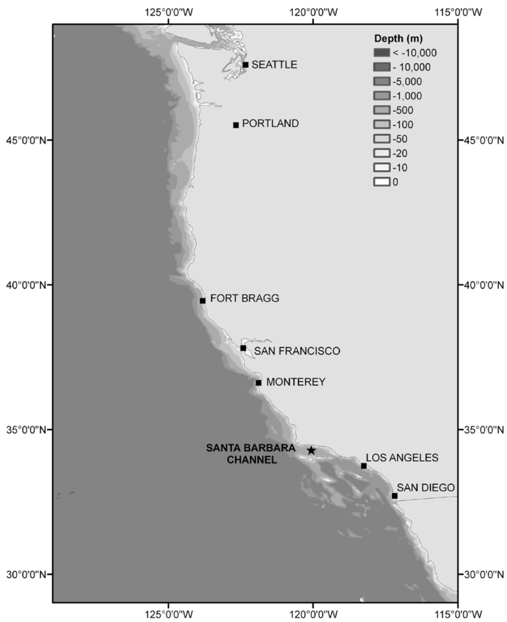


Figure 10. Overview of the coast of California, Oregon, and Washington State

B. E&P Industry Activity

E&P industry activity on the U.S. Pacific Outer Continental Shelf (OCS) is predominantly concentrated off the coast of Southern California. Petroleum fields have been discovered along the majority of the OCS; however, only the fields discovered offshore of Southern California are currently exploited (Figure 11).

Production

There are currently 23 active platforms along the Pacific OCS (MMS, 2008). The first platform was constructed during 1967, and, by 1970, five platforms were producing offshore. Platform construction peaked between 1978 and 1984, with ten platforms constructed within 6 y. Construction of platforms steadily increased, including the construction of an offshore processing facility in 1980, to number 24 offshore structures by 1989 (Figure 12). Decommissioning began in 1994 with the removal of the Santa Ynez offshore storage and treatment facility (OS&T) platform; further decommissioning activity is planned for the future, and total platform numbers are expected to decrease (MMS, 2008).

Drilling activity offshore from California has been documented since 1990, with information freely available via Baker Hughes–Hughes Christianson rig counts (see www.bakerhughes.com). From their data, it is possible to discern the average number of rigs actively drilling/wk (Figure 13). Drilling activity is steady, with on average two to four rigs actively drilling/wk annually. A peak in activity was recorded in 1993 with, on average, six rigs actively drilling/wk that year. Dips in activity occurred during 1999 and 2007 when, on average, only 1.5 drilling rigs were active/wk.

For the platforms constructed off the coast of California, there has been a trend of moving into deeper offshore waters in recent years; platform water depth and distance from shore are compared along with the date of installation (Figure 14). The two most recent platforms were constructed in the deepest water, > 300 m, taking advantage of improved technology that allows viable exploration and production at depth. All platforms are found relatively close to shore, 7 to 19 km distance, with a slight trend of moving further offshore over time.

Exploration

Seismic data were obtained from the MMS, provided as part of the conditions of survey permits. However, these data can only provide a rough estimate of the actual activity carried out and cannot represent the true amount of data acquired by the industry. This is because of the volume of data, constraints on when pre-lease data can be released, and other administrative issues. Therefore, the amount of data readily available in the public domain is constrained. The data we were able to obtain show that activity has occurred since 1968, with early activity solely undertaken using 2D survey techniques (Figure 15). The seismic activity shows three peaks in 2D survey activity—pre-1977, 1982 to 1984, and 1988—and then an increase in 3D activity after a period of inactivity. The levels of 2D activity coincide with platform construction, with the majority of seismic and platform construction occurring before 1990. More

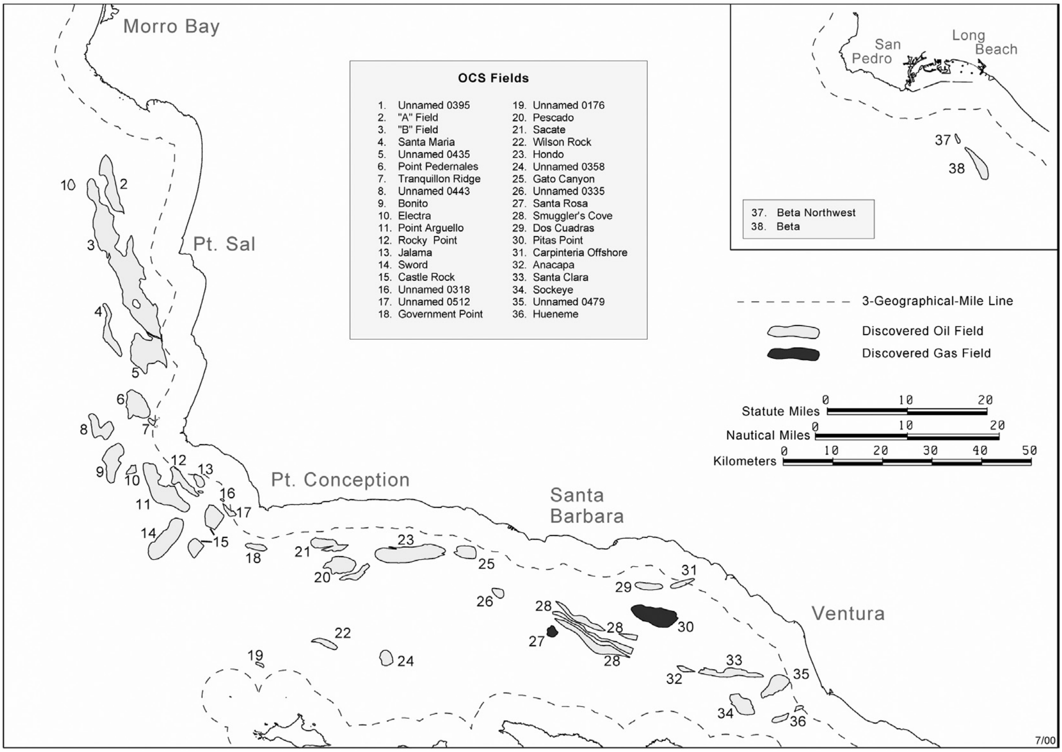


Figure 11. Map of discovered fields in the Pacific OCS Region (offshore Southern California) (Dunkel, 2001)

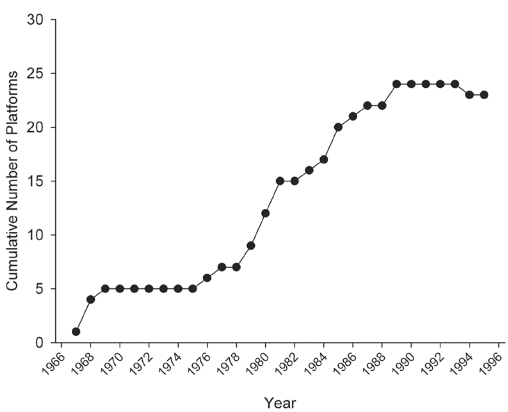


Figure 12. Cumulative platform numbers over time offshore of California (*Source:* Bureau of Ocean Energy Management, Regulation and Enforcement [BOEMRE], U.S. Government)

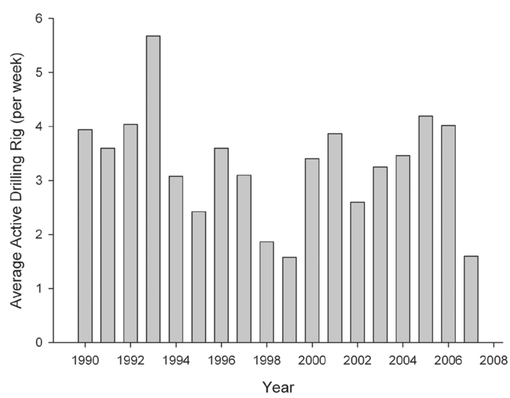


Figure 13. Average drilling rigs/wk between 1990 and 2007 offshore California (www.bakerhughes.com)

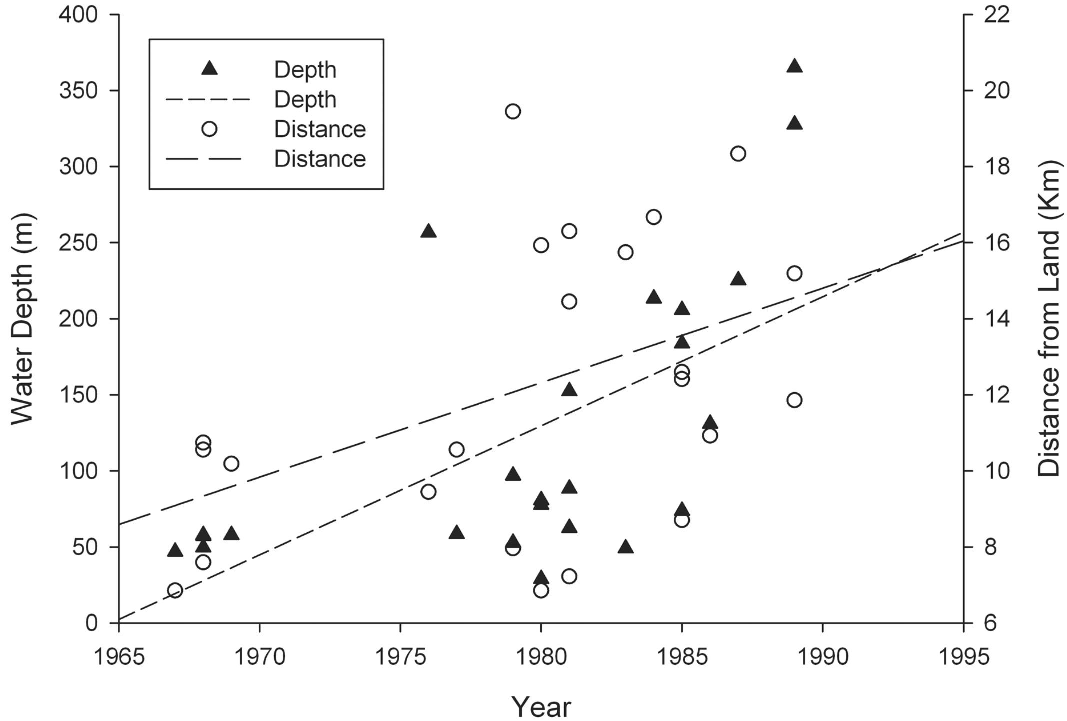


Figure 14. Platforms over time with water depth (m) and distance from land (km) (*Source:* BOEMRE, U.S. Government)

recently, 3D surveys have been carried out. These are restricted solely to the Southern California area (Figure 15) and, although the surveys do not coincide with any platform construction, they represent a renewed interest in Southern California by the E&P industry. Figure 15 shows seismic activity over time for the whole Pacific OCS. However, it is difficult to obtain data to extrapolate seismic activity into specific geographical areas. Table 6 provides a breakdown for total 2D survey activity over the Pacific OCS, giving an indication of where seismic activity is concentrated.

While E&P industry activity is predominantly focused within Southern California, seismic activity has occurred as far north as Washington and Oregon. Figure 16 shows the distribution of the seismic surveys contained within the Dellagiarino et al. (2002) report, showing that 3D surveys have only occurred within the Southern California Planning Area, highlighting the concentration of activity within this area.

C. Stock Assessment of Humpback, Blue, and Fin Whales

Despite the considerable cetacean diversity off the coast of California (see Carretta et al., 2009a), the actual number of species that merit a closer look with regards to E&P industry occurrence is rather limited, with many odontocete species distributed farther offshore (e.g., sperm whales) or in areas with rather low E&P industry activity. A number of species are also only sporadically present such as pilot whales and pygmy and dwarf sperm whales. For mysticetes, data for Bryde's (*Balaenoptera edeni*), sei (*B. borealis*), and minke whales are rather sparse, with probably only minke whales appearing in any significant numbers. Conversely, humpback, blue, and fin whales have been thoroughly investigated, and they overlap in distribution with the E&P industry off the Santa Barbara region and in adjacent waters, although to different degrees. All three species are also known to produce vocalisations that are well within the range of E&P related sound (for an overview, see Richardson et al., 1995).

Population Structures

All three species are represented off the Californian coast as subpopulations within larger populations/stocks. Humpback whales form several subpopulations within the North Pacific, with summer feeding grounds from Southern California up to Alaska, and with breeding grounds off Mexico and Hawaii. The blue whales found off California, Washington State, and Oregon belong to the

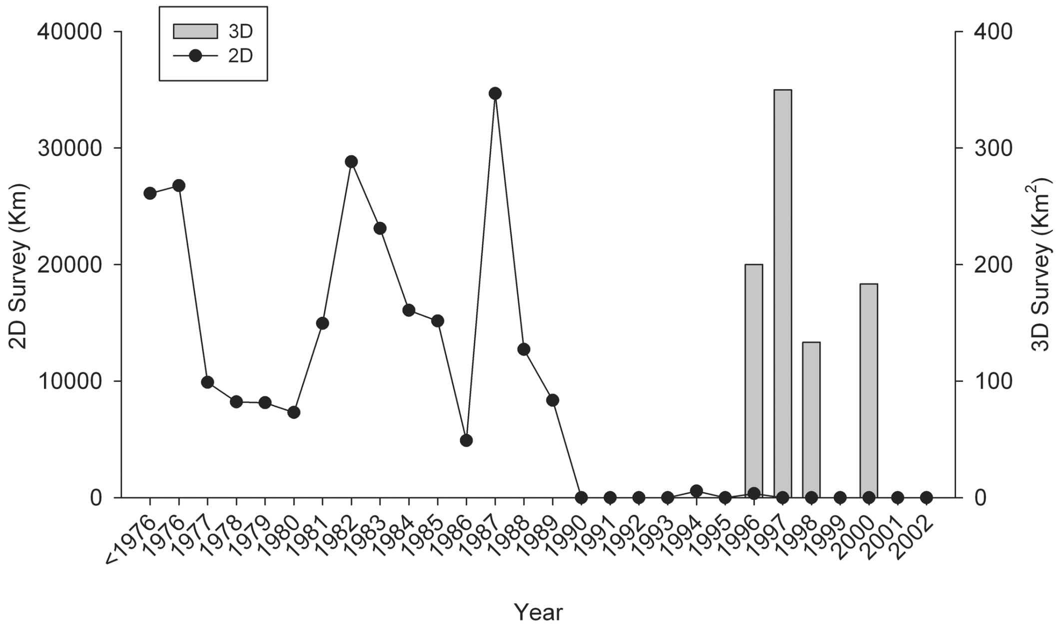


Figure 15. Total km of 2D surveys and total km² of 3D surveys carried out within the Pacific OCS between 1968 and 2002 (adapted from Dellagiarino et al., 2002)

Table 6. 2D surveys within the Pacific OCS Planning Areas between 1968 and 2002 (Dellagiarino et al., 2002)

Planning area	2D survey in km
Southern California	157,420
Central California	38,892
Northern California	35,188
Washington-Oregon	14,816
Total	246,022

North Pacific stock (Carretta et al., 2009b; for a detailed species description, see www.nmfs.noaa.gov). For information on acoustic repertoires and morphometric features, see Gilpatrick et al., 1997; Stafford et al., 2001). The waters off California represent an important feeding area for blue whales in summer and autumn (Carretta et al., 2007b). For fin whales, information on population structure is insufficient and, in principle, three stocks are recognised in the North Pacific, with the total current number of animals uncertain.[8] Seasonal patterns of abundance of fin whales are less well understood than those for both humpback and blue whales, yet some observations indicate a higher presence in summer and autumn off California compared to spring and winter (NMFS, 2006; Carretta et al., 2007b).

Population Size and Potential Biological Removal[9]

The most recent assessments give an abundance estimate of 1,391 for humpback whales (Carretta et al., 2009b). For blue whales, the estimate is 2,842 (Carretta et al., 2009b). However, this is based solely on the average of mark-recapture estimates, thus providing an estimate of total population size (comparatively, line transect estimates reflect the average density of whales in the study area during the survey periods). Fin whales in this region have an abundance estimate of 2,636 based on line transect estimates (for CVs and CIs, refer to Table 7). Potential biological removals (PBRs)—the maximum number of animals not including natural mortalities that may be removed from a stock while allowing that stock to reach or maintain its optimum sustainable population—are 2.5 in humpbacks, 2.0 in blue whales, and 14 in fin whales (units: animals/y; Carretta et al., 2009b).

[8] In 1973, Oshumi and Wada (1974) estimated the North Pacific fin whale population to be comprised of 13,000 to 18,000 animals.

[9] *Potential Biological Removal (PBR) Level* is defined by the Marine Mammal Protection Act of 1972 (U.S.) as the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population (for details, see www.nmfs.noaa.gov).

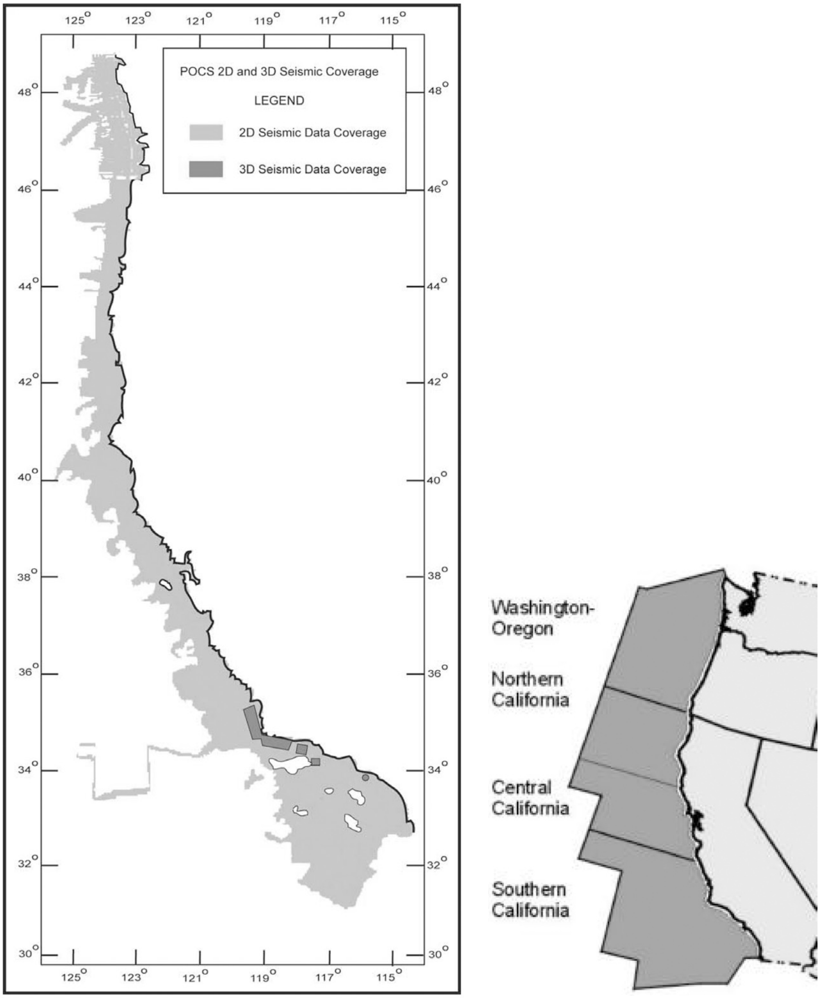


Figure 16. 2D and 3D seismic coverage, and Pacific OCS Planning Areas (adapted from Dellagiarino et al., 2002) (*Source:* www.boemre.gov/itd/index.htm)

Demographic Variables
Calambokidis & Barlow (2004) observed 17 humpback whale mothers with calves in 2003, accounting for 4.4% of the individuals identified in that year. They note that this relatively low observation rate is consistent with observations from previous years. However, survey effort was higher in late summer when some of the calves might have been weaned and difficult to recognise as such. No data on sex ratio or age classes in any of the three species are provided, and there is no mention of sexual segregation in any publication that we are aware of, indicating that males and females occur in relatively equal proportions (for data from stranding, see Norman et al., 2004; for acoustic studies in blue whales with reference to sexes, see Oleson et al., 2007a, 2007b). The estimated annual mortality from serious injury due to entanglement in fishing gear for humpbacks (3.6 individuals/y between 2003 to 2007) exceeded the PBR (for U.S. waters only) (Carretta et al., 2009b). This is not the case for blue and fin whales whose mortality estimates from ship strikes of 1.2/y (in California, 2003 to 2007) and 1.6/y (2002 to 2006), respectively, are lower than the calculated PBR rates (Carretta et al., 2009b).

Migrations/Seasonality
The Northeast Pacific humpback whales move between summer feeding grounds off California, Washington State, and Oregon and winter breeding grounds off Mexico and Hawaii (Carretta et al., 2009b). Blue whales are seasonal in distribution too, with summer areas off California,

especially concentrated in the Monterey Bay area, and winter breeding areas near Mexico and Costa Rica (Calambokidis et al., 1990; Mate et al., 1999; Stafford et al., 2001). It is interesting to note however, that blue whales are thought to also feed on breeding grounds (Reilly & Thayer, 1990; Palacios, 1999). Fin whales are less migratory than both humpback and blue whales; they have been observed off California year-round, with the highest numbers in summer and autumn (NMFS, 2006). Passive acoustics have confirmed a year-round trend, though calling frequency is highest between September and March (Moore et al., 1998; Watkins et al., 2000).

Population Trends

Whaling has affected population trends in all three stocks to the greatest degree. The North Pacific humpback whale stock was originally estimated at 15,000 animals (Rice, 1978) but was reduced to approximately 1,200 by 1966 (Johnson & Wolman, 1984). About 8,000 whales were taken off the west coast of Baja California, California; Oregon; and Washington (Rice, 1978). A total of 9,500 blue whales were killed in the North Pacific between 1910 and 1965 of which 2,000 were taken off the west coast of North America, leaving a stock of approximately 2,000 individuals in the entire North Pacific in 1970 (Reeves et al., 1998). Finally, the original North Pacific stock of fin whales of 42,000 to 45,000 was down to 13,000 to 18,000 at the beginning of the 1970s (NMFS, 2006; Carretta et al., 2007b). If we try to discern population trends for all three species off the California coast, we see a complex picture and a good example of uncertainties that can persist even when sampling effort is comparably high. According to Carretta et al. (2007b), systematic line transect surveys were done in 1996, 2001, 2005, and 2007, with additional photo-identification studies for humpback whales and blue whales since the 1980s. Still, population trends are far from certain, though various estimates for the three species have been published in NOAA SARs since 1995, including the most recent one from 2007 (Table 7).

It seems that the most straightforward case when it comes to interpreting trends is for humpback whales. There is a general upward trend in abundance of humpback whales off California (Table 7), well in line with a general increase of the North Pacific population, which recovered to more than 6,000 by around 1992 (Carretta et al., 2009a). Some estimates are as high as 8,000 whales, which is about 40 to 50% of the pre-whaling population estimate (Carretta et al., 2007b). A photo-identification study carried out from 2004 to 2006 estimated the abundance of humpback whales in the entire Pacific Basin to be approximately 18,000 to 20,000 (Calambokidis et al., 2008). Still, Calambokidis & Barlow (2004) noted a drop in numbers for the California population estimates (although it was not statistically significant) in 1999/2000 and 2000/2001, and an increase thereafter. Interestingly, this increase might have been the result of an influx/recruitment of individuals from other areas since there was a relatively high proportion of "new" whales seen in 2003 (Calambokidis et al., 2004). Overall, numbers of humpback whales were thought to be increasing off California at a rate of 8%/y (Calambokidis et al., 1999). Yet, this positive trend should be viewed with caution when looking at the very large CIs in the stock numbers (Table 7).

For fin whales, the numbers from various reports indicate an increase from 1979/1980 and 1996, although, as noted by NMFS (2006), this trend was not statistically significant. Recent estimates were made over a larger area and were difficult to compare to the 1995/1996 data. Since abundance estimates are constantly being reassessed, comparisons based on the NOAA SARs are quite challenging. According to Carretta et al. (2007b), population estimates from line transect surveys in an area out to 300 nmi in 1996, 2001, and 2005 were 2,921, 3,636, and 3,281 (CV = 0.31, 0.5, and 0.25; CI = 1,121 to 4,781, 0 to 7,272, and 1,641 to 4,922), respectively, with no population trend discernible.

The presence of blue whales off California is noteworthy in the light of their rarity in these regions prior to the late 1970s. Calambokidis (1995) concluded that such changes in distribution reflect a shift in feeding from the more offshore euphausiid, *Euphausia pacifica*, to the primarily neritic euphausiid, *Thysanoessa spinifera*. Population estimates derived from line transect surveys declined between 1991 and 2005 and stayed level until 2002 for the mark-recapture data, indicating that there is considerable interannual variability in the fraction of the North Pacific population that utilizes California waters during the summer and spring. Using passive acoustic techniques, Oleson et al. (2007a) observed an increase in the length of the overall calling season in blue whales recorded off Cortez and Tanner Banks from 2000 to 2004 and concluded that this might be due to increased prey availability in the Southern California Bight relative to more southerly feeding areas. The latest stock assessment (Carretta et al., 2009b) concludes there is no evidence showing that the eastern North Pacific stock is currently growing (see Table 7).

Table 7. Overview of abundance estimates for three species of baleen whales off California, Washington State, and Oregon according to NOAA SARs 1995-2007 (after Barlow et al., 1995, 1997; Forney et al., 2000; Carretta et al., 2001, 2003, 2004, 2007)

Species/year	Humpback whale	Blue whale	Fin whale
1995	597 (0.07)* [513-681]	2,134 (0.27)*** [982-3,286]	935 (0.63)* [0-2,113]
1996	"	1,785 (0.24)*** [928-2,642]	933 (0.27)* [429-1,437]
1999	843 (0.06)* [742-944]	"	"
2000	905 (0.06)* [796-1,014]	1,940 (0.15)*** [1,358-2,522]	1,236 (0.20)* [742-1,730]
2001	1,024 (0.10)* [819-1,229]	"	1,851 (0.19)*^ [1,148-2,554]
2003	1,314 (0.30)** [526-2,102]	1,480 (0.32)*** [533-2,427]	3,279 (0.31)*^ [1,246-5,312]
2004	"	1,744 (0.28)*** [767-2,721]	"
2007	1,396 (0.15)*** [977-1,815]	1,186 (0.19)*** [735-1,637]	3,454 (0.27)*^ [1,589-5,319]
2008	1,391 (0.13)*** [1,029-1,753]	1,368 (0.22)*** [766-1,970]	2,636 (0.27)**^ [1,213-4,059]
2009	"	2,842 (0.41)* [512-5,172]	"

* = mark recapture estimate, ** = line transect estimate, *** = combination of mark recapture and line transect estimates; " = numbers unchanged; ^ = survey area for fin whales different from 1995 to 2000 surveys; value in parentheses = CV; value in brackets = 95% CI, calculated by the authors from CVs

D. Documented Response of Humpback, Blue, and Fin Whales to E&P Sound

Table 9 summarises potential effects of E&P sound on the three species. Richardson et al. (1995) summarise the sparse pre-1995 information for the three species and cite two studies with very little (humpback whales) or no documented responses during seismic explorations (blue and fin whales). McCauley et al. (2000) found no changes in distribution of humpback whales during 3D seismic surveys compared to those observed before or after the survey. They noted localised avoidance by the whales up to 3 km at modelled received SPLs of 157 to 164 dB re 1 µPa (rms) (32 depth). The authors also noted that several individuals approached a firing airgun to 100 m distance and then swam away in an apparent investigative attempt, probably because the sound was similar to that produced by breaching individuals (McCauley et al., 2000). Clark & Gagnon (2006) reported cessation of vocalisation in fin whales across a large area (10,000 nmi^2) coincident with a seismic survey. Data were collected using an array of hydrophones located at the continental slope off western Europe. The vocalisations started again once the surveys were completed, indicating that whales went silent rather than moving out of the area in response to the surveys (Clark & Gagnon, 2006). Castellote et al. (2009) found some evidence that fin whales in the Mediterranean moved out of an area with seismic shooting, indicated by the directions from which sounds were picked up. However, both the study by Clark & Gagnon (2006) and Castellote et al. (2009) are based on rather qualitative observations. Recently, Di Iorio & Clark (2010) observed that blue whales increased their calling rate in response to seismic surveys using a sparker (SL: 193 dB re 1 µPa [peak to peak], frequency range: 30 to 450 Hz). The increase in calling was interpreted as a compensatory mechanism to the higher received sound levels during seismic surveys (Di Iorio & Clark, 2010). Pinet et al. (2010) have criticised some of the conclusions made by Di Iorio & Clark (2010).

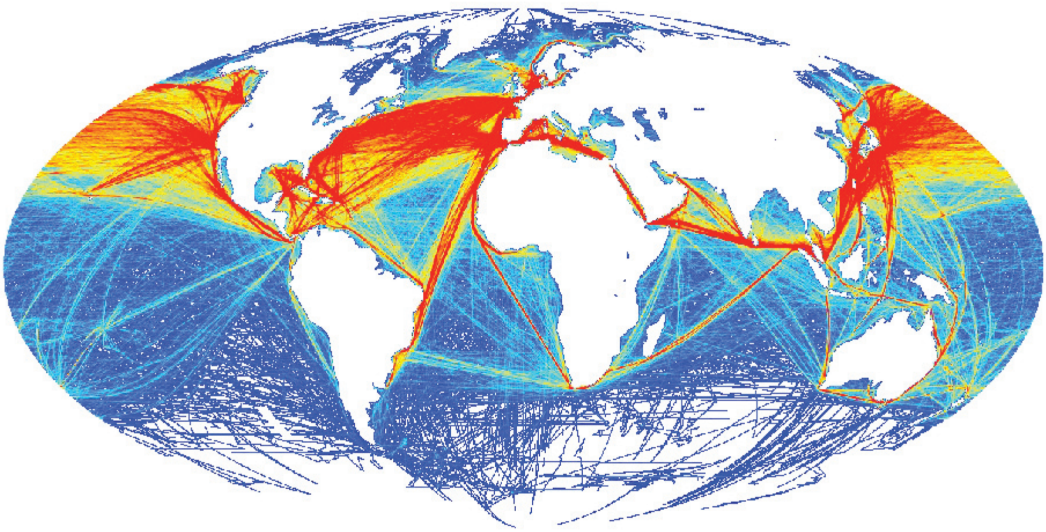


Figure 17. Major commercial shipping lanes in the world's oceans; red lines indicate greatest intensity. (Reprinted with kind permission of the National Center for Ecological Analysis and Synthesis, www.nceas.ucsb.edu/globalmarine/impacts)

E. Other Factors Affecting Stocks

Fisheries
Many fishing vessels emit sound mostly in the lower frequency range which matches the frequency range of social sounds emitted by humpback, blue, and fin whales to a certain extent (see reviews in Richardson et al., 1995; OSPAR, 2009; see "Shipping" section for more details). Therefore, effects such as behavioural response and masking cannot be ruled out (see Clark et al., 2009). Mortality due to entanglement is only quantifiable for humpback whales (Carretta et al., 2007a).[10]

Food Depletion
Californian humpback whales feed on krill (*Euphasia* spp.) and smaller fish (herring and others; NMFS, 1991). Fin whales in the North Pacific feed on euphausiids (*Euphausia pacifica*, *Thysanoessa longipes*, *T. spinifera*, *T. inermis*); large copepods (*Calanus cristatus*); and schooling fish such as herring, walleye pollock, and capelin (NMFS, 2006). The primary and preferred diet of blue whales is krill (euphausiids). In the North Pacific, blue whales prey mainly on *E. pacifica* and secondarily on *T. spinifera*. Other prey species, including fish and copepods, have been mentioned in the scientific literature, yet it is unclear to what extent they feature in the diet of blue whales off the California coast (see NMFS species description under www.nmfs.noaa.gov/pr/species/mammals/cetaceans/bluewhale.htm). In summary, although all three species feed on zooplankton, a part of the diet is also comprised of fish. Therefore, competition with fisheries cannot be ruled out.

Shipping
The west coast of North America is made up of busy shipping lanes (Figure 17) with the potential to affect low-frequency cetaceans (for a recent overview, see OSPAR, 2009).

Especially off the California coast, shipping density is high in the area used by blue whales in summer and autumn. Most coastal vessel traffic passes through the Santa Barbara Channel *en route* to major ports on the U.S. West Coast. Exceptions to this pattern are supertankers, which, for safety reasons, generally avoid the channel by travelling to the south of the Channel Islands. Transportation within the channel includes tankers, container ships, bulk carriers, military and research vessels, cruise ships, tugs and tows, commercial fishing boats, and other commercial vessels. Between San Francisco Bay, the Port of Los Angeles (POLA), and the Port of Long Beach (POLB), large vessels make an estimated 4,000 coastal transits/y (approximately 11/d).

[10] It should be noted that despite the lack of observed fisheries interactions in the last decade, incidental take in fisheries might threaten the three species for two reasons. First, past records of entanglements suggest that interaction with fishing gear may affect the three species. Second, entanglement rates may be underestimated because whales may break through or carry away fishing gear, perhaps suffering unrecorded subsequent mortalities or serious injuries.

About 20% of these transits are made by crude oil tankers. Most of the remainder is represented by large commercial vessels greater than 300 gross tons, including container ships and bulk carriers (www.noaa.gov; for detailed information, see also Southall, 2005; MMC, 2007).

Large commercial ships can produce low-frequency underwater sound in the range of 190 dB re 1 µPa (rms) or even louder (Richardson et al. 1995; OSPAR, 2009). Many baleen whales, including the three species studied here, use sound at low frequencies that overlap with the main frequency band of shipping sound (see review by Richardson et al., 1995; Clark et al., 2009). This is especially true for blue and fin whales as the sounds they emit are mainly in frequencies below 100 Hz where ship sound can be loudest (Watkins et al., 1987; Richardson et al., 1995; Oleson et al., 2007a, 2007b). In addition to their songs, which are mainly produced during the breeding season (Payne & Payne, 1985), humpback whales emit feeding calls that are relatively low in frequency (Thompson et al., 1986). Looking at sound emitted by ships vs the frequencies of sounds used by the three whale species, it is clear that there is considerable potential for masking that might interfere with feeding activities or reduce the range over which individuals communicate (Richardson et al. 1995; Janik, 2005; Clark et al., 2009). However, investigations dealing with masking have been mainly concerned with modelling exercises used to predict the potential masking zone, which can be quite large (e.g., Erbe & Farmer, 2000; Erbe, 2002; Janik, 2005; Thomsen et al., 2006b; Clark et al., 2009). Empirical studies on masking are difficult. For example, movement responses might be a poor indicator for masking as animals might have to travel large distances in order to avoid a sound. In one study, Gray whales (*Eschrichtius robustus*) ceased to use a particular breeding lagoon after an increase in industrial activities, including shipping and dredging (Bryant et al., 1984). However, no studies were made of the increase in sound or of the received SPLs. Nowacek et al. (2004) found no change in diving behaviour of northern right whales (*Eubalaena glacialis*) during playbacks of vessel sound (RL [received sound pressure level] = 140 dB re 1 µPa), indicating some habituation to shipping sound in the studied individuals at least in terms of movement response. Killer whales and northern right whales compensate for masking effects with a change in acoustic behaviour—for example, by increasing the pitch or the duration of their calls (see Foote et al., 2004; Parks et al., 2007, 2010). Further studies will help shed light on the effects of masking on humpback, blue, and fin whales.

Ship Strikes

Mortality due to ship strikes might be of relatively high concern. The average number of mortalities in California attributed to ship strikes is estimated to be 0/y for humpback whales, 1.2/y for blue whales, and 1.6/y for fin whales (Carretta et al., 2009a). Between 2003 and 2007, there were six injuries of unidentified large whales attributed to ship strikes off the California coast (Carretta et al., 2009b). Additional mortality might not be reported because the struck whales do not strand, or if they do, they do not have obvious signs of trauma (Carretta et al., 2009b). On a larger scale, in the eastern North Pacific, ship strikes were implicated in the deaths of five blue whales from 2003 to 2007 (Carretta et al., 2009b). Ship strikes were implicated in the deaths of seven fin whales and the injury of another from 2002 to 2006 (Carretta et al., 2009a).

Tourism

Whale watching is one of the major tourist attractions off the west coast of the U.S. with the highest concentrations off California. In 2008, there were 73 tour operators with increasing activity from northern to southern California, with a total of 390,000 boat-based whale watchers (O'Connor et al., 2009). It should be noted here that the primary focus of whale watching tourism in California is the winter migration of gray whales between November and May, although summer whale watching of blue and humpback whales is offered in some regions—for example, off Monterey and in the Santa Barbara channel area (O'Connor et al., 2009). It is also noteworthy that although the number of operators slightly increased in 2008 compared to 2001 (65 operators in 2001), the overall number of boat-based tourists has decreased compared to 2001 (750,000 whale watchers in 2001) (Hoyt, 2001). O'Connor et al. (2009) discussed several reasons for this—for example, a reported decline in sightings of gray whales and a redistribution of whale watching tourists across locations. Additionally, all three species are being watched in their wintering grounds, with the highest activity off the coast of Mexico (206 operators and 169,000 whale watchers in 2006).

Since the introduction of this industry in the 1970s, the potential effects of whale watching have been intensively debated within the scientific community (see review by Hoyt, 2002, 2008). Effects can principally come in two ways: (1) sound of the vessels may affect the behaviour of the observed animals (see Erbe, 2002, for an exemplary estimation of impact ranges) and (2) movements of the observation vessel might result in startle or even flight responses. Both effects are difficult to separate, but reactions of odontocete cetaceans to vessels are well-documented in the literature (e.g., Richardson et al. 1995; Janik & Thompson, 1996; Nowacek et al., 2001; Williams et al., 2002; Hastie et al., 2003; Constantine et al., 2004; Bejder et al., 2006a). It is largely unknown how the rather temporary changes in behaviour of one or two individuals might translate into significant biological effects at higher levels (e.g., population level effects). Williams et al. (2006) explore the energetic costs of behavioural disruptions in killer whales. Bejder et al. (2006b) showed that whale watching led to a decrease in size of one small population of bottlenose dolphins off Australia. Behavioural reactions to whale watching vessels have been observed in humpback whales, including short-term movement response (Corkeron, 1995; Scheidat et al., 2004b; Stamation et al., 2010) and changes in vocal behaviour (Sousa-Lima et al., 2002). However, long-term consequences of these responses are not known.

Pollution

There is only limited information on levels of contaminants in the three species on the Pacific OCS. Humpback and blue whales off the Gulf of St. Lawrence carry concentrations of PCB and DDT in their blubber, though the levels are two orders of magnitude lower than those reported for beluga whales from the same region (Metcalfe et al., 2004). It is likely that all three species are less susceptible to accumulation of organochlorine or metal contaminants, compared to odontocetes, due to their partly planktivorous diet and, hence, their relatively low trophic level feeding (for a systematic investigation in trophic levels in cetaceans, see Pauly et al., 1998).

Industrial Activities

Dredging (e.g., to extract geological resources such as sand and gravel) to maintain shipping lanes and to route seafloor pipelines is frequent along the U.S. West Coast (see www.mms.org for information). There have been only a very few studies describing dredging sound from North America and the UK. These cover a variety of dredger types. In general, sound associated with dredging is predominantly of low frequency, below 1 kHz, and estimated source SPLs range between 168 and 186 dB re 1 µPa (rms) at 1 m (review by Thomsen et al., 2009). Richardson et al. (1995) provided an overview of investigations into behavioural responses of cetaceans to dredging. Bowhead whales did not apparently respond to a suction dredge in one study (Richardson et al., 1985, as cited in Richardson et al., 1995), but individuals avoided these dredges when exposed to 122 to 131 dB re 1 µPa (rms) (or 21 to 30 dB above ambient noise) in another investigation (see Richardson et al., 1990). Gray whales ceased to use a particular breeding lagoon after an increase in industrial activities, including shipping and dredging (Bryant et al., 1984). However, it is not clear if this was due to sound or the increased presence of ships; no studies were made of the increase in sound or of received SPLs. There are, to our knowledge, no recent studies (post-1995) on the effects of dredging sound on cetaceans (for a review, see Thomsen et al., 2009).

Military Activities – Sonars

The U.S. Navy uses the waters along the southern West Coast regularly in naval exercises (see map in Jasny et al., 2005). Sonars can be categorised into low (< 1 kHz), mid (1 to 10 kHz), and high frequency (> 10 kHz), with military sonars using all frequencies (ICES-AGISC, 2005). Information on some parameters from sonar currently used by naval ships is given in Table 8. It can be seen that source levels are generally very high and, looking at the emitted frequencies, it might be best to focus our assessment on the SURTASS LFA that also utilises a considerable ping duration. Research on LFA is relatively advanced, and studies have revealed that foraging blue and fin whales off California were unaffected by playbacks of LFA with received levels of 140 dB re 1 µPa (rms). Yet the sample size was small, and the animals were thought to be rather transitory as resightings were rare (Croll et al., 2001). Humpback whales exposed to received sound levels of 120 to 150 dB re 1 µPa increased the duration of their songs, indicating a compensatory effect. Five out of 18 whales ceased

Table 8. Military sonar systems relevant to beaked whale stranding events (from Zimmer, 2004)

Sonar model	SURTASS LFA	SLC TVDS LF	SLC TVDS MF	AN/SQS-53C	AN/SQS-56
Stranding event	None	Greece 1996	Greece 1996	Bahamas 2000	Bahamas 2000
Frequency (kHz)	0.1-0.5	0.45-0.65, 0.7	2.8-3.3	2.6, 3.3	6.8, 7.5, 8.2
SPL (dB re 1 µPa at 1 m)	240	214-228	223-226	235	223
Pulse duration (s)	6-100	2+2	2+2	0.5-2	--
Pulse interval (s)	360-900	60	60	26	26
Depth (m)	122	60-90	60-90	7.9	6.1

singing (Miller et al., 2000; see also Fristrup et al., 2003).

Much attention has been drawn recently to stranding events of cetaceans, mostly beaked whales, that occurred at the same time as military exercises (reviewed in ICES-AGISC, 2005; Nowacek et al., 2007). Yet, these stranding events only involved baleen whales in very limited numbers (see Table 1.3 in Jasny et al., 2005). (For mitigation measures employed in naval operations worldwide, see ICES-AGISC, 2005; OSPAR, 2009).

Historical Pressure: Acoustic Thermometry of Ocean Climate (ATOC), 1995 to 1999

The ATOC project aimed to acoustically measure the ocean temperature. Two sound sources were installed for the first phase of the ATOC feasibility study: one on Pioneer Seamount off central California and one north of Kauai, Hawaii. The signal transmission started in 1995 and ended in 1998 (California) and 1999 (Hawaii) (http://atoc.ucsd.edu). Transmission of sounds from the transmitting station off Hawaii were undertaken between 2002 and 2006 under a different name (the NPAL project). The signal source level was 195 dB re 1 µPa (rms) with a centre at 75 Hz (60 to 90 Hz bandwidth), very much in the range of acoustic signals of all three of the whale species that are investigated here. In the NPAL project, which had identical characteristics to the earlier ATOC project, there were six transmissions of 20 min (one every 4 h), every fourth day, with each transmission preceded by a 5-min ramp-up period (Office of Naval Research, 2001). Nowacek et al. (2007) lists the results of the different studies that indicated behavioural response in humpback whales (longer dives, more distance covered during dives) at received levels of 130 dB re 1 µPa (rms) in two investigations. The results of these studies indicate rather subtle behavioural reactions by the whales, but, again, we have to bear in mind that received SPLs were rather low. Since signal transmission off California ceased 10 y ago, any effect of the ATOC system on whales would be historical as animals would have to be very close to the source to be injured (see Southall et al., 2007, for exposure levels).

F. Overview of Human Pressures

Table 9 shows the human activities leading to pressures and potential effects on humpback, blue, and fin whales. E&P exploration activity is high, construction and production activity is regarded as medium (e.g., if we compared the sites being operated and constructed off California with the amount in the Gulf of Mexico), and several potential effects are possible. Fisheries, shipping, and tourism all have high levels of activity, with effects due to ship strikes from shipping a particular concern. The popular whale watching industry might lead to behavioural changes of animals, but uncertainties over consequences of these effects are high. Other activities which lead to effects are those leading to pollution, dredging, and military cruises, but activity levels are impossible to assess currently.

G. Conclusions

E&P industry activity has been high off the California coast in terms of seismic exploration and medium in terms of construction and production activities, with platforms located off the Southern California coast. Humpback whales have been increasing in numbers since the cessation of whaling with a recovery rate of 8%/y, albeit with considerable statistical variance in this estimate. Blue whales have inhabited Californian waters only since the 1970s and have undergone shifts in distribution, probably due to shifts in prey abundance more than anything else. Fin whales are abundant off California, and results from line transect surveys indicate that numbers in that particular area have remained the same since the 1990s, although no statement regarding trends can be made due to the uncertainty in the assessments. There are several activities besides E&P industry sound that can potentially affect stocks such as fisheries, shipping, and tourism, although the uncertainty about effects is high in all cases.

Table 9. Overview of human pressures on humpback, blue, and fin whales off California and an estimate on relative levels of activities and type and scale of potential effects on marine life

Activity	Pressure	Activity level	Potential effects	Comments	Uncertainty
E&P industry: Exploration	Vessel sound Airgun array sound	+++	Vessel: masking, behavioural response (long); Airgun: PTS (short), TTS (short), behavioural response (long)	Very limited number of studies	High
E&P industry: Construction	Pile driving sound Vessel sound	++	Pile driving: PTS (short), TTS (short), behavioural response (long); Vessel: masking, behavioural response (long)	Little information	High
E&P industry: Production	Drilling sound Drillship sound	++	Drilling and drillship: masking, behavioural response (short)	Little information	High
Fisheries	Vessel sound Fishing operations (nets), driftnets Competition	+++	Vessel: masking, behavioural response (long); Fishing operations: death, injury due to entanglement (short); Food depletion (long)	No information on effects of vessel sound/ entanglement concern for humpback whales; food depletion possible if piscivorous part of diet is relatively high	High
Shipping	Ship sound Ship strikes	+++	Ship: masking, behavioural response (long); Ship strikes: injury, death (short)	Little information on masking effects; ship strikes potentially an important issue	High
Tourism	Whale watching vessel sound, recreational boat sound, cruise ship sound	+++	Masking, behavioural response (long)	Well-developed whale watching industry; results of studies show short-term response	High
Various activities	Pollution	*	Physiological effects (long)	Little information; effects depending on diet (plankton vs fish)	High
Sand and gravel extraction; capital dredging for waterways and ports	Dredger sound Vessel sound	*	Dredger and vessel: masking, behavioural response (long)	Little information on activities; some studies documented behavioural response but no recent investigations	High
Sonar (military, private, research)	Vessel sound Sonar ping	*	Vessel: masking, behavioural response (long); Sonar: PTS (short), TTS (short), behavioural response (long)	Documented behavioural response to low-frequency sonar; little evidence for mid-frequency sonar effects; amount of activity unknown as mostly classified	High

+ = low level of activity, ++ = medium level of activity, +++ = high level of activity; spatial scale of effects: short = in close vicinity of the activity or area activity is carried out, long = beyond the activity area (depending on species and activity); * = insufficient data for a firm assessment

6. Case Study 3: Scotian Shelf – Northern Bottlenose Whales

A. Introduction to the Area

The Scotian Shelf surrounds the Canadian province of Nova Scotia and extends more than 200 nmi from the coast at some points (Figure 18). To the north, the Laurentian Channel separates it from the Newfoundland Labrador Shelf. To the south, it extends to the Fundian Channel (Northeast Channel). The Scotian Shelf has a complex topography consisting of numerous offshore shallow banks and deep mid-shelf basins (see www.dfo-mpo.gc.ca; Figure 19). One important area along the Scotian Shelf is The Gully, located approximately 40 km east of Sable Island on the eastern Scotian Shelf. The Gully is a submarine canyon, 70 km long, up to 20 km wide, and more than 2,000 m deep at its mouth. On a wider scale, The Gully ecosystem comprises an upper trough area, smaller canyons, the relatively shallow banks on either side of the canyon, and parts of the Scotian Slope. As a result, The Gully ecosystem contains many diverse habitats and is highly productive (details in Davis et al., 1998; Department of Fisheries and Oceans [DFO], 1998).

B. E&P Industry Activity

Production

The E&P industry off Nova Scotia has been active since exploration began in 1959 (Shaw et al., 2000). Production within the area is relatively small, with only two offshore projects historically producing oil and gas: (1) the Cohasset-Panuke project, producing oil from 1992 to 1999 and (2) the Sable Offshore Energy Project, producing natural gas since 1999. Offshore E&P industry activity has been predominantly in the Sable Island area (Figure 19), which lies close to the marine protected area of The Gully. Before 2000, of the wells that had been drilled, all significant and commercial discoveries were located in the Sable Island area, approximately 150 km offshore (Canada-Nova Scotia Offshore Petroleum Board [CNSOPB], 2000). There has been an interest in exploiting the southwestern area of the Georges Bank; however, a moratorium within this area has been in place since 1988 and has been extended until 2012. More recently, exploration activity has also occurred off the deepwater Scotian Shelf (information provided by CNSOPB; see www.cnsopb.ns.ca).

The first well drilled on the Scotian Shelf was an exploratory well drilled by Mobil in June 1967, with the first offshore discovery at Sable Island in 1971. Since then, an additional 203 wells have been drilled, the vast majority of which (62.0%) were exploratory wells (Figure 20). The drilling of development wells began in 1991 and, of the 79 wells drilled since then, 50 have been development wells. The total depth of the wells drilled along the Scotian Shelf varies in depth from 829 m (Company: Shell, Fox well) to 6,676 m (Company: Marathon Canada, Crimson well; information provided by CNSOPB; see www.cnsopb.ns.ca).

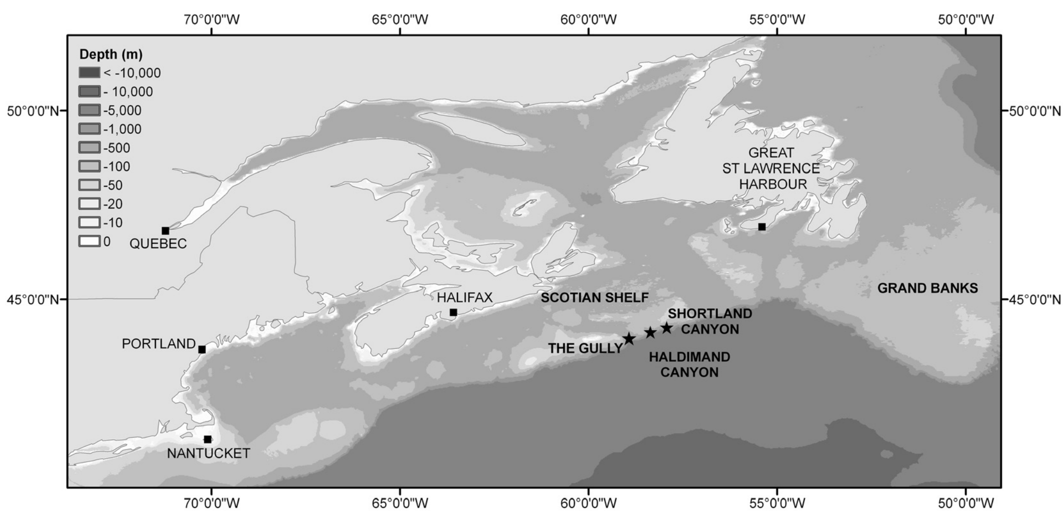


Figure 18. Map of the Scotian Shelf

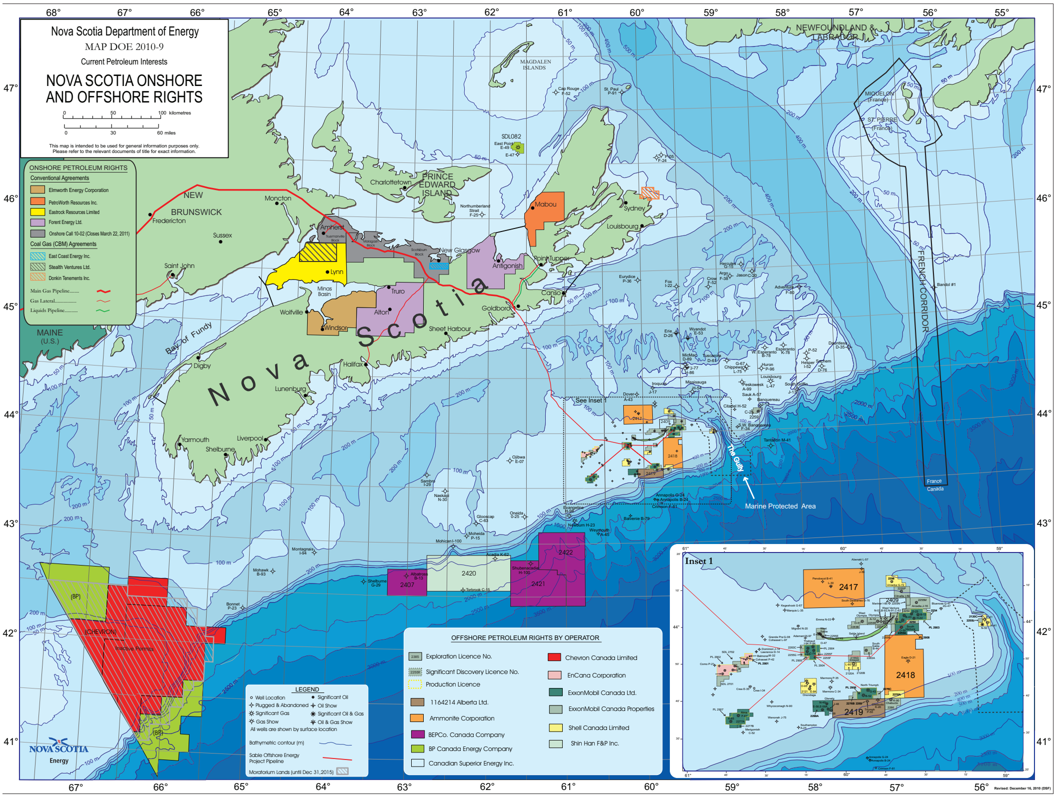


Figure 19. Map of offshore petroleum activity in the Nova Scotia area (*Source:* www.gov.ns.ca/energy/resources/RA/maps/Onshore-Offshore-Rights.pdf)

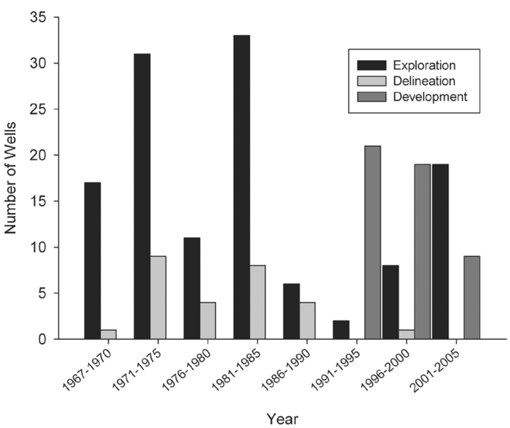


Figure 20. Number of wells drilled along Scotian Shelf, 1967-2005 (*Source:* Canada-Nova Scotia Offshore Petroleum Board [CNSOPB])

Exploration

Seismic exploration of the Scotian Shelf using 2D methods first began in 1960 (Figure 21). By 2004, approximately 400,034 km had been covered using 2D seismic mapping techniques. In that time, there were three peaks of seismic exploration activity. These were during 1969 to 1972, 1981 to 1984, and 1998 to 1999, when data acquisition covered 96,805 km, 112,058 km, and 71,144 km, respectively. Seismic exploration using 3D methods did not begin until 1985, and around 30,000 km^2 had been covered by 2004. The peak of 3D seismic surveying occurred between 1999 and 2001 when 19,964 km^2 were covered. During 1992 and 1995, no seismic exploration of either sort was recorded (information provided by CNSOPB; see www.cnsopb.ns.ca).

Seasonal variation in recent seismic activity can be determined using detailed seismic data available from the CNSOPB. By averaging the days spent to complete a reported survey and averaging the km recorded during a survey, an indication of seasonal peaks in activity can be determined (Figures 22 & 23). Peaks in activity for both 2D and 3D surveys can be seen in 2000 and 2001, showing the highest number of days spent surveying. It can also be seen that little or no activity occurred during the winter months, with high levels of seismic activity occurring over early

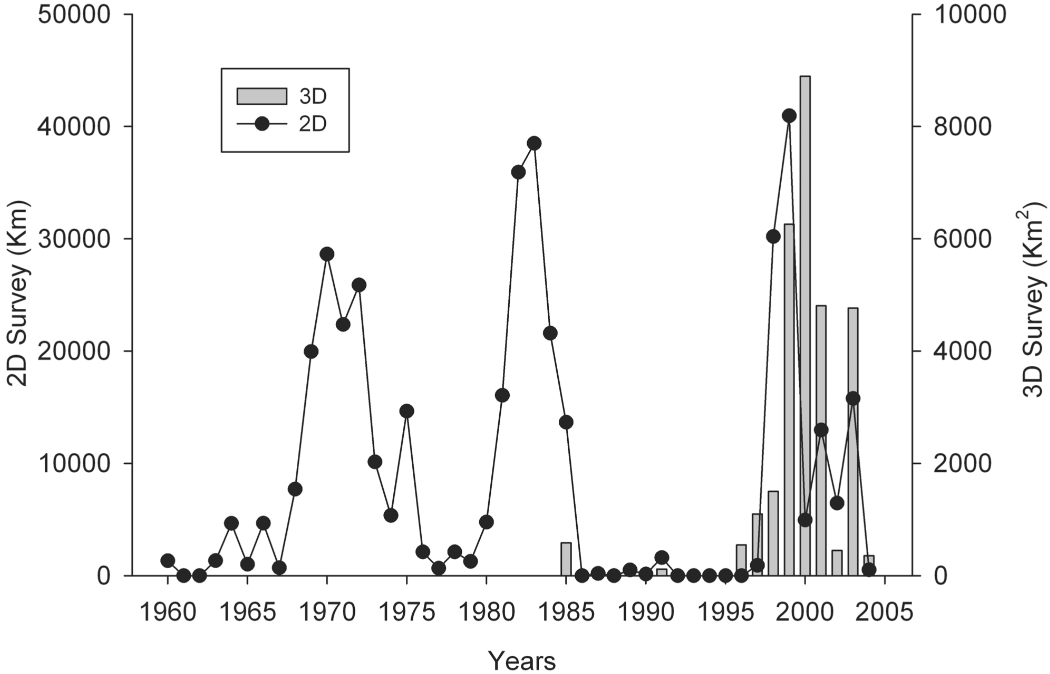


Figure 21. Kilometres of reflection seismic data acquired along the Scotian Shelf, 1960-2004 (*Source:* CNSOPB)

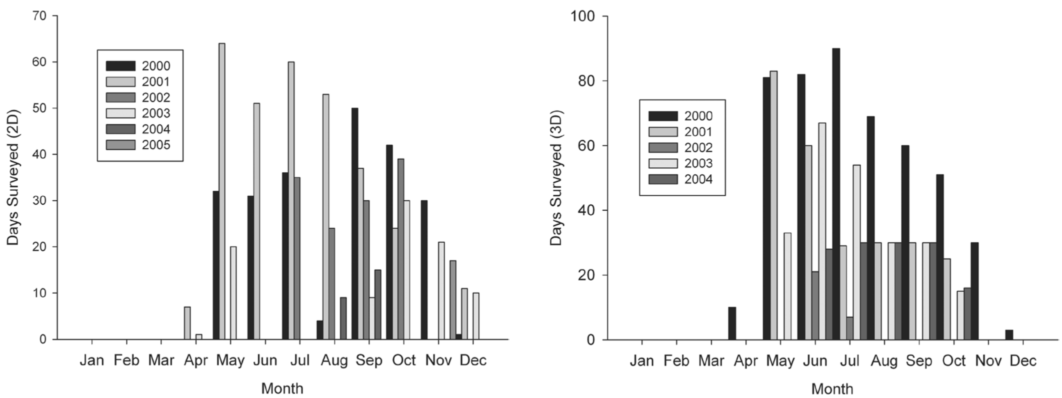


Figure 22. Seasonal variation in seismic 2D days surveyed (2000 to 2005) and 3D days surveys (2000 to 2004) (adapted from data provided by the CNSOPB)

summer to late autumn. The highest total number of survey days occurred during May 2001, with 64 d spent surveying by three vessels for 2D seismic data; and during July 2000, with 90 d spent surveying by three vessels for 3D seismic data. The total distance of seismic data can be averaged out over the duration of the survey to provide an indication of the distance acquired each month (Figure 23).

Looking at the distance covered within surveys conducted per month, significant peaks in activity can be seen in 2D seismic survey data during 2000, during which approximately 25,846 km and 15,123 km of data were obtained in September and October, respectively. The quantity of 3D data obtained appears to be more evenly spread out over the years, with 2000, 2001, and 2003 being the years with the largest area of 3D data gathered.

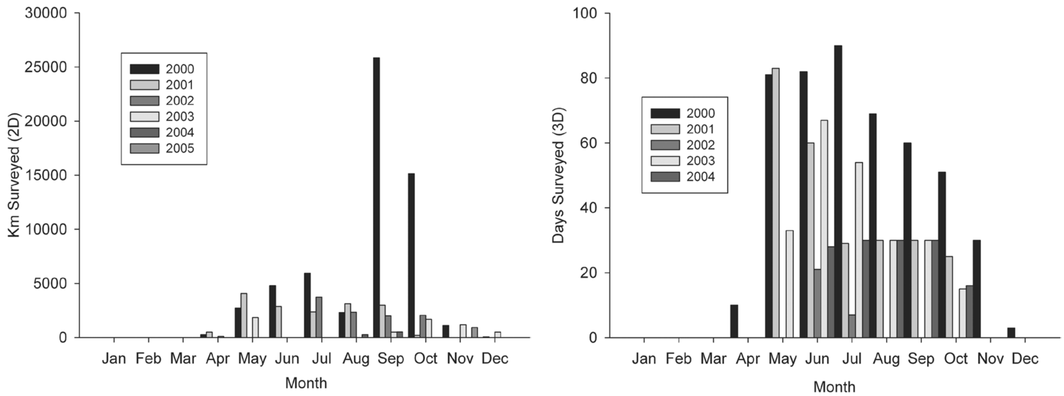


Figure 23. Seasonal variation in distance surveyed, 2D km (2000 to 2005) and 3D km^2 (2000 to 2004) (adapted from data provided by the CNSOPB)

C. Northern Bottlenose Whales Stock Assessment

A variety of cetacean species are regularly present over the Scotian Shelf, albeit with some seasonal differentiation; the list includes ten odontocetes and six baleen whales (Blaylock et al., 1995; Davis et al., 1998, and therein; Lawson et al., 2000; Simard et al., 2006; NOAA, 2007). The Gully is of special importance for a small and probably resident population of northern bottlenose whales, the only ziphiid (beaked) group studied on a long-term basis (e.g., Whitehead & Wimmer, 2005). The Gully is probably of importance to other cetaceans as well, but abundance estimates necessary for the present assessment are available only for the former.

Population Structure and Trends

Published results on population trends of northern bottlenose whales in The Gully are based on field data collected between 1988 and 2003 (Whitehead et al., 1997a, 1997b; Hooker, 1999; Gowans et al., 2000; Whitehead & Wimmer, 2005). Studies have also dealt with social organisation (Gowans & Rendell, 1999), seasonal trends and movement patterns (Gowans et al., 2000; Wimmer & Whitehead, 2005), dietary preferences (Hooker, 1999; Hooker et al., 2001), diving behaviour (Hooker & Baird, 1999), and genetics (Dalebout et al., 2006). These studies combine to provide a detailed picture of this species within The Gully and adjacent regions. The level of detail from these studies makes it possible to analyse the population with respect to the background presence of at least 6 y of E&P industry exploration, some years of construction activities, and the early stages of E&P platform operation in the region.

Whitehead et al. (1997a) were the first to note that northern bottlenose whales are present year-round in The Gully, that there is residency for some individuals, and that the whales in The Gully are morphologically different from bottlenose whales in other regions. They also expressed their concern that the start of E&P industry exploration and construction activities along the Scotian Shelf would negatively affect the presumably distinct northern bottlenose whale population in The Gully. Hooker (1999) found fluctuations in sighting rates and, hence, abundance of whales in different years (1988 to 1998), but no overall positive or negative trend. Hooker also found indications that these whales feed predominantly on squid (*Gonatus steenstrupi*), which are moderately sized (mantle ~10 cm) and are thought to live around the sea floor on continental slopes. The diving behaviour of bottlenose whales in The Gully, with animals diving to depths of over 800 m every 80 min for up to 70 min, is consistent with benthic or bathypelagic foraging behaviour (Hooker, 1999; Hooker & Baird, 1999; Hooker et al., 2001). Hooker (1999) also found little displacement of individuals over time and concluded that the apparent lack of movement indicates that the canyon provides these northern bottlenose whales with an important and sustainable food resource.

Based on these results, Hooker et al. (1999) suggested that The Gully should be designated as a marine protected area, which was implemented by the Canadian Government in 2004 (for more information, see www.dfo-mpo.gc.ca). Later investigations confirmed the residency of the whales in The Gully but also showed that northern bottlenose whales are present in two other underwater canyons in the vicinity as well (Shortland, 50 km east; Haldiman, 100 km east) and that there are movements of individuals between canyons, especially by males (Wimmer & Whitehead, 2005). The population in The Gully appears to be genetically distinct. Since no indications for genetic bottlenecks were found, The Gully population is probably not a relic of a historically wider distribution. Instead, the rather unique ecosystem appears to have provided a stable year-round habitat for a distinct population of northern bottlenose whales (Dalebout et al., 2006).

As can be seen in Table 10, Whitehead et al.'s (1997a, 1997b) estimates are higher than both the following calculations by Gowans et al. (2000) and Whitehead & Wimmer (2005). Yet, as Gowans et al. (2000) point out, this is due to methodological reasons—for example, the different estimation between the studies with regards to the percentage of animals classified as marked in the mark-recapture analysis—and it should be noted that the latter estimates seemed to be more accurate (see Table 10). The differences between Gowans et al. (2000) and Whitehead & Wimmer (2005) are probably also methodological as higher numbers in the latter study are likely due to animals whose primary habitat is outside The Gully and who rarely visit it (Whitehead et al., 1997a, 1997b; Gowans et al., 2000; Whitehead & Wimmer, 2005). Considering documented trends, this population of northern bottlenose whales seems to have remained constant over the course of the studies cited. If we assume that Gowans et al. (2000) estimates are closest to reality, it can be concluded that *ca*. 130 (range ~100 to 160) northern bottlenose whales were present between 1988 and 2003 in The Gully, with no apparent upward or downward trend. Mortality (as estimated by a combination of mortality, emigration, and mark-changes) is 12%/y. Still, much of the 12.0% is probably related to changes in body markings (Committee on the Status of Endangered Wildlife in Canada [COSEWIC], 2002). Caution is urged when drawing conclusions about population trends for this group as CIs were high. Looking at the sighting rate/h searching between 1988 and 1999, the values are stable between years, especially between 1996 and 1999 (Gowans et al., 2000). This might indicate that the overall number of animals remained unchanged.

D. Documented Response of Northern Bottlenose Whales to E&P Sound

There are no published data on the hearing ability of northern bottlenose whales. Hooker & Whitehead (2002) recorded clicks between 2 and 24 kHz with some differences between clicks emitted by socialising whales at the surface and clicks produced by whales, presumably foraging, at depth. Earlier reports by Winn et al. (1970) of whistles between 3 and 16 kHz and burst pulses were challenged by Hooker & Whitehead (2002) as potentially coming from pilot whales. The click frequencies and inter-click intervals recorded by Hooker & Whitehead (2002) indicate that these pulsed vocalizations are used to forage on the squid (see also Hooker, 1999; Hooker et al., 2001). Based on the bandwidth of the emitted sounds, one could assume that northern bottlenose whales are sensitive to sounds between 2 and 24 kHz. Yet, Hooker & Whitehead (2002) made it clear that their recording system had a higher cutoff at 35 kHz. They could not rule out that clicks are emitted above 35 kHz. While it is difficult to confirm the hearing range without a direct auditory test, there is reason to assume that northern bottlenose whale hearing covers a wide range of frequencies similar to that of other odontocetes of comparable size (e.g., belugas and killer whales; Southall et al., 2007). Southall et al. provisionally placed this species in their mid-frequency category (functional hearing range 150 Hz to 160 kHz). It is therefore reasonable to assume that northern bottlenose whales are able to perceive a considerable amount of E&P industry-related sound that could lead to a variety of effects (see Table 11).

Table 10. Overview of the results by different studies on the abundance of northern bottlenose whales in The Gully

Study period	Method	Estimate	Trend	Source
1988-1995	Mark-recapture based on photo-identification	230 (95% CI = 160-360)	Not investigated	Whitehead et al., 1997a, 1997b
1988-1999	Mark-recapture based on photo-identification	Left side: 133 (95% CI = 111-166) Right side: 127 (95% CI = 106-160)	Left side: -0.13% per year (95% CI = -3.4 to 3.9% [n.s.]) Right side: -0.43% per year (95% CI = -4.5 to 3.1% [n.s.])	Gowans et al., 2000
1988-2003	Mark-recapture based on photo-identification	163 (95% CI = 119-214)	= +0.7 to +2.5% per year (n.s.)	Whitehead & Wimmer, 2005

n.s. = nonsignificant

Perhaps most relevant for the issue of potential disturbance on northern bottlenose whales by seismic surveys are results from various field studies conducted in 2003 in The Gully and adjacent waters, which were compiled by Lee et al. (2005). In general, these studies dealt with acoustic monitoring and marine mammal surveys in The Gully and Scotian Shelf both before and during seismic surveys. Of particular value were the studies by Austin & Carr (2005) who examined received SPLs at distances of up to 55 km from a 3D seismic operation. They found received levels of 152 dB re 1 $\mu Pa^2 \cdot s$ (SEL), 167 dB re 1 µPa (rms), and 175 dB re 1 µPa (peak) at 2.6 km from the source. At 55 km, the corresponding values were 130 dB re 1 $\mu Pa^2 \cdot s$ (SEL), 133 dB re 1 µPa (rms) and 143 dB re 1 µPa (peak) for 77 m and 123 dB re 1 $\mu Pa^2 s$ (SEL), 126 dB re 1 µPa (rms), and 136 dB re 1 µPa (peak) at 180 m water depth. Most energy was at frequencies below 100 Hz. McQuinn & Carrier (2005) provided a range of far-field measurements at different water depths that are depicted in Table 23 in the Appendix. The received sound level was measured in The Gully, while the seismic vessel was surveying outside The Gully at distances 30 to 100 km from the recording site. As can be seen in Table 23, received SPLs can be as high as 147 dB re 1 µPa (peak) at 100 km which is well above the ambient noise level typical for The Gully (see Zakarouskas et al., 1990; Davis, 1998). The authors concluded that the "worst case" sound level in The Gully with an exposed animal 0.8 km away from the source was 178 dB re 1 µPa (peak). In another study, Simard et al. (2005) reported received SPLs between 103 dB re 1 µPa (rms) and 135 dB re 1 µPa (rms) (91 to 31 km ranges). Finally, Potter et al. (2005) confirmed earlier observations that some of the sound from seismic surveys has energy at higher frequencies, up to 4 kHz; however, they also showed that most energy was below 500 Hz.

Looking at potential short-term disturbance, Lee et al. (2005) present studies that are difficult to assess because of methodological pitfalls, especially small sample sizes; they cover northern bottlenose whales only to a limited degree. For example, Moulton & Miller (2005) monitored marine mammals before and during seismic activity (on/off) from a 3D seismic survey vessel. They found some indications of avoidance by whales due to seismic activities, judging by the number of animals seen during seismic surveys compared to when no surveys were taking place and the distance of the observation to the seismic vessel during surveys compared to nonsurvey observations. However, sample sizes were too small to demonstrate this unequivocally. Received levels were measured during this survey (Austin & Carr, 2005), and modelling exercises indicated that they could be as high as 190 dB re 1 µPa at 150 m from the vessel. Northern bottlenose whales were only observed once, so no conclusions could be drawn. Potter et al. (2005) reported avoidance by cetaceans towards a 3D survey vessel at distances up to 100 m, yet the overall number of cetaceans in the observable radius did not change significantly when the seismic source was on compared to when it was off. Cetaceans were observed in larger groups and became less vocal when the array was on. However, the authors also noted that bias might have been introduced because no distinction was made in the analysis between baleen and toothed whales. Gosselin & Lawson (2005) investigated the distribution and abundance of cetaceans in The Gully before and during seismic surveys based on line transect surveys, but the observed trends could not be attributed to sound from seismic activities.

E. Other Factors Potentially Affecting the Stock

Information on other factors potentially affecting northern bottlenose whales on the Scotian Shelf is sparse. Whitehead et al. (1997a) provide an overview. Historically, whaling might have led to a reduction of up to 40% of the original population of northern bottlenose whales off the Scotian Shelf. Between 1962 and 1967, 87 northern bottlenose whales were killed by whalers from Blandford, Nova Scotia, with most individuals taken from within and around The Gully. Current threats include collision with ships, entanglement in fishing gear, effects from marine debris (e.g., litter), fishing (groundfish = shallow areas bordering The Gully; Redfish = midwater draggers in and around The Gully), and chemical pollution. Whitehead et al. provide no further information on the exact or assumed impact of these factors on the population. What follows is an assessment of these different factors based on some additional data provided from other sources.

Fisheries

Fishing effort on the Scotian Shelf is significant and targets groundfish (Atlantic cod [*Gadus morhua*], pollock [*Pollachius pollachius*], haddock [*Melanogrammus aeglefinus*], silver hake [*Merluccius bilinearis*], redfish [*Sebastes* spp.] etc.), pelagic species (Atlantic herring [*Clupea harengus*], Atlantic mackerel [*Scomber scombrus*] etc.), and crustaceans (American lobster [*Homarus americanus*], northern shrimp [*Pandalus borealis*], snow crab [*Chionoecetes opilio*], and molluscs [clams, e.g., *Mya arenaria* and scallops, e.g., *Placopecten magellanicus*]). Even so, the ground fishery was greatly reduced during the 1990s (closure of some areas from 1993 onwards), and most of the remaining fisheries occur in the southwestern part of the Shelf (years 1995/1996, maps in Davis et al., 1998). The Gully itself remains important for long-line fisheries for halibut (*Hippoglossus hippoglossus*) (2001 catch = 47 tons; CNSOPB, 2003). There are more extensive reports on the activities of the fishing industry on the Scotian Shelf (Davis et al., 1998; Harrison & Fenton, 1998; CNSOPB, 2003), which could be referred to for more detail. By-catch or entanglement in fishing gear was noted by Whitehead et al. (1997a) as a potential limiting factor as "a number of northern bottlenose whales in The Gully show evidence of encounters with fishing gear" (p. 290) (see also Figure 1 in Whitehead et al., 1997a); however, Whitehead et al. (1997a) is the only source that mentions direct mortality through entanglement. It is therefore impossible to assess the importance of entanglement on this group. Disturbance by sound is a potential threat if we consider that fishing vessels can be quite noisy, particularly when towing bottom gear (source levels: 140 to 160 dB re 1 µPa (rms) at 1 m, 10 Hz to 10 kHz, most below 1 kHz, trawler data; Richardson et al., 1995). However, there are no studies on the hearing of northern bottlenose whales, so any assessments on sound impacts from vessels are speculative.

Depletion of food resources is probably not an issue with regard to northern bottlenose whales in The Gully since their preferred prey is not targeted by the fishing industry. Remaining issues in relation to direct impacts from fisheries are litter and large debris (pollution) from fishing vessels, and both seem to occur in The Gully at comparatively high levels (Lucas, 1992; Dufault & Whitehead, 1994).

Shipping
The Gully is located 30 km from one of the major shipping lanes off the east coast of North America: the east-west trans-Atlantic shipping route (Figure 17; COSEWIC, 2002). Ship strikes are possible, though COSEWIC notes that there are no known reports of northern bottlenose whale fatalities due to ship strikes (see also Whitehead et al., 1997a; Hooker et al., 1997). Zakarauskas et al. (1990) reported high ambient noise levels for the Scotian Shelf region that are typical for areas located in heavily used shipping lanes (Wenz, 1962; Urick, 1983) and are similar to those described by Thomsen et al. (2006b) in their review for the German North Sea under comparable wind speeds. However, in coastal areas with a lot of traffic to and from ports, ambient noise levels can be much higher (Nedwell et al., 2007). It is important to note that the water depths in The Gully are probably sufficient to cut off sound transmission from large distances as sound transmission will follow spherical transmission (20 log R) (Urick, 1983) due to the water depths. Nevertheless, without systematic measurements, it is difficult to assess the effects of ambient noise in relation to other sound sources.

Pollution
Hooker et al. (2008) analysed biopsy samples from northern bottlenose whales from The Gully (periods 1996/1997 and 2002/2003) and the Davis Strait, Labrador, taken in 2003. They documented blubber contaminants and concentrations were consistent with other North Atlantic cetaceans. The documented levels were lower than those that are thought to cause health problems in more contaminated cetacean species. Scores for CYP1A1 expression, which is thought to reflect recent exposure to contaminants, were low in the sampled whales, with most samples scoring zero. From the few animals that expressed CYP1A1, those sampled in 2002/2003 had higher concentrations than those sampled in 1996/1997. Hooker et al. also detected a range of PCB congeners and organochlorine compounds with PCB showing no trend; HCHs and endosulfans showing significant decreases; and DDT and chlordanes showing significant increases over time. These changes are attributed to a temporal change of contaminant levels in the water or in prey species. Although it was not likely that contaminants were released by nearby oil rigs or during seismic exploration, Hooker et al. did not rule out the possibility that E&P industry activities led to the remobilisation of persistent contaminants from sediments on the Scotian Shelf. Still, these conclusions should be interpreted with caution as, with one exception, different animals were analysed between 1996/1997 and 2002/2003. The single animal sampled for both periods showed the same trend as reported for the whole dataset; however, contaminant levels of different individuals are difficult to compare over time as other factors might be responsible for the observed changes.[11] The authors provided no explanation for the decrease in other contaminants. Finally, sample sizes for the CYP1A1 were too small to draw any conclusions on temporal trends.

Sonar
Military sonar of low, mid, and high frequency could potentially affect northern bottlenose whales (see Table 11), but there is no information on the level of activity in the region.

[11] For example, in mature females, there is the possibility of downloading of lipophilic contaminants to offspring and, therefore, reduced contaminant levels would be observed for mature females.

F. Pressure Assessment

It is clear from the information provided in Table 11 that the effects of most human activities on northern bottlenose whales in The Gully are impossible to assess at the moment. E&P industry exploration activity is certainly high in the nearby areas, and major shipping lanes are located in the region, albeit at some distance from The Gully. Both activities could potentially lead to behavioural reactions such as avoidance behaviour, but studies on the effects of seismic surveys on cetaceans have so far only produced conclusive results with regards to recorded SPLs at various distances from seismic survey vessels. Effects from fisheries are possible, but they are impossible to assess at the moment. The overall picture is that of a limited number of human pressures that cannot be assessed at present.

G. Conclusions

E&P industry activity has been present off Nova Scotia, especially during the late 1990s, with widespread seismic exploration and construction and production activities since the beginning of this century. Field studies conducted between 1988 and 2003 indicate that overall numbers of northern bottlenose whales have remained constant during those years. Still, due to the relatively short history of field studies and the high variability in abundance estimates, further studies are required to clarify the demographic features for northern bottlenose whales in The Gully and adjacent waters. There are a limited number of human pressures that could lead to effects, but these are impossible to assess currently.

Table 11. Overview of human pressures on northern bottlenose whales off Nova Scotia and an estimate on relative levels of activities and type and scale of potential effects on marine life

Activity	Pressure	Activity level	Potential impacts	Comments	Uncertainty
E&P industry: Exploration	Vessel sound Airgun array sound	+++	Vessel: masking, behavioural response (long), Airgun: PTS (short), TTS (short), behavioural response (long)	Field studies provide extensive sound measurement but little information on behavioural response	High
E&P industry: Construction	Pile driving Vessel sound	++	Pile driving: PTS (short), TTS (short), behavioural response (long); Vessel: masking, behavioural response (long)	No studies	High
E&P industry: Production	Drilling sound Drillship sound	+	Drilling and drillship: masking, behavioural response (short)	No studies, but only limited number of platforms	Medium
Fisheries	Vessel sound Fishing operations (nets), driftnets Competition	++	Vessel: masking, behavioural response (long); Fishing operations: death, injury due to entanglement (short); Food depletion (long)	Fishing is restricted; entanglement in fishing gear possible but little evidence; little competition on food sources	High
Shipping	Vessel sound Ship strikes	+++	Vessel: masking, behavioural response (long); Ship strikes: injury, death (short)	Shipping lanes located 30 km from The Gully; no evidence for ship strikes	Medium
Various activities	Pollution	*	Physiological effects (long)	Study shows rising levels of DDT and chlordane, but results are difficult to interpret	High
Sonar (military, private, research)	Vessel sound Sonar ping	*	Ship: masking, behavioural response (long); Sonar: PTS (short), TTS (short), behavioural response (long)	No information on activity in the region	High

+ = low level of activity, ++ = medium level of activity, +++ = high level of activity; spatial scale of effects: short = in close vicinity of the activity or area activity is carried out, long = beyond the activity area (depending on species and activity); * = insufficient data for a firm assessment

7. Case Study 4: UK East Coast – Harbour Porpoises and Minke Whales

A. Introduction to the Area

The North Sea covers about 625,000 km^2; there are deep regions to the north, especially where the sea borders Norway, but otherwise it is a shallow-shelf sea, generally with depths of less than 200 m, and an average depth of just 25 to 35 m in the southern North Sea (Figure 24). Shallow depths mean the water column is well mixed by tidal and wind forces. The North Sea is influenced by inflow of Atlantic water through the Dover Straits to the southwest, and to a lesser extent by Atlantic water from the north. The North Sea is a heavily utilised body of water, with fishing grounds, shipping lanes, and E&P industry activity all extending across this area.

B. E&P Industry Activity off the UK East Coast

Production

E&P industry exploration began on the United Kingdom Continental Shelf (UKCS) in 1964, with the first licenses granted and the first well drilled in the central North Sea soon after (see www.ukooa.uk). Exploration drilling continued, and the first North Sea gas field began production in 1967 (BERR, 2008). Drilling activity remained high in the North Sea with 159 exploration wells drilled in 1990, 289 wells drilled in 1998, and 201 wells drilled in 2006 (BERR, 2008). The principal infrastructure off the UK east coast, including all E&P terminals, pipelines and fields, licensed areas, and wind farm sites as of 2008, is a vast extent of the industry in a small area (Figure 25 courtesy of BERR, 2008). Currently, there are 284 UKCS installations in production (Table 12). The first platform installations were predominantly in the southern North Sea, followed later by increased activity in the northern North Sea, the Moray Firth, and the Irish Sea. The largest increase in platform numbers occurred during the late 1980s, with over 80% of current platforms in production by 1997. Most recently, activity has moved into the central North Sea and to the west of the Shetland Islands, with an increase in platform numbers between 1997 and 2007.

Over the last 40 years, production off the east coast of the UK has steadily increased. The cumulative total number of platforms within the Moray Firth, central North Sea, and southern North Sea has risen accordingly (Figure 26). The southern

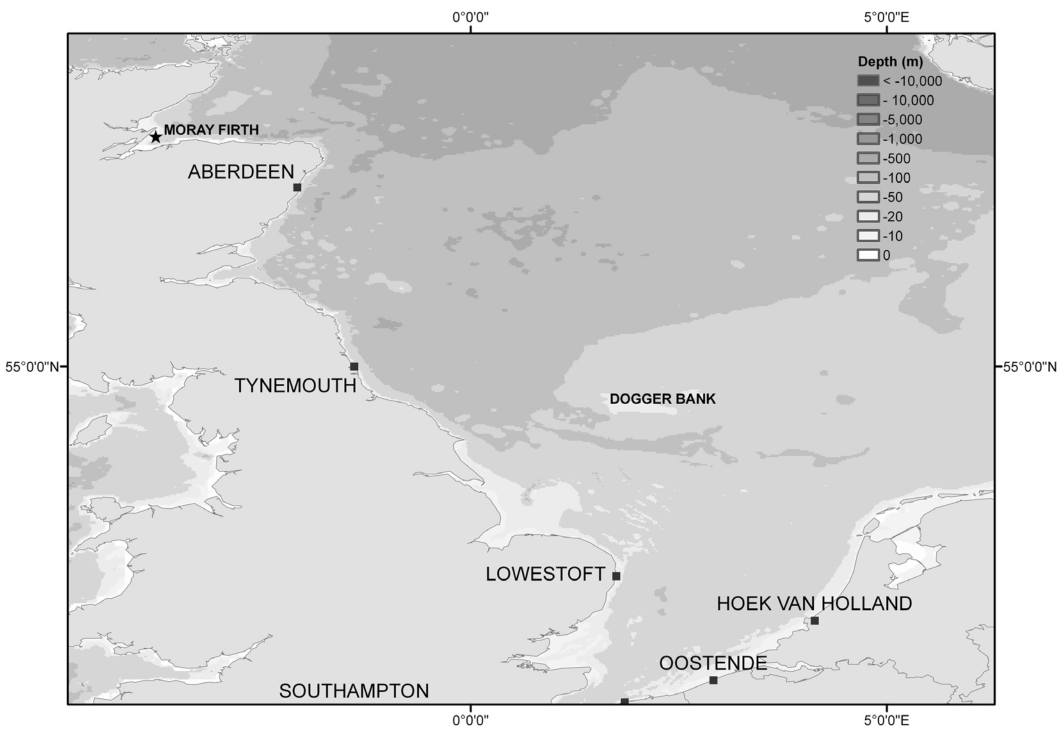


Figure 24. Overview of the southern North Sea

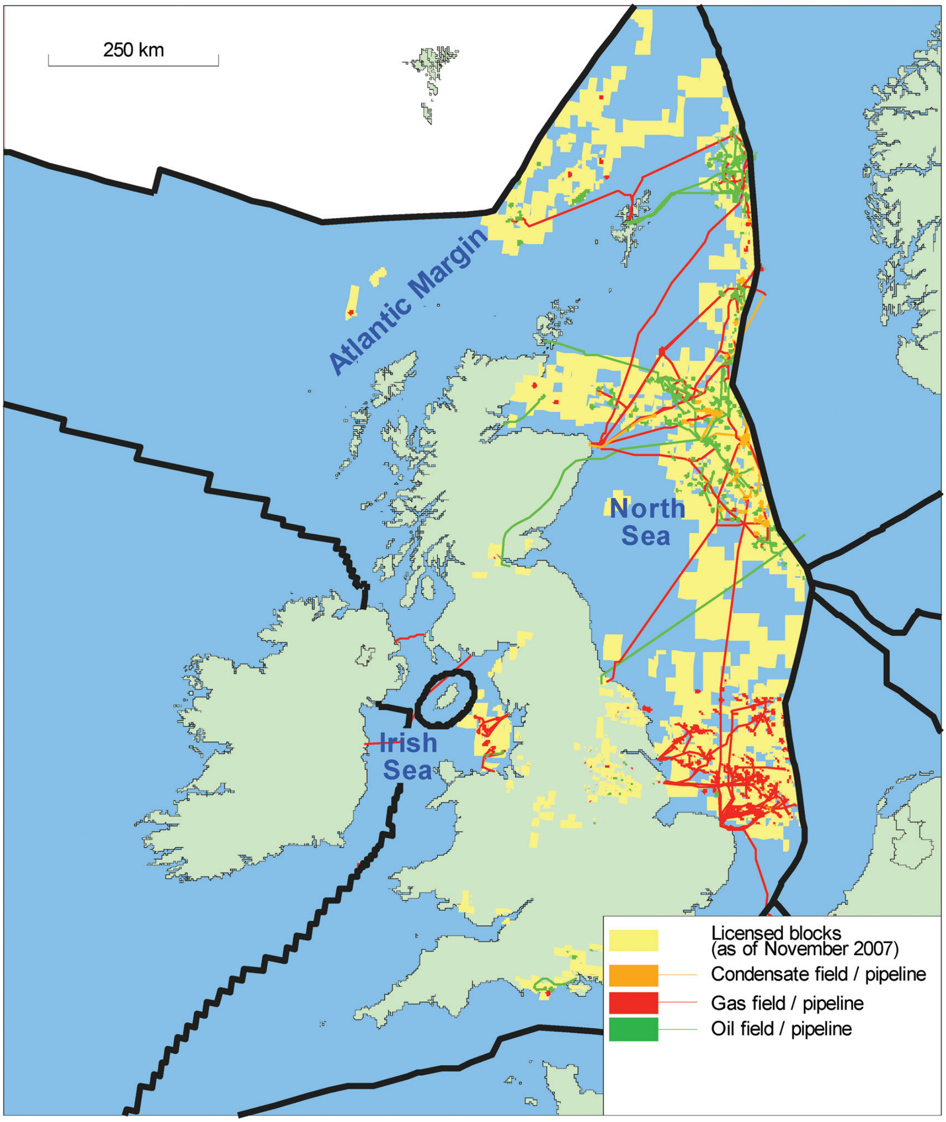


Figure 25. UKCS principle infrastructure (Gray, 2008; Crown Copyright); cropped to show UK east coast structures (*Source:* www.nationalarchives.gov.uk/doc/open-government-licence)

Table 12. Cumulative totals by area of installations in production on the UK Continental Shelf (UKCS) between 1997 and 2007 (BERR, 2008)

	Cumulative platform total by first production date			
Area	1977	1987	1997	2007
Northern North Sea	7	21	34	34
Central North Sea	8	12	26	43
Southern North Sea	71	83	139	168
West of Shetland	0	0	1	3
Irish Sea	0	7	15	17
Moray Firth	3	8	17	19
Total	89	131	232	284

North Sea has seen the highest activity in terms of platform numbers, reaching a cumulative total of 168 by 2007. The greatest increases were seen in 1967 to 1973 and 1987 to 1990 when platform totals rose from 5 to 68 and 83 to 115, respectively. The central North Sea has seen a smaller number of platforms built, with a cumulative total of 43 in place by 2007. A steady rise in the number of platforms began in 1993 when numbers rose from 14 to 38 in 2002. The Moray Firth also saw a similar increase, albeit on a smaller scale in terms of numbers, during this period, with the most notable increase of 13 to 19 platforms between 1996 and 1999 (Figure 26).

Exploration

Seismic surveys have been carried out in the North Sea since 1963, with the majority being 2D line transects. With the developing 3D technology, surveying began in 1978 with high numbers of 3D surveys concentrated in the southern North Sea and the north-central North Sea. Over the last ten years, activity has begun moving into areas west of the Shetland Islands and into the Irish Sea (information obtained from UK Deal; www.ukdeal.co.uk) (Figure 27). The industry splits areas of the UK coast up into quadrants for reference (Figure 28), and these quadrants will be referred to in the following text. The amount of seismic activity within Quadrants 11 to 57 has varied between 1997 and 2003 (Figure 29). The highest activity was in 1997 when 10,705 km and 6,441 km^2 of 2D and 3D surveys were made, respectively. Overall, 2000 was the "quietest" year in terms of surveys, with only 210 km and 463 km^2 of 2D and 3D seismic activity, respectively. Between 1997 and 2003, Quadrants 12, 20, 21, 29, and 30 experienced the highest seismic activity (Figure 30). The highest level of activity was seen in Quadrant 30 with 2,421 km and 5,663 km^2 of 2D and 3D survey work being carried out. Quadrants 20 and 21 saw high levels of 2D survey activity (2,441 and 2,345 km, respectively) but relatively lower levels of 3D surveying (1,534 and 454 km^2, respectively). In contrast, Quadrant 12 saw 5,046 km^2 of 3D surveying but only 376 km of 2D surveying.

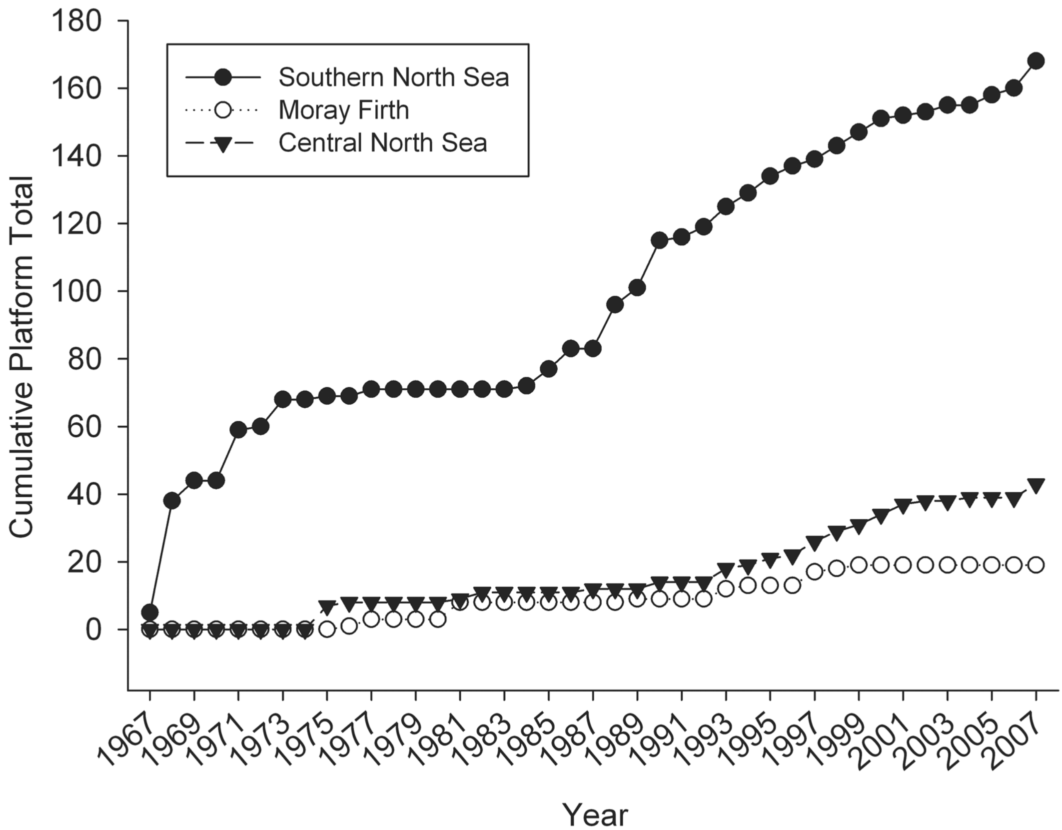
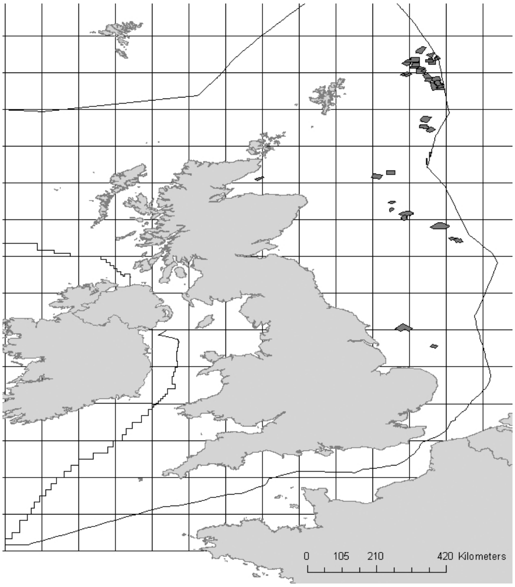
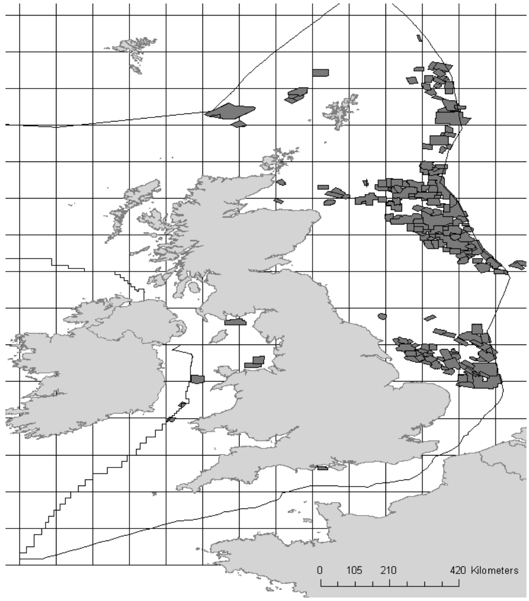


Figure 26. Cumulative platform numbers within the Moray Firth, central North Sea, and southern North Sea from 1967 to 2007 (BERR, 2008)



A



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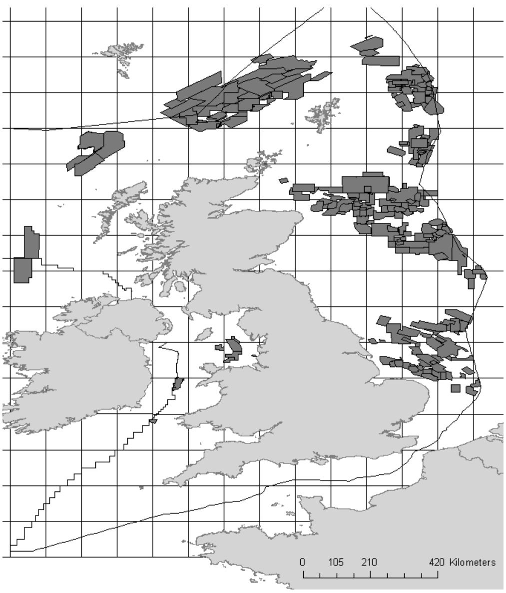

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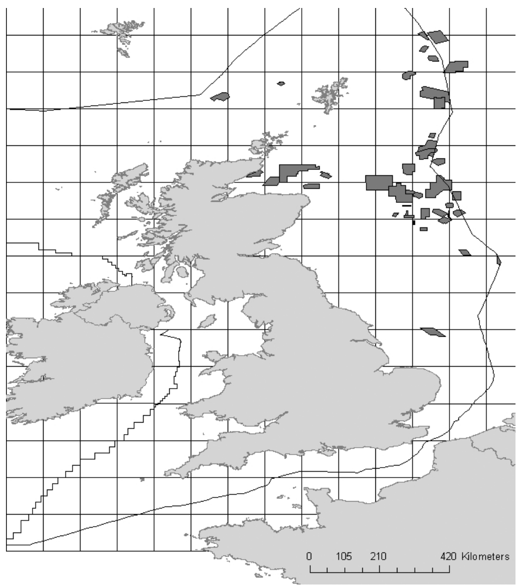

D

Figure 27. Historical 3D seismic activity of UK coast; Map A: Pre-1985, 47 surveys; Map B: 1985 to 1995, 224 surveys; Map C: 1995 to 2005, 261 surveys; Map D: Post-2005, 44 surveys) (data from www.ukdeal.co.uk).

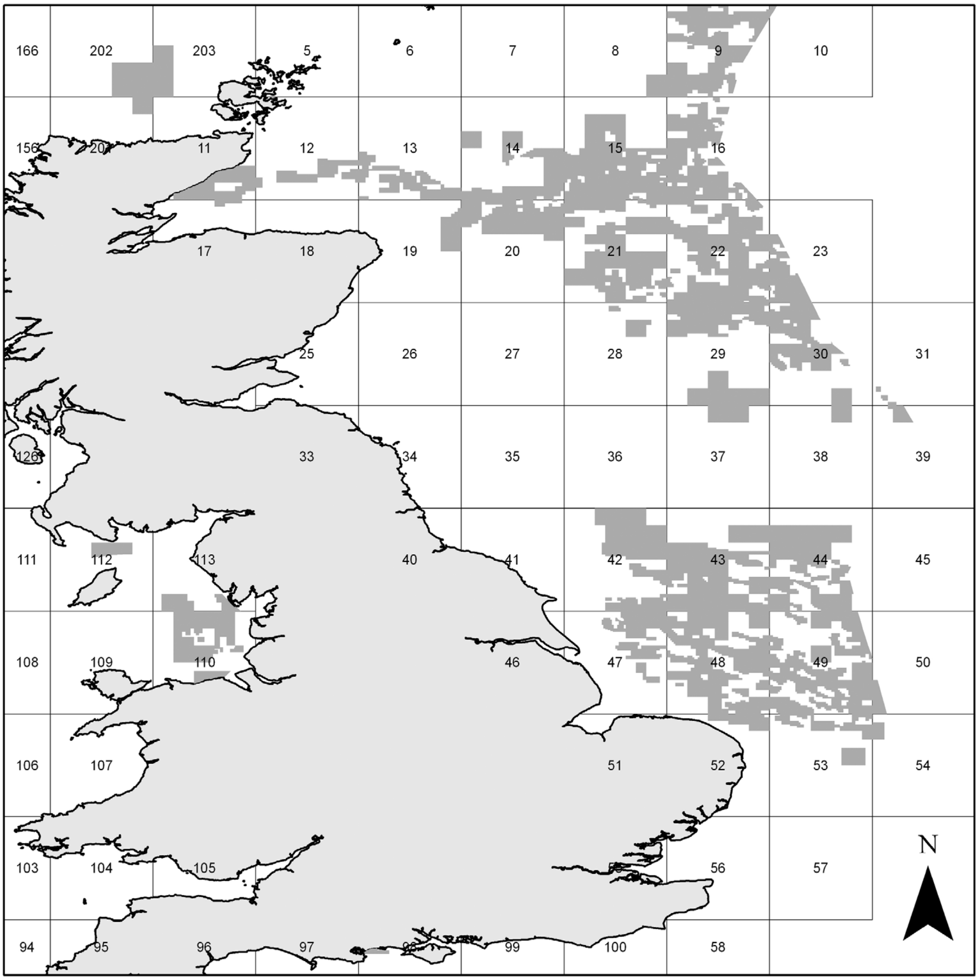

Figure 28. Map of UK east coast showing quadrant numbers used by the industry, with the areas shaded that are currently under licence (BERR, 2008)

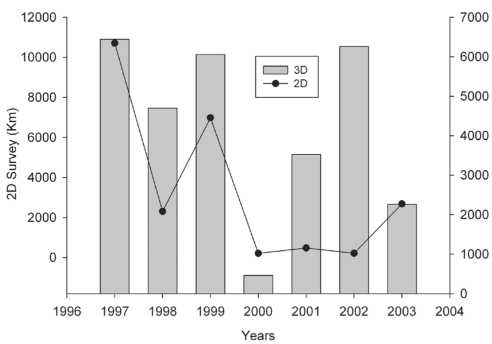

Figure 29. Total km of 2D survey and total km^2 of 3D survey carried out within Quadrants 11 to 57 of the UKCS between 1997 and 2003 (adapted data from ASCOBANS, 2005)

C. Cetaceans off the UK East Coast

The waters of northwest Europe support a rich diversity of cetaceans; 28 species have been recorded, although not all of them are found in the North Sea (Reid et al., 2003). The two species that are found most frequently off the UK east coast are the harbour porpoise and minke whale. The harbour porpoise is the smallest and most numerous of the cetaceans found in northwestern European continental shelf waters; typically, they occur in small groups of one to three animals (Reid et al., 2003) and are also distributed along the UK coast (Figure 31 & Reid et al., 2003). They are commonly seen around most of the coast, with smaller numbers in the southern North Sea and the English Channel area. Minke whales are the smallest baleen whale and are the

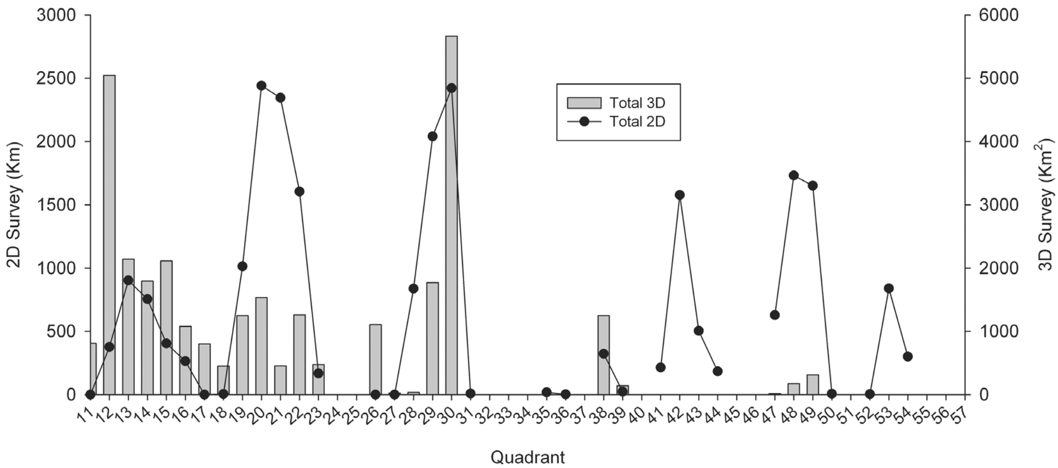

Figure 30. Total km of 2D survey and total km^2 of 3D survey carried out between 1997 and 2003 within Quadrants 11 to 57 of the UKCS (adapted data from ASCOBANS, 2005)

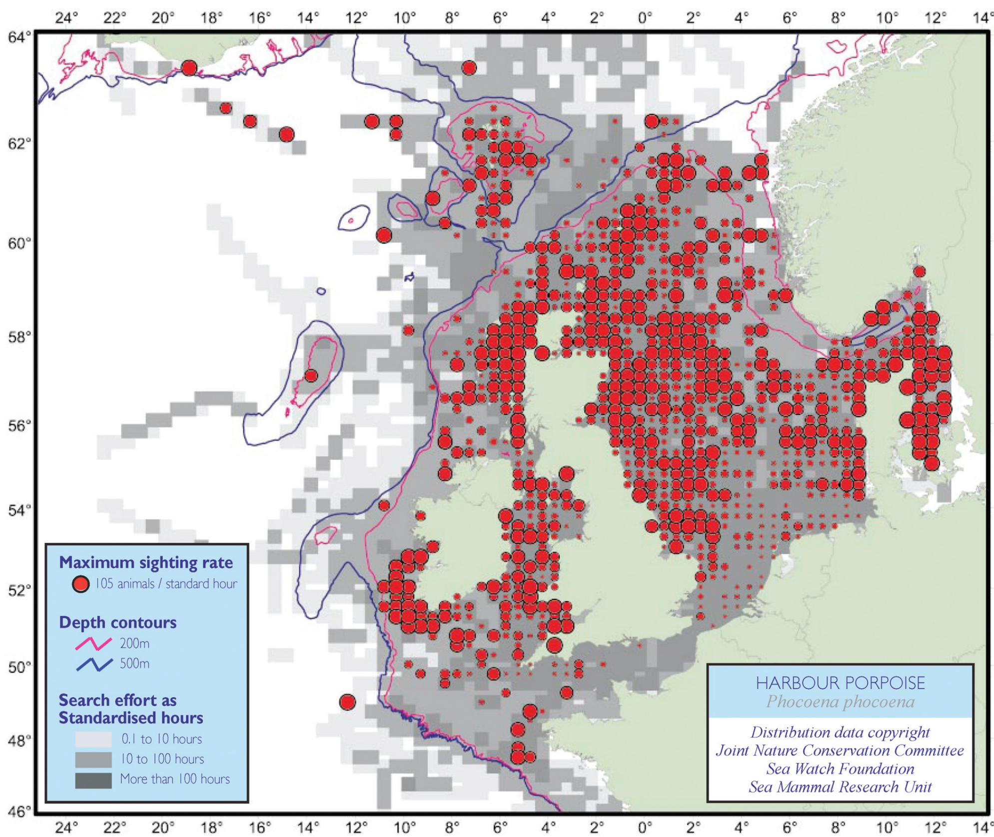

Figure 31. Distribution of harbour porpoise sightings around the UK (Reid et al., 2003; Crown Copyright)

most common mysticete in these waters; their distribution around the UK coast is estimated from data collected prior to 2003 (Figure 32 & Reid et al., 2003). They are not sighted as commonly as harbour porpoises, and their distribution is not as extensive. They are most frequently seen in the northwest region of the North Sea, close to the UK east coast, but they become rare south of approximately 54° N and also in the central and eastern parts of the North Sea (Reid et al., 2003).

D. Harbour Porpoise Stock Assessment

Population Structure

The question of whether harbour porpoises from the North Sea and English Channel can be split into subpopulations/stocks, and where these divisions should occur, has been contested in the literature. Based on mitochondrial DNA analysis, Walton (1997) suggested a division of the North Sea animals into northern and southern stock areas as a result of the large genetic differences found between them, while no differences were identified between animals from the Dutch and English coasts. Conversely, Tolley et al. (1999) and Andersen et al. (2001) suggested a division of the northern North Sea into eastern and western subpopulations. In 2000, the International Whaling Commission (IWC)/Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) divided the harbour porpoises occurring in the North Sea for practical management purposes into a northern North Sea stock, a central and southern North Sea stock, and an additional stock located in the western English Channel (ASCOBANS, 2006; Eisfeld, 2006).

Population Size

The most comprehensive population estimates are the SCANS surveys undertaken during the summer of 1994 and 2005 (for the survey blocks used, see Figures 33a & 33b). The survey blocks of the North Sea that we are interested in, and that were used during the SCANS survey in 1994, are Blocks C (bordering the UK east coast), F (north-central North Sea), and G (south-central North Sea).

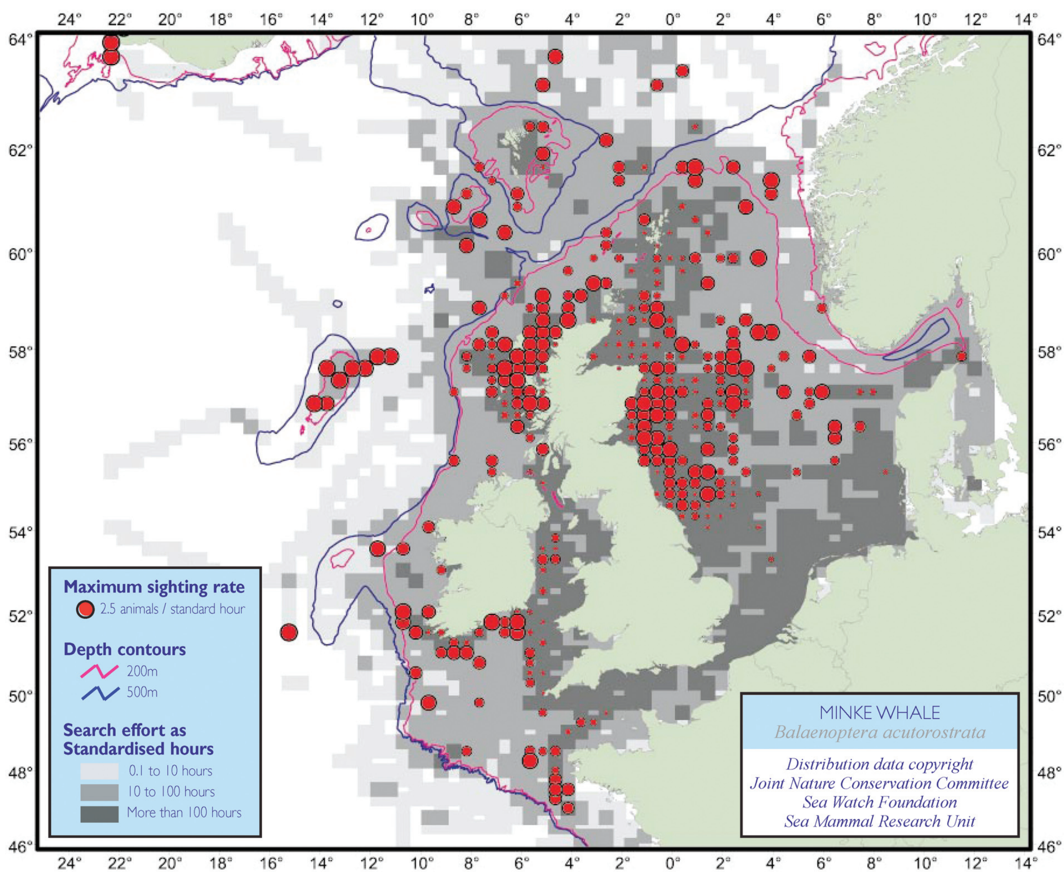

Figure 32. Distribution of minke whale sightings around the UK (taken from Reid et al., 2003; Crown Copyright)

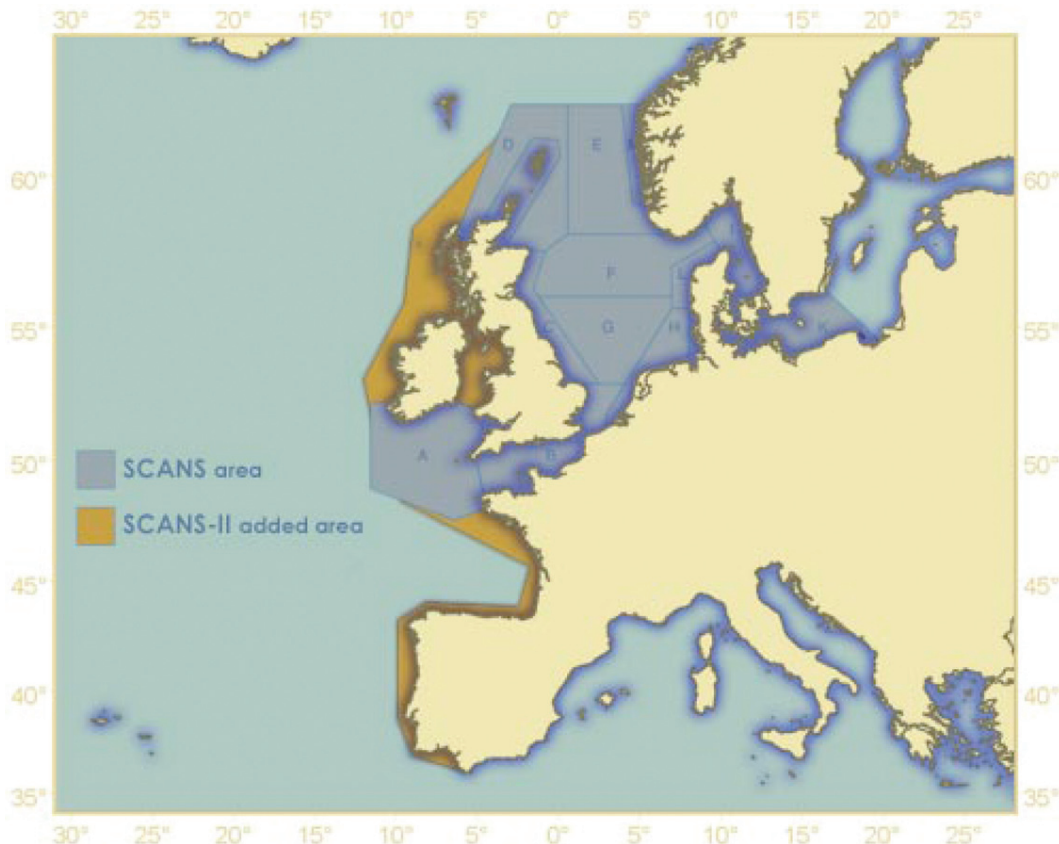

Figure 33. SCANS and SCANS-II areas (taken from ICES, 2007)

However, interest in possible southward shifts in porpoises (see Hammond, 2006b) lead us also to investigate Block B (far south of North Sea and Channel, which is of interest due to the southern North Sea area). Changes to SCANS survey blocks for SCANS II in 2005 mean we also have to incorporate Block H (coastal German waters) to enable comparisons to be drawn between results.

Table 13 gives the estimated abundances and absolute densities for these areas. The SCANS survey was repeated in 2005 (Hammond, 2006a) and, although the blocks were not labelled in the same way (see Hammond et al., 2002; Hammond, 2006a; Figure 33), comparable areas were surveyed. Approximately, 250,000 and 230,000 animals were estimated for the North Sea and English Channel in the 1994 and 2005 surveys, respectively (Hammond, 2006a). When separating out areas of interest (the North Sea, south of the Moray Firth, and, consequently, the English Channel due to the survey block), the corresponding estimates were 152,106 in 1994 and approximately 180,000 in 2005, indicating an overall increase in the number of harbour porpoises in this area, in particular in numbers of harbour porpoises in Block B, which was estimated at zero in 1994 and > 40,000 in 2005. This might identify a southward shift in distribution of harbour porpoises, which is reflected in the density plots (Figure 34).

Demographic Variables

Lockyer & Kinze (2003) examined the age structure of about 1,645 stranded and by-caught harbour porpoises from Danish waters. With movements of animals between these waters and the North Sea, it is likely that the reported age frequency distributions provide a good estimate of that seen in the North Sea animals. It was found that mortality in the first year was very high, with a greater decline seen in males. Longevity was 22 to 23 y regardless of sex, with less than 5% of animals living beyond 12 y. The maximum observed age was 24 y (Lockyer, 2003; Lockyer & Kinze, 2003).

From studies of directly caught, by-caught, and stranded animals in the North Atlantic, Lockyer & Kinze (2003) found that the sex ratio is biased towards males (see, also, Lockyer, 2003). It is possible that sexes are seasonally segregated,

Table 13. SCANS I and II survey results by area for harbour porpoise (for 1994 and 2005 [ship], the 95% CIs were calculated by the authors based on CV; for 2005 [aerial], 95% CIs as given) (data from Hammond et al., 2002; Hammond 2006a; see also Burt et al., 2006a, 2006b, 2006c)

Survey year	Survey block	Animal abundance (CV)	95% CI for abundance	Animal density (animals km²)
1994	B (far south and Channel)	0.000		0.000
1994	H (German coast)	4,211 (0.29)	1,769-6,653	0.095
1994	C (coastal waters east UK)	16,939 (0.18)	10,841-23,037	0.387
1994	G (south-central NS)	38,616 (0.34)	12,357-64,875	0.340
1994	F (north-central NS)	92,340 (0.25)	46,170-138,510	0.776
		Total = 152,106		
2005	B (far south and Channel) (aerial)	40,927 (0.38)	19,192-84,607	0.330
2005	H (German coast) (aerial)	3,891 (0.38)	1,599-9,160	0.334
2005	U (southern NS) (ship)	88,943 (0.23)	47,574-128,626	0.562
2005	V (northern NS) (ship)	47,131 (0.37)	12,246-81,954	0.294
		Total = 180,892		

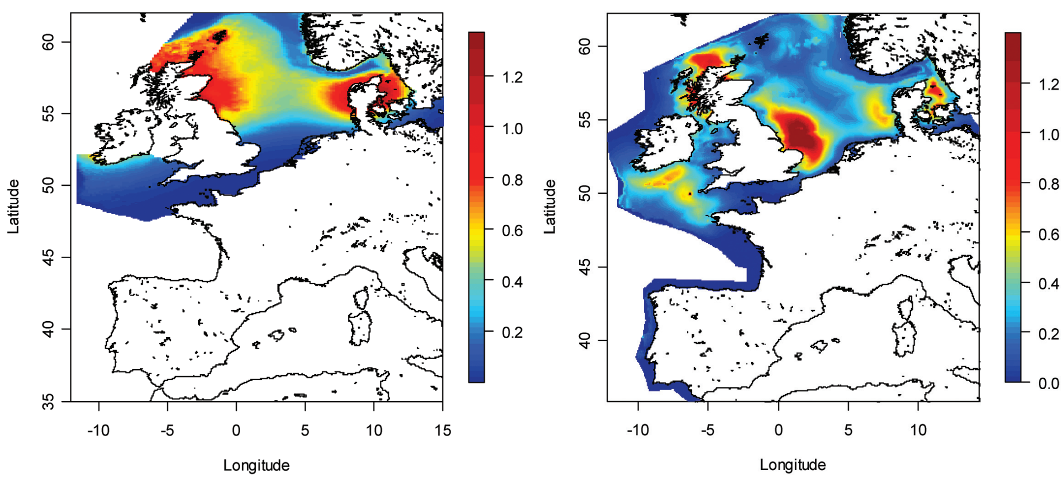

Figure 34. Density surface of harbour porpoise abundance (animals/km²) from the SCANS 1994 (left frame) and SCANS II 2005 (right frame), which highlights the southern shift of harbour porpoises to the southeast UK coast (taken from Hammond, 2007) (Permission granted by St Andrews University)

with males more present in areas of higher fishing operations (Lockyer & Kinze, 2003).

Migrations/Seasonality
Northridge et al. (1995) reported that, at the start of the year, harbour porpoises in the North Sea formed two major groupings: one to the west of Denmark in the eastern North Sea, and another, more scattered, in the deeper waters of the northwestern North Sea. During the second quarter, especially in May and June, the main area of distribution is from Yorkshire to the Shetlands along the western North Sea margin, where animals are possibly joined for the calving season by animals from the eastern North Sea and those from farther north; during this time, the sighting rate increases but is superseded by sightings in the third quarter that extend over most of the North Sea north of 55°N (Northridge et al., 1995). Given the reported southern shift in distributions (see Hammond, 2006b), this information has to be reviewed to incorporate recent trends.

The hypothesis that harbour porpoises breed close to the coast has been considered within ASCOBANS (2006) who believed that, despite the high probability of mixing in the middle of the North Sea, harbour porpoises could be associated with separate breeding areas near the coast.

Such a division in subpopulations may be created by philopatric behaviour of females (Andersen, 2003). Siebert et al. (2006) found evidence for a strong seasonality of harbour porpoise occurrence in some regions off the German coast, with the highest numbers being seen during summer months. Scheidat et al. (2004a) also found that, during summer, harbour porpoises did not distribute uniformly, with the highest densities found off northern Frisia close to the Danish border.

Population Trends

At first sight, the results from the SCANS I and II surveys indicate that harbour porpoise population size in the North Sea has remained largely unchanged between 1994 and 2005. When the larger SCANS survey area is split between north and south, it appears that harbour porpoise distribution has undergone a southward shift, with a two-fold increase in the number of porpoises in the southern North Sea strata (from 102,000 to 215,000) while harbour porpoise numbers in the northern North Sea strata are halved (from 239,000 to 120,000; Hammond, 2007). Studies using mainly stranding data and marine mammal observations from seabird surveys indicate an increase of harbour porpoises in the southern North Sea, most notably along the Dutch and Belgian coast (Camphuysen, 1994, 2005; Witte et al., 1998; Haelters et al., 2004). However, this research provided no estimates for the absolute densities of harbour porpoises. The results of a systematic and quantitative aerial line transect study in an area off East Frisia, southern North Sea, by Thomsen et al. (2006a) support this trend. It is unlikely, however, that this trend is explained by a resurgence of a "local population." First, it is still debatable whether a separate subpopulation exists in the southern North Sea (Andersen, 2003). Second, the annual increase of 40.0% in sighting-rates observed by Camphuysen (2005) far exceeds the maximum potential rate of a 10% increase for the species (Stenson, 2003; Camphuysen, 2005). It is therefore likely that the reappearance of harbour porpoises in the southern North Sea might result from a recruitment of harbour porpoises from other areas, which might, in turn, be caused by environmental factors such as the reduced local availability of prey (Camphuysen, 2005; for findings in the central North Sea, see Thomsen et al., 2007).

E. Documented Response of Harbour Porpoises to E&P Sound

We have discussed some of the implications with regards to potential effects of E&P sound on harbour porpoises briefly in Chapter 2. Due to their very wide hearing range, harbour porpoises could be affected by E&P sound in various ways, which are outlined in Table 17. Direct masking of biologically relevant signals by E&P sounds might not be an important issue for harbour porpoises as their click signals, used for echolocation (Au et al., 1999) and also potentially for communication (Clausen et al., 2010), are in the ultrasonic range (main frequency, 110 to 140 kHz) (Au et al., 1999) where E&P sound has little energy. However, E&P sound might mask other biological or nonbiological sounds that could be of relevance for harbour porpoises, and we have therefore included masking as a potential effect. Stone & Tasker (2006) studied seismic survey effects on cetaceans and found that, between 1998 and 2000, 37 sightings of harbour porpoises occurred (111 individuals), and they were found to remain farther from the source when it was active; their orientation was also affected. Although harbour porpoises showed some avoidance to sound sources associated with the industry, the species does not appear to have shifted its distribution permanently out of areas of intensive activity. In fact, the southwards shift in distribution that they have exhibited actually showed more animals closer to areas of higher E&P activity than was the case in 1994. In a recent experiment, Lucke et al. (2009) exposed a harbour porpoise to sounds from a single airgun. They found that at 4 kHz, the TTS criterion at received levels of 200 dB re 1 µPa (peak) and a sound exposure level of 164 dB re 1 $\mu Pa^2 \cdot s$ was exceeded. These levels are lower than those reported for other toothed whales so far and indicate much larger zones of TTS around a seismic airgun than those that can be inferred from experiments on other species, at least for this individual (overview in Southall et al., 2007). The animal also consistently showed aversive behavioural reactions at received SPLs above 174 db re 1 µPa (peak-to-peak) or a SEL of 145 dB re 1 $\mu Pa^2 \cdot s$ (Lucke et al., 2009), although these observations could be regarded as qualitative.

F. Other Factors Potentially Affecting Harbour Porpoises

Harbour porpoise health may be indirectly affected by changes in the quality of their habitat due to human activities such as the discharge of contaminants, shipping, hydrocarbon exploration and production, sewage discharge, construction, aquaculture, mineral extraction, recreational activities, competition for prey by fisheries, and military use (Table 14 & ASCOBANS, 2006). Data on human activities suggest that harbour porpoises from the central and southern North Sea are more at risk and exposed to higher levels of these activities than those in the northern North Sea (Table 14).

Fisheries

Almost all fishing gear and, in particular, gill and tangle nets, bear the risk of incidental entanglement of harbour porpoises (ASCOBANS, 2006). ASCOBANS (2006) and Stenson (2003) have reviewed the incidental catches in the North Sea for the period 1980 to 2001 (Table 15).

Table 14. Approximate distribution and scale of human uses in the North Sea in relation to the harbour porpoise subpopulations

	Northern North Sea	Central and southern North Sea
Fishing	+++	+++
Contaminant discharge	+	++
Shipping	+	+++
Hydrocarbon exploration	+++	+++
Sewage discharge	+	+++
Construction	+	+++
Aquaculture	++	+
Mineral extraction		++
Recreation	+	+++
Military	+	+

+++ = major use, ++ = medium use, + = minor use (adapted from ASCOBANS, 2006)

Based on earlier suggestions by the International Whaling Commission and ASCOBANS (2000), the OSPAR[12] commission adopted an Ecological Quality Objective (EcoQO) stating that the annual by-catch of harbour porpoises should be reduced to below 1.7% of the best population estimate. This objective aims to reduce by-catch to a level that would allow the population to recover to at least 80.0% of the ecosystem's long-term carrying capacity (see OSPAR, 2005). As can be seen in Table 15, the total known by-catch in the central and southern North Sea was high, potentially exceeding this level in the years up to 2001 (see also Stenson, 2003). The high numbers of by-catch led to the adoption by the European Union (EU) of a regulatory measure concerning incidental catches (EC 812/2004) to alleviate the problem (ASCOBANS, 2006). This regulation includes requirements for monitoring by-catch as well as taking measures to reduce by-catch in certain fisheries (see OSPAR, 2005).

One way to mitigate by-catch is to use acoustic harassment devices (pingers) that scare harbour porpoises away from nets (for a review, see OSPAR, 2009); these devices are mandatory in some sectors of the Danish North Sea. In addition, fishing effort in the Danish and UK set net fisheries has decreased since the mid-1990s, leading to reduced by-catch rates (Stenson, 2003). Still, exact rates of by-catch are difficult to assess at present—not least due to problems with reporting and monitoring (for details, see ICES, 2009, 2010). OSPAR (2005) concludes that the EcoQO is probably not being met in the east-central North Sea (see also OSPAR, 2010). Applying the 80.0% criterion, Hammond (2006a) calculated examples of by-catch limits based on the SCANS II data for two management procedures (Potential Biological Removal [PBR] and Catch-Limit-Algorithm [CLA], developed by the IWC) that were tuned according to different scenarios. For the southern North Sea example, by-catch limits are 1,127 and 2,124, respectively.

Shipping

The predominant effect of shipping on harbour porpoises is the sound that emanates from the ship's propellers, machinery, the hull's passage through the water, and the use of sonar; this sound generated by a vessel may impede communication between individuals[13] and cause behavioural and distributional changes (ASCOBANS, 2006). Yet, results on the effects of shipping are equivocal. Herr et al. (2005), comparing vessel traffic density and harbour porpoise sightings in the German North Sea, found that neither ships nor harbour porpoises were evenly distributed, with a concentration of ships in the southeast and harbour porpoises in the northwest of the region. They described a negative correlation between both and concluded that harbour porpoises were avoiding areas with dense vessel traffic. However, the authors do point out that the survey grid had a large number of blank values, which may not permit a full interpretation of the data. The establishment of a cause-effect relationship, identified by the authors on the basis of correlations, seems speculative.[14] Evans (2003)

[12] OSPAR is the Convention for the Protection of the Marine Environment of the North-East Atlantic. It combines and updates the 1972 Oslo Convention on dumping waste at sea and the 1974 Paris Convention on land-based sources of marine pollution.

[13] However, the use of low frequencies at or below 2 kHz for communication in harbour porpoises remains speculative (see Thomsen et al., 2006b; Hansen et al., 2008). Recent investigations indicate that high-frequency clicks are used in communication (Clausen et al., 2010).

[14] For example, it is well known that the major shipping lanes in German waters are outside high-density areas of harbour porpoises; yet, it is completely unknown if both are related in any way. Harbour porpoises seem to target areas of northern Frisia in spring and summer, probably due to favourable conditions and not because they would avoid busy shipping lanes (for distribution in German waters, see Scheidat et al., 2004a; for habitat modelling, see Skov & Thomsen, 2008).

Table 15. Incidental catches of harbour porpoises in the North Sea from Stenson (2003) and ASCOBANS (2006) (extrapolated from by-catch rates determined from observers 1987 to 2001); first estimate is based on fleet effort, and the second is based on landings as used by Vinther (1999). For detailed references, see Stenson (2003).

Year	Catch	Country	Estimation method
1980-1981	91	Denmark	Collections
1986-1989	105	Denmark	Collections
1986-1989	< 5/y	Netherlands	Reports
1990-1995	66	UK	Collections
1990-1994	23	Germany	Collections
1994-1998	6,785/y	Denmark	Observer program
1987	5,322/6,630	Denmark	Observer program
1988	5,938/6,727	Denmark	Observer program
1989	4,973/5,230	Denmark	Observer program
1990	5,191/5,257	Denmark	Observer program
1991	6,312/6,573	Denmark	Observer program
1992	6,543/7,099	Denmark	Observer program
1993	6,709/7,421	Denmark	Observer program
1994	7,366/7,566	Denmark	Observer program
1995	6,737/7,308	Denmark	Observer program
1996	5,991/6,762	Denmark	Observer program
1997	5,308/5,731	Denmark	Observer program
1998	5,206/4,974	Denmark	Observer program
1999	4,227/3,840	Denmark	Observer program
2000	4,149/3,266	Denmark	Observer program
2001	3,887/2,867	Denmark	Observer program
1995	818	UK	Observer program
1996	624	UK	Observer program
1997	627	UK	Observer program
1998	490	UK	Observer program
1999	436	UK	Observer program
2002-2003	25-30 (annual estimate)	Germany	Observer program
2004	7	Belgium	Strandings
2004	3-10	Belgium	Strandings
2003-2004	100 (annual estimate)	Netherlands	Strandings
1990-2001	17	Germany	Strandings

reported avoidance of oncoming vessels by harbour porpoises in the Shetland Isles. It was found that harbour porpoises were more likely to respond negatively to speedboats and large ferries, both of which they experienced only infrequently, compared with sailing boats and smaller ferries, with some habituation occurring later in the summer season. They were also more likely to respond negatively when occurring singly or as adult-calf pairs as opposed to when in groups. Avoidance of ships by harbour porpoises to a distance of up to 1 km has been observed by Palka & Hammond (2001).

Dolman et al. (2006) indicated that ship strikes of harbour porpoises occurred in the North Sea, yet no exact numbers were given. Nonfatal propeller cuts have been identified on harbour porpoises (Evans, 2003). In addition, Evans highlights that harbour porpoises could be at risk from frequent high-speed ferry crossings in the North Sea.

Pollution

Harbour porpoises are top predators with a limited capacity for metabolism and elimination of organohalogen contaminants and can accumulate high blubber concentrations of these persistent and lipophilic compounds from their diet (Law et al., 2008, 2010a, 2010b). In addition, the major part of a mother's body burden of these compounds are transferred to her calf during parturition and (particularly) lactation (Borrell & Aguilar, 2005). Within the UK marine mammal stranding programme, possible associations between contaminant concentrations in tissues and infectious disease mortality were investigated; statistically significant associations were found for elevated levels of PCBs in blubber and mercury in liver (Jepson et al., 1999; Bennett et al., 2001; Law et al., 2002). Mercury contamination also has been reported by Siebert et al. (1999). They found that harbour porpoises from the German North Sea were carrying a significant burden of mercury, while those from the Baltic had lower levels. Higher loads of mercury were associated with a higher prevalence of parasitic infection and the incidence of certain pathological diseases such as pneumonia.

Further studies of contaminants found in stranded harbour porpoises by Law & Whinnett (1992) and Law et al. (2006b) have confirmed the susceptibility of harbour porpoises to environmental contaminants, with low level but detectable concentrations of 2 to 4 ring polycyclic aromatic hydrocarbons (PAH) being found in muscle tissue and elevated levels of a range of flame retardant compounds in blubber. Law et al. (2006a) investigated the levels of brominated flame retardants in the blubber of stranded harbour porpoises from the UK. Hexabromocyclododecane (HBCD) dominated and was detected in all samples, and the maximum concentration was about double that reported in earlier UK studies; this may be a result of changing patterns of use of HBCD following limitations on the production and use of two polybrominated diphenyl ether (PBDE) products (the penta- and octa-mix formulations) within the EU (see Law et al., 2008).

Bull et al. (2006) explored the relationship between parasitic load (nematodes) and contaminant burdens in harbour porpoises stranded on UK coasts using a 15-y dataset. A positive association between 25 PCBs and cardiac stomach nematodes was observed, and PCB-related immunosuppression was discussed as one possible explanation; there was evidence to suggest a threshold concentration level for the sum of 25 PCB congeners beyond which cardiac stomach nematodes become significantly more abundant.

Many international instruments and regulations (e.g., OSPAR, Water Framework Directive, MARPOL [International Convention for the Prevention of Pollution from Ships]) aim to reduce or eliminate the discharge of contaminants (ASCOBANS, 2006), which may reduce the levels of contaminant discharge in the future. It is the contaminants already in the environment that pose a threat to harbour porpoises given the properties that allow these chemicals to accumulate and remain in the sediment and also in the food chain for many decades.

Environmental Changes

It is difficult to assess whether food depletion due to changes in environmental conditions might affect harbour porpoise distribution in the North Sea. Harbour porpoises have been reported to be opportunistic feeders; for example, Lockyer et al. (2003) and Vikingsson et al. (2003) found more than 40 prey taxa in stomachs of Icelandic harbour porpoises. Diet composition may be dependent on local availability and abundance of prey, which is likely to vary between regions and seasons. For instance, Lockyer & Kinze (2003) found some dietary differences between harbour porpoises from the North Sea and inner Danish waters, and considerable seasonal variations in the diet of harbour porpoises off Iceland have been identified (Vikingsson et al., 2003). Even though a wide range of species has been recorded in their diet, harbour porpoises tend to prefer two to four main species (e.g. whiting [*Merlangius merlangus*] and sandeels [Ammodytidae] in Scottish waters) (Santos & Pierce, 2003). Literature on harbour porpoise diets in the northeast Atlantic suggests that a long-term shift from predation on clupeid fish (mainly herring) to predation on sandeels and gadoid fish (e.g., whiting in Scottish waters) is possibly related to the decline in herring stocks since the mid-1960s (Santos & Pierce, 2003).

It is evident that harbour porpoises are opportunistic foragers, which indicates that they might quickly adapt to changes in prey abundance. On the other hand, not all prey is of equal energetic value, and harbour porpoises have a seasonally fluctuating, but overall very high, metabolism, resulting in the more or less constant need for sufficient and nutritious food (Kastelein et al., 1997). MacLeod et al. (2007b) investigated stomach contents from stranded harbour porpoises in Scottish waters and found substantially smaller proportions of sandeels in 2002 to 2003 when compared to a baseline period (1993 to 2001). They also reported an increase in the proportion of animals that died due to starvation (1993 to 2001: 5%; 2002 to 2003: 33%); the sample size for the latter period was relatively small (16 individuals, compared to 51 animals from 1993 to 2001), and details on how starvation was identified were not given. However, the study indicates that porpoises might be susceptible to changes in food abundance in some regions, including the UK east coast. Consequently, the shift of harbour porpoises from the northern to the southern North Sea has been linked to changes in prey abundance (Camphuysen, 2005; Thomsen et al., 2006a).

Marine Construction and Industrial Activities

Pile driving is used in harbour works, bridge construction, E&P platform installations, and in construction of offshore wind farm foundations. Most recent published work has concerned this last activity. Source levels vary depending on a variety of factors (e.g., sediment properties, water depth, hammer energy, pile dimensions) and the method of pile driving (impact or vibro-piling; Table 16). The frequency spectrum ranges from less than

Table 16. Overview of some studies measuring sound from impact pile driving

Activity	Pile-driving method	Measurement	Reported sound pressure levels	Source
Construction of aviation fuel receiving facility	Impact pile-driving	dB rms at various distances from source	> 170 dB re 1 μPa (rms) at 250 m	Würsig et al., 2000
Offshore wind farm construction	Impact pile-driving Ø = 3 m	SEL at various distances in Sweden	~ > 200 dB re 1 $\mu Pa^2 s$ (at 1 m)	McKenzie-Maxon, 2000
Oakland Bay Bridge construction	Impact pile-driving	dB peak and rms at various distances from source	185-196 dB re 1 μPa (rms) at 100 m 197-207 dB re 1 μPa (peak to peak)	Caltrans, 2001
Offshore wind farm construction	Impact pile-driving Ø = 1.5 m	dB zero peak and SEL at various distances in German North Sea	228 dB re 1 μPa (zero to peak at 1 m)	Thomsen et al., 2006b
Offshore wind farm construction	Impact pile-driving Ø = 4.0-4.7 m	dB peak to peak at various distances and four different sites in the UK	243-257 dB re 1 μPa (peak to peak at 1 m)	Nedwell et al., 2007

20 Hz to more than 20 kHz, with most energy around 100 to 200 Hz (for overviews, see Nedwell et al., 2003, 2004; Madsen et al., 2006b; Thomsen et al., 2006b; OSPAR, 2009; Bailey et al., 2010).

The southern North Sea and adjacent waters, of which the UK east coast is part, is a centre for offshore wind farm development in European waters. A very detailed account of offshore wind farm developments and plans can be found in OSPAR (2008). According to OSPAR, there were 13 offshore wind farms operational in the North Sea and adjacent waters as of February 2008, with a cumulative size of 800 km^2. At that time there were a further 28 and 42 projects authorised and applied for respectively (total number of turbines ~5,600). Recently, developments have been intensified with 14 wind farms operational in the southern North Sea alone (for most recent updates, see http://rave.iset.uni-kassel.de/rave/pages/map and www.thecrownestate.co.uk/70_interactive_maps_marine.htm). Most existing offshore wind farms are coastal; however, many license applications—for example, in the German EEZ—are much further offshore (OSPAR, 2008). Of particular relevance for investigating the impacts of offshore wind farms on harbour porpoises are the results of the recent empirical studies by Tougaard et al. (2003b), Tougaard et al. (2005), and Carstensen et al. (2006) during construction of offshore wind farms at Horns Reef (North Sea) and Nysted (Baltic). At Horns Reef, acoustic activity of harbour porpoises decreased shortly after each ramming event and went back to baseline conditions after 3 to 4 h. This effect was not only observed in the direct vicinity of the construction site but also at monitoring stations approximately 15 km away, indicating that harbour porpoises either decreased their acoustic activity or left the area during ramming periods (Tougaard et al., 2003b). It was also found that densities of harbour porpoises in the entire reef area during ramming were significantly lower than during baseline conditions. During ramming, harbour porpoises exhibited more directional swimming patterns compared to observations obtained on days without construction, when more nondirectional swimming patterns were observed. This effect was found at distances of more than 11 km and possibly up to 15 km from the construction site (Tougaard et al., 2003a). Similar effects were found during the construction (combination of pile driving and vibro-piling) of the Nysted offshore wind farm. There was no return to baseline levels after construction was completed (Tougaard et al., 2005; Carstensen et al., 2006); however, since the abundance of harbour porpoises was low from the start, this finding might be incidental and is difficult to attribute to the construction activity (Tougaard et al., 2005). Furthermore, both studies should be interpreted with caution as there was no documentation of received levels and there were also other methodological limitations (see discussions in Thomsen et al., 2006b; OSPAR, 2009). Future investigations, modelling, or measuring of received SPLs should give a better understanding of the effects of pile-driving sound on harbour porpoises. Very recently, Brandt et al. (2011) found indications for avoidance response in harbour porpoises due to pile driving at a mean distance up to 17 km. At a distance of 2.6 km, acoustic activity of harbour porpoises stayed below normal levels for 24 to 72 h after pile driving. In contrast, measurements obtained during the operation of offshore wind farms show much lower sound levels than during construction, with little turbine sound detectable by a hydrophone at distances beyond the wind farm site in many cases (Madsen et al., 2006a; Thomsen et al., 2006b; Nedwell et al., 2007; Tougaard et al., 2009). Effects on harbour porpoises might only be short range behavioural responses, if any (Koschinski et al., 2003; Lucke et al., 2007b; Tougaard & Henriksen, 2009).

Mineral extraction is restricted to relatively small areas in the North Sea; however, in the central and southern North Sea—for example, off the coast of Suffolk and Norfolk—it is conducted to some extent. Therefore, this activity will intersect with harbour porpoise distribution. The main concern from this activity is the removal of the top layer of the seabed that may affect habitat for prey species (e.g., sandeels) of harbour porpoises (ASCOBANS, 2006) and minke whales in the North Sea. Another concern is the underwater sound emitted during dredging, but studies so far show lower source SPLs compared to other activities (see Department of Energy, Food, and Rural Affairs [Defra], 2003; Thomsen et al., 2009), suggesting that behavioural disturbance will be limited to close or medium ranges.

High-Frequency Sonar (Military, Fish Finders)

Military high-frequency sonar used in shallow waters like the North Sea in offensive or defensive systems is potentially not as harmful as mid- or low-frequency sonar due to the rapid absorption of higher frequencies; disturbance to harbour porpoises might be reduced by the use of monitoring systems and other mitigation measures (see ICES-AGISC, 2005; ASCOBANS, 2006). In addition, military high-frequency sonar usage is generally restricted to more or less confined exercise areas (ICES-AGISC, 2005). As high-frequency cetaceans (see Southall et al., 2007), harbour porpoises might be susceptible to high-frequency sonar; however, the supposedly limited application could reduce overall impact.

Fish finders, which are used in commercial and recreational fisheries, operate typically between 24 and 200 kHz, which overlaps with the hearing range of harbour porpoises (upper limit of audiogram 160 kHz; see Kastelein et al., 2002). However, the power signal is comparatively low, the beam relatively narrow, and pulses are rather short, indicating that effects on harbour porpoises might be moderate (ICES-AGISC, 2005). The very wide application of fish finders in the North Sea throughout the year might lead to a closer look at potential impacts in the near future (see, also, Tasker et al., 2010).

G. Pressure Assessment and Conclusions for Harbour Porpoises

As shown in Table 17, harbour porpoises off the UK east coast are exposed to a wide variety of pressures that could lead to a number of effects. The area is characterised by mostly high activity levels (exploration and production, fisheries, shipping, sand and gravel extraction), and the emerging offshore wind farm industry could lead to additional pressure. Effects due to the various pressures have been documented in some cases (e.g., mortality due to by-catch, behavioural response to sound during offshore wind farm construction); in other cases, evidence is sparse or lacking. It is clear, however, that a number of activities could impact the population off the UK east coast.

H. Conclusions

The North Sea houses a large amount of E&P industry activity, with the southern North Sea being the area of greatest increase. The North Sea has a large amount of seismic surveying, too. For harbour porpoises, results from large-scale surveys could not find significant changes in abundance between 1994 and 2005, which could be attributed to the very high variability in abundance estimates. Numbers of harbour porpoises in the southern North Sea have doubled in 2005 compared with 1994, most likely due to a shift in distribution for animals from the north which, in turn, might have been caused by shifts in prey distribution. By-catch numbers have decreased recently, possibly as a result of declines in commercial fisheries, improvements in nets, and mitigation measures. The overview of pressures indicates that a variety of human activities impact individuals, yet effects on populations are difficult to discern.

I. Minke Whale Stock Assessment

Population Structure

In 1977, the IWC split the North Atlantic minke whale population into four areas for management purposes. The British Isles' minke whales were grouped with the minke whales of Svalbard and Norway and were named the northeastern stock; however, the information supporting these divisions was thought to be weak even for management purposes (Horwood, 1990). More recent data from genetic, mark-recapture, and other identification studies tend to support these divisions (NAMMCO, 2008). Genetic studies indicate that the west Greenland and central Atlantic minke whales do not belong to the same stock as the northeastern Atlantic minke whales (NAMMCO, 1999). Mark-recapture analyses of animals tagged in the central and northeast Atlantic stock areas show little evidence of mixing between these two areas (IWC, 1991). This northeastern stock area is larger

Table 17. Overview of human pressures on harbour porpoises off the UK east coast and an estimate on relative levels of activities and type and scale of potential effects on marine life

Activity	Pressure	Activity level	Potential impacts	Comments	Uncertainty
E&P industry: Exploration	Vessel sound Airgun array sound	+++	Vessel: masking, behavioural response (long); Airgun: PTS (short), TTS (short), behavioural response (long)	One field study shows short-term behavioural reactions to seismic surveys but no long-term trends; TTS in one animal at relatively low sound levels	Medium
E&P industry: Construction	Pile driving Vessel sound	+	Pile driving: PTS (short), TTS (short), behavioural response (long); Vessel: masking, behavioural response (long)	No studies on E&P construction, but data on pile driving impacts for offshore wind farms indicates short-term avoidance	High
E&P industry: Production	Drilling sound Drillship sound	+++	Drilling and drillship: masking, behavioural response (short)	No studies	High
Fisheries	Vessel sound Fishing operations (nets), driftnets Competition	+++	Vessel: masking, behavioural response (long); Fishing operations: death, injury due to entanglement (short); Food depletion (long)	Extensive studies on by-catch but difficulties in reporting post-2001	High
Shipping	Ship sound Ship strikes	+++	Ship: masking, behavioural response (long); Ship strikes: injury, death (short)	Individuals are known to avoid ships; results on large-scale avoidance at shipping lanes equivocal; ship strikes possible	High
Various activities	Pollution	++	Physiological effects (long)	Good information status on contaminant levels; little information on effects	High
Various activities	Environmental changes	++	Short- and long-term changes to habitat conditions with range of consequences (long)	Effects speculative as of yet	High
Sand and gravel extraction	Dredger sound Vessel sound	+++	Dredger and vessel: masking, behavioural response (long)	No information on effects	High
Offshore wind farm construction	Pile driving Vessel sound	++	Pile driving: PTS (short), TTS (short), behavioural response (long); Vessel: masking, behavioural response (long)	Field studies indicate large-scale and short-term avoidance	Medium
Offshore wind farm operation	Operational sound Maintenance vessels	+	Operation: masking, behavioural response (short); Vessel: masking, behavioural response (long)	Sound measurements suggest only short-range effects from operational wind farms, if any	Medium
Sonar (military, private, research)	Vessel sound Sonar ping	*	Vessel: masking, behavioural response (long); Sonar: PTS (short), TTS (short), behavioural response (long)	Little information on activities; no information on effects	High

+ = low level of activity, ++ = medium level of activity, +++ = high level of activity; spatial scale of effects: short = in close vicinity of the activity or area activity is carried out, long = beyond the activity area (depending on species and activity); * = insufficient data for a firm assessment

than we are concerned with for this case study, so abundance estimates of these large, geographically diverse stocks make it difficult to infer any real population estimates for minke whales for the North Sea.

Population Size, Demographic Variables, and Trends
The 1989 NASS surveys yielded abundance estimates for minke whales in the northeastern stock area of 67,380 (95% CI: 46,572 to 97,485; Schweder et al., 1997). The NASS survey of 1995 repeated these estimates and numbers rose to 112,125 (95% CI: 91,498 to 137,401; NAMMCO, 1998b); however, because of the large variability, there was no statistically significant difference between the two estimates. Using the same blocks and regions of the North Sea designated earlier for harbour porpoise (see Figures 33a & 33b), the abundance estimates for minke whales obtained in the SCANS surveys (Hammond, 2006b) are shown in Table 18. Despite the numbers for this area appearing to be greater in 2005 than in 1994, the survey area for 2005 was also larger (1,370,000 km^2 compared to 1,040,000 km^2 in 1994). For the North Sea, the total estimate of minke whale abundance of 10,500 (2005) animals was not statistically significant from the figure of 7,300 obtained in 1994 (Table 18 & Figure 35; Hammond, 2007).

Walton (1997) believed that minke whales appear to be segregated by age/sex classes more than any other baleen whale. This segregation coupled with potential changes to age class structures due to whaling means that age classes are difficult to determine, and it also makes historic tables from whaling catches unreliable (e.g., see Horwood, 1990). For minke whales, much of the biological information comes from whaling records, which presents problems given that whalers often targeted one sex as a result of its size. Additionally, segregation of the sexes often meant biased catches of large numbers of one sex. Therefore, biological data derived from whaling records needs to be viewed with caution. The minke whale catch by month by Icelandic whalers (1974 to 1978) provides cautionary records along with the percentage of females in that catch (Table 19; Horwood, 1990). This trend is opposite to that observed in English catches, in which in September and October, the catch was mainly mature females (Table 19; Horwood, 1990).

Horwood (1990) found that estimates of average and age-specific mortality from whaling records were unreliable, but the best of these estimates was 0.13/y (using a geometric model and catch at age summed across a few earlier years). Further data indicated a natural mortality rate of about 10.0%/y. As there was inadequate evidence to argue for any age-specific trend in natural mortality rate, it is likely that juvenile mortality rates are higher than adult mortality rates, leading to relatively high overall values.

Table 18. SCANS I and II survey results by area for minke whales (for 1994 and 2005 [ship], the 95% CIs were calculated by the authors based on CV; for 2005 [aerial], 95% CIs as given) (data from Hammond et al., 2002; Hammond, 2006a; see also Burt et al., 2006a, 2006b, 2006c)

Survey year	Survey block	Animal abundance (CV)	95% CI for abundance	Animal density (animals km^2)
1994	B (far south and channel)	0	--	0
1994	H (German coast)	0	--	0
1994	C (coastal waters east UK)	1,073 (0.42)	172-1,974	0.0245
1994	G (southern central NS)	1,001 (0.70)	0-2,402	0.0088
1994	F (northern central NS)	1,354 (0.36)	379-2,329	0.0114
	Animal abundance total = 3,428			
2005	B, H, Y, and L (far south, Channel German and Danish coast) (aerial)	1,202 (0.96)	243-5,952	0.009
2005	U (southern NS) (ship)	3,519 (0.69)	0-9,378	0.022
2005	V (northern NS) (ship)	4,449 (0.45)	445-8,455	0.028
	Animal abundance total = 9,170			

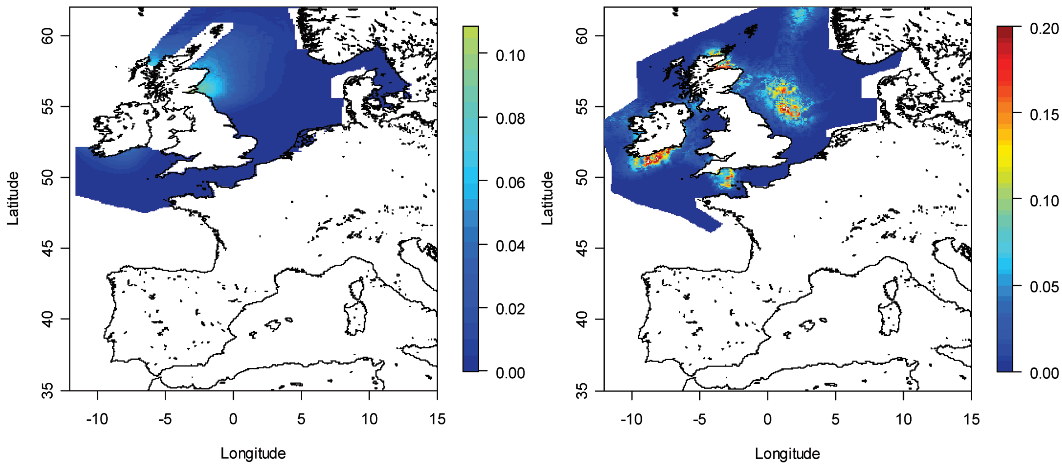

Figure 35. Density surface of minke whale abundance (animals/km^2) from the SCANS (left frame) and SCANS II (right frame) (taken from Hammond, 2007) (Permission granted by St Andrews University)

Table 19. Percentage of minke whales caught by month from Iceland, 1974 to 1978, and percentage of females in the catch (from Horwood, 1990)

	March	April	May	June	July	Aug	Sept	Oct	Nov
% of minke whales caught by month	1.6	8.2	10.8	14.9	30.3	18.5	10.5	4.5	0.6
% of females in the catch	76.9	65.2	58.2	54.3	41.6	38.4	34.3	44.4	66.7

Migrations/Seasonality

Northridge et al. (1995) reported minke whales to be rare in British waters during the first quarter of the year; but during the second quarter, they move into coastal waters off northeast England and the Hebrides and are then joined by more animals during the third quarter along with animals appearing off the east coast of Scotland. In the fourth quarter, there are still some minke whales present in the Hebrides and a few off the east coast of Scotland (Northridge et al., 1995). Weir et al. (2007) found that minke whales were sighted off the Aberdeenshire coast during the month of August only. In the outer Moray Firth (Scottish east coast), Robinson et al. (2007) found that from 2001 to 2006 (May-October), minke whales were recorded during all survey months, with peak occurrence during July and August. Further seasonal studies of minke whale distributions in the UK and adjacent waters were made by MacLeod et al. (2007a), who collated ferry sightings data for a number of regions. In the northern North Sea, data were available from April to September from 2002 to 2006. Sightings of minke whales increased from April to July before falling rapidly in August and September; however, in April to June, sightings were primarily in more open waters away from the coast, while in July to September, they were restricted to more coastal waters. The authors suggested that sightings fell in July and August as a result of minke whales moving into coastal waters where the ferry route does not run. These findings seem to support those of Robinson et al. (2007), with the movement of minke whales in summer months in this area.

Although results from surveys indicate that minke whales appear in some numbers off the east coast and that densities and abundance have increased between 1994 and 2005 in the wider North Sea, this is not statistically significant due to the high variability both in the SCANS I and II and the NASS data.

J. Documented Response of Minke Whales to E&P Industry Sound

According to Stone & Tasker (2006), minke whales did not exhibit behavioural response during seismic surveys. Sightings on 79 occasions (103 individuals) found no effects on the occurrence or behaviour of minke whales.

K. Other Factors Potentially Affecting Minke Whales

Whaling

Minke whales have historically been hunted in the wider North Sea and off the UK east coast (Horwood, 1990), and whaling continues off Norway and Iceland. From 1977 to 1982, the northeastern stock of minke whales had an annual quota of 1,790 placed upon it by the IWC (Table 20). No catch limit was agreed for 1983; for 1984, a quota of 635 was set to halt the decline and stabilise the stock. In 1986, the IWC gave it protected status with a zero catch limit; however, this was rejected by Norway (Table 20; Horwood, 1990).

Table 20. Catches of minke whales from northeastern stock by Norwegians, 1978-2006 (figures from www.nammco.no); post-1985 catches were made under the objection of the IWC, and catch figures from 1986 to 2006 courtesy of IWC (www.iwcoffice.org/_documents/table_objection.htm).

Year	Number of minke whales taken
1978	1,383
1979	1,786
1980	1,807
1981	1,771
1982	1,782
1983	1,688
1984	630
1985	634
1986 (86/87)	379
1987 (87/88)	373
1993	157
1994	206
1995	218
1996	388
1997	503
1998	625
1999	591
2000	487
2001	552
2002	634
2003	647
2004	544
2005	639
2006	545

Fishing

Minke whales are infrequently entangled in fishing gear (NAMMCO, 2008), with no reports from UK waters. Van Waerebeek & Reyes (1994) reported on the accidental fishing mortality of two minke whales in artisanal gill nets in 1991 off Peru. In the North Atlantic, minke whales consume mainly krill, herring, capelin (*Mallotus villosus*), sandeel, cod, polar cod (*Boreogadus saida*), and haddock, as well as other species of fish and invertebrates (NAMMCO, 1998a). Prey choice will vary spatially and temporally and is dependent upon availability. Many of these commercially important species have seen decreases in the North Sea in recent years, leading to potential adverse effects on minke whales.

Pierce et al. (2004) found that in the North Sea, sandeels comprised the principal prey item for minke whales, constituting approximately 70% by weight of their diet. In the Moray Firth, Robinson & Tetley (2007) hypothesised that schooling mackerel perform the role of compacting targeted sandeel prey into concentrated bait balls during summer, on which the minke whales forage. If this is the case, minke whales in this area might be reliant on mackerel being present, which could be affected by fisheries. It is possible that the absence of either of these fish species during the summer of 2004 was liable for the total absence of minke whale sightings that year.

Shipping

Evans (2003) reports that minke whales in the Hebrides exhibited little or no reaction after increased exposure to vessels. Also, a much greater number of whales seem to interact with whale watching vessels compared to when the industry started in the mid-1990s, which might be the result of habituation. Evans suggests that if high-speed ferries were introduced in the Hebrides or Northern Isles of Scotland, the minke whale in particular might be affected, and the same applies to routes crossing the northern North Sea.

Minke whales are infrequently struck by vessels (NAMMCO, 2008); however, there have been a number of such deaths reported in the literature, with most observations having anecdotal character (Dolman et al., 2006). From the UK, reports have been received of direct observation of collisions of ships with minke whales (Evans, 2003).

Pollution

There is no evidence that contaminants are presently affecting minke whales in the North Atlantic (NAMMCO, 2008); however, Kleivane & Skaare (1998), analysing blubber samples from 72 minke whales from the northeast Atlantic, found the following organochlorines to be present: (1) industrial chemicals/PCBs (polychlorinated biphenyls), (2) pesticide DDTs (dichlorodiphenyltrichloroethanes), (3) HCHs (hexachlorocyclohexanes), (4) HCB (hexachlorobenzene), and (5) CHLs (chlordanes). Interestingly, concentrations of three major pollutants varied with sex, and mature males had higher concentrations than mature females or juveniles. As suggested by the authors, this may be a consequence of geographic separation and changes in diet across years/areas.[15] Also, males cannot transfer any of their body burdens of lipophilic contaminants to offspring and so their burden continues to increase as they age. The findings of Kleivane & Skaare (1998) were supported by Hobbs et al. (2003) who analysed blubber from 155 minke whales from seven different regions of the North Atlantic, one of which was the North Sea. Minke whales from the North Sea did not have the highest concentrations of PCBs but did have higher loadings of more highly chlorinated PCBs and recalcitrant OC pesticides than animals from Greenland. However, general similarities in contaminant levels suggest that the minke whales are quite mobile and may feed in multiple areas within the northeastern Atlantic.

Marine Industrial Activities (Sand and Gravel Extraction; Offshore Wind Farm Construction and Operation)
Information on the distribution of these activities and the distribution of the species off the UK coast (e.g., Reid et al., 2003) suggest that individual minke whales could be exposed to impacts, mainly those associated with underwater sound. However, there is no information on effects as yet.

Sonars (Including Military)
Data reviewed by Evans (2003) suggest no avoidance responses of minke whales to a vessel throughout the time an EK 500 echo sounder was operating; whales were seen in close proximity, and none of them appeared to move away even when the vessel approached and passed the whales. However, no information on sound levels was given. Most echo sounders are of higher frequencies (mainly 38 kHz and higher; see Knudsen, 2009), and audiograms of minke whales are not available. Therefore, it is not clear if and how far minke whales could detect higher frequency sonar. In the Bahamas in 2000, two minke whales live stranded in the presence of 2.6 to 8.2 kHz active sonar sounds generated during military exercises (reviewed in ICES-AGISC, 2005). Both animals stranded at different places than the other species involved in the event and returned to deeper water. They were not reported to re-strand. Since no examinations on the animals were undertaken, the cause of the stranding is unknown, albeit strandings of minke whales in the Bahamas are unusual (Evans & England, 2001).

[15] Lower levels in females might also be related to the transfer of contaminants during lactation.

L. Pressure Assessment and Conclusions for Minke Whales

Table 21 indicates that pressures on minke whales are very similar to those on harbour porpoises but that the information on effects is much sparser. It can be assumed that a wide variety of activities could lead to effects on minke whales, but currently no statement on the nature and extent of these potential effects can be made.

M. Conclusions

Survey results seem to point towards an increase in numbers of minke whales in the North Atlantic, yet this trend is not significant due to high error margins. Localised fluctuations are most likely a result of changes in prey distribution. Minke whales remain the most abundant balaenopterid in the North Atlantic and may be approaching pre-exploitation levels (NAMMCO, 1999). There are a variety of human pressures that could lead to adverse impacts; however, there is almost no documentation on effects on individuals. If effects occur, these do not appear to have led to changes at the population level.

Table 21. Overview of human pressures on minke whales off the UK east coast and an estimate on relative levels of activities and type and scale of potential effects on marine life

Activity	Pressure	Activity level	Potential impacts	Comments	Uncertainty
E&P industry: Exploration	Vessel sound Airgun array sound	+++	Vessel: masking, behavioural response (long); Airgun: PTS (short), TTS (short), behavioural response (long)	One field study does not show behavioural reactions	High
E&P industry: Construction	Pile driving Vessel sound	+	Pile driving: PTS (short), TTS (short), behavioural response (long); Vessel: masking, behavioural response (long)	No studies	High
E&P industry: Production	Drilling sound Drillship sound	+++	Drilling and drillship: masking, behavioural response (short)	No studies	High
Fisheries	Vessel sound, Fishing operations (nets), driftnets Competition	+++	Vessel: masking, behavioural response (long); Fishing operations: death, injury due to entanglement (short); Food depletion (long)	No information on entanglement in fishing off the UK but there is for other regions	High
Shipping	Ship sound Ship strikes	+++	Ship: masking, behavioural response (long); Ship strikes: injury, death (short)	No studies	High
Various activities	Pollution	++	Physiological effects (long)	Some studies indicated presence of contaminates in blubber; no studies on effects	High
Various activities	Environmental changes	++	Short- and long-term changes to habitat conditions with range of consequences (long)	Effects speculative as of yet	High
Sand and gravel extraction	Dredger sound Vessel sound	+++	Dredger and vessel: masking, behavioural response (long)	No studies	High
Offshore wind farm construction	Pile driving Vessel sound	++	Pile driving: PTS (short), TTS (short), behavioural response (long); Vessel: masking, behavioural response (long)	No information effects	High
Offshore wind farm operation	Operational sound Maintenance vessels	+	Operation: masking, behavioural response (short); Vessel: masking, behavioural response (long)	Sound measurements suggest only short-range effects from operational wind farms, if any	High
Sonar (military, private, research)	Vessel sound Sonar ping	*	Vessel: masking, behavioural response (long); Sonar: PTS (short), TTS (short), behavioural response (long)	No information on activities; studies on effects are equivocal	High

+ = low level of activity, ++ = medium level of activity, +++ = high level of activity; spatial scale of effects: short = in close vicinity of the activity or area activity is carried out, long = beyond the activity area (depending on species and activity); * = insufficient data for a firm assessment

8. General Discussion

This investigation provided new insights into trends for selected cetacean stocks that are exposed to E&P industry sound and a variety of other anthropogenic pressures. In doing so, we were guided by a *conservation-level approach* by looking at population-level trends in relation to exposure to human impacts, although we also dealt with consequences on an individual level (for terms, see, e.g., Whitehead et al., 2000). In discussing population trends, we attempted to list the various pressures affecting stocks in the case studies. Here, we conclude findings by reflecting on the main outcomes.

A. The Overall Picture

It is apparent that there are large gaps in our understanding of the distribution and abundance of cetaceans in areas of high E&P industry activity. The data on long-term trends is only sufficient for areas off the northwestern European coast and off North America; but even in these areas, only a few stocks lend themselves to more detailed examination with regard to exposure to E&P industry sound. The lack of adequate data becomes especially apparent if we turn to areas off Africa, Indonesia, and South America. This is a serious gap as these areas are under increasing focus by the E&P industry for future exploitation (see Table 22 in the Appendix), and regulatory frameworks and mitigation measures are probably different from those in more "developed" areas. We have already mentioned that one important future research task should be a more comprehensive mapping of cetacean stocks worldwide, particularly off the west coast of Africa but also off Asia. This is also important if we consider that exposure to pressures can vary greatly across regions, making extrapolations on effects of human activities from one area to another challenging. Data must be of high temporal resolution, preferably spanning at least 10 y (Whitehead et al., 2000).

Another confounding factor in this analysis was the lack of open-access data on E&P platforms and even more so in the number of seismic surveys in almost all parts of the world. It was difficult to quantify the impact from seismic surveys. It should be in the interest of industry to provide data as needed to foster transparency and research on any potential impacts.

B. A Closer Look

In this study, we closely investigated the development of stocks/populations of seven cetacean species in different parts of the world that are heavily used by the E&P industry. This overview is far from providing a complete picture and should be viewed as a first step to outline major points that might be addressed in further investigations. As this paper was being prepared, other teams were also investigating cetacean stocks in various regions associated with the E&P industry. We chose different representative areas to avoid overlap, but this means that our selection is not representative of the whole status globally. We encourage further investigations to provide a more comprehensive view of the relationship between E&P industry and cetacean populations. One of the stocks that we have analysed indicated population growth (Californian humpback whales) and for the remaining six, no trends can be derived due to the high variability in the estimates.

Clearly, most cetacean abundance estimates are too imprecise to detect differences. This is an important argument that is often raised when studying potential impacts on population level trends in cetaceans. For example, Whitehead & Weilgart (2000) argue that looking at the published studies on cetacean distribution and abundance, CVs of more than 0.20 are too high to indicate population-level trends over the comparatively short periods over which most stock assessments are undertaken. This issue will be difficult to solve as the uncertainty in population abundance estimates is not just a measurement problem but at least partly an inherent problem in this type of assessment (see discussion in NRC, 2005, and Taylor et al., 2007). Looking at our case studies, uncertainties remain for all stocks investigated. For harbour porpoises, density surface modelling allowed for a comparison between surveys with no overall changes observed, but a significant shift in distribution from North to South (Hammond et al., 2002; Hammond, 2006a). It is true that SCANS I and II only provided snapshots; however, there is confirmation of a distributional shift in the North Sea porpoises by smaller scale investigations that allowed for statistical comparisons between surveys (Thomsen et al., 2006a, 2007). But again, the statement that no overall change in the population has occurred between 1994 and 2005 might be misinterpreted given that under a worst-case scenario, by-catch numbers were approximately 3,000 to 4,000 individuals/y between 1994 and 2005; the resulting 36,000 to 48,000 extra mortalities might have led to an overall decrease of the population of < 10% and might not be identified due to high statistical variability.

A way to reduce the uncertainty in assessing trends in cetacean populations would be to increase monitoring effort (see suggestions by

Taylor et al., 2007), perhaps allowing for shorter survey intervals and a higher number of transects per survey as in some case studies (e.g., Thomsen et al., 2006a, 2007). A combination of methods should also be considered; for example, passive acoustic tracking and visual line transect counts can be used to investigate habitat preferences of a target species that could aid in the designation of areas that would be suitable for protection (e.g., see Skov & Thomsen, 2008). Tracking movements using satellite telemetry could lead to important clues about distribution patterns over long periods and could thus complement the snapshot survey data (e.g., see Teilmann et al., 2008). Finally, the application of power analysis could foster investigation of long-term population trends (for a recent review, see Diederichs et al., 2008; see recommendations below).

It is possible that cetacean populations may experience no measurable difference even when individuals are affected. Looking at the sound profiles from the E&P industry on the one hand and the hearing systems of cetaceans on the other, we might say that cetaceans perceive E&P industry sound over comparably large areas, and PTS and TTS might happen at some distance from the source.[16] We have also documented published disturbance reactions for each case study species. The abundance estimates of humpback whales, which seem to be statistically more robust in comparison, indicate that this population might increase.[17] In this case, it could be that the pressures we discussed are either not severe enough or that individuals are able to adapt to changes in their environment to compensate for negative effects. With regards to sound effects, it might be argued that the oceans are noisy places and that cetaceans are adapted to deal with relatively high received SPLs (for overview of ocean sounds, see Urick, 1983; for cetacean hearing overview, see Au et al., 2000). Yet, we should be careful with this argument. It is true that there are a variety of sources of sound in the marine environment that occur naturally such as vocalisations of marine mammals, fish, and certain crustaceans or sounds that are induced by rain; wind and waves; and subsea volcanic eruptions, earthquakes, and lighting strikes. Some of them can reach high levels; source SPLs of click sounds used by toothed whales for navigation and foraging can be as high as 235 dB re 1 µPa (peak to peak) (sperm whale clicks: Møhl et al., 2003). Another example is snapping shrimp (Family Alpheidae), which influence ambient noise levels in tropical and subtropical waters to a high degree and might contribute to ambient noise levels in some areas of higher latitudes as well (Wenz, 1962; NRC, 2003; Hildebrand, 2005). However, in the case of biosonar, the emitted sound is highly directional and the chance of being "hit" is less than for anthropogenic sonars (Møhl, 2003). Furthermore, many biological sounds are seasonal, and the ocean is, therefore, not constantly a noisy environment. Finally, anthropogenic sound *adds* to the sound that is already out there; it cannot be ruled out that in noisy areas, even moderate levels are enough to increase ambient noise profiles considerably (Ross, 1993; NRC, 2003; McDonald et al., 2006; see below).

If sound disrupts cetacean behaviour, it is likely that they would have developed mechanisms to compensate for negative effects even if disruption by human sound is a relatively new phenomenon. Behavioural responses include altering the timing and the design of social signals and a wide range of behavioural reactions (Miller et al., 2000; Foote et al., 2004; see review in Nowacek et al., 2007). Many cetaceans cover large distances during any given day (see species chapters in Perrin et al., 2002, 2008), and changes in behaviour, such as startle responses or changes in swimming pattern due to sound exposure, might be negligible when looking at the overall movement pattern. Investigations that suggest otherwise (e.g., Williams et al., 2006) are, as yet, speculative. Studies that actually show a decline in the study species, like the bottlenose dolphins observed by Bejder et al. (2006b), have been targeting highly resident groups. The discussion on the biological significance of short-term response will continue. For example, Bejder et al. (2009) have discussed potential costs of behavioural adaptations and recommend a more careful use of the terms *habituation*, *sensitisation*, and *tolerance*.

The concept that a behavioural response could, in turn, lead to population-level consequences, might be inappropriate in some cases. Animals might not react to unwanted signals because there are other things more important to them during the time of exposure. We should consider here that animals have evolved in such a way that there is a trade-off between individual costs (e.g., reduced survival, reduced short-term well-being) and benefits (e.g., value of the habitat/foraging, etc.) to optimise their fitness (e.g., Krebs & Davies, 1997). In other words, anthropogenic sound might be unwanted, disturbing, and/or unpleasant, but the rewards from staying in the habitat outweigh the costs (Barnard, 2007; McGregor, 2007). It is difficult to assess the value of the habitat for each of our case study species as the areas we were

[16] We should keep in mind that for most cetaceans, no audiograms are available.

[17] In general, mark-recapture estimates based on photo-identification yield better results in terms of statistical power than line transect surveys (see results in Table 7).

looking at are quite large and movements of the animals within the case study area are not completely understood. At least it seems that northern bottlenose whales seem to rely on deep-water channels like The Gully as they are specialised foragers on bottom dwelling prey. It is likely, therefore, that their threshold for disturbance is much higher than in other species that use their habitat on a much more opportunistic basis, such as the blue whales off California or harbour porpoises off the UK east coast, which have shown some drastic changes in response to prey availability (see Case Studies 3 & 4). One should therefore be cautious in interpreting a lack of behavioural response as showing that anthropogenic factors have no effects.

C. Short-Term vs Long-Term Impacts

In this review, we were able to identify a number of factors that potentially lead to negative effects on individual cetaceans. Looking at the factors inducing change, we should investigate further those that are long lasting as it is the potential effects of those that might be of greatest concern. Climate could impact cetacean populations both directly (e.g., reduced sea ice) and indirectly (e.g., changes in the distribution and abundance of prey) (see reviews in Whitehead et al., 2000; Moore, 2005; Learmonth et al., 2006). However, at present, it is very difficult to assess the effects of climate change on cetaceans as the whole research field is still very much in its infancy. Lusseau et al. (2004) report that climate change affects grouping behaviour in both wild killer whales and bottlenose dolphins. However, as the authors themselves point out that they were not able to establish causal relationships but, rather, looked at very indirect links between a "critical group size" and parameters indicating prey availability. The same is true for MacLeod et al. (2007b) who investigated stomach contents of stranded harbour porpoises found in two arbitrarily selected "periods" 1993 to 2001 and 2002 to 2003. They drew conclusions on the potential effects of climate change on sandeel (*Ammodytes* spp.) distribution based on a very limited number of samples. On the other hand, there are some very convincing investigations by Trites et al. (2007) and Guenette et al. (2006), who investigated the decline of Steller sea lions (*Eumetopias jubatus*) in the Gulf of Alaska and the Aleutian Islands using a variety of methods and could show that ocean climate played a role in the decline; but they found that other factors also contributed (see Section D). Investigations on environmental factors that are governing the distribution of cetaceans are just emerging (e.g., see Skov & Thomsen, 2008), and it will probably take some time before the way climate changes could affect cetaceans are better understood.

D. Cumulative Effects

It is likely that none of the individual factors we identified in the case studies is harmful enough to cause a decline in cetacean stocks on its own, but together they may create conditions which lead to reduced productivity and survival. In their investigation on Steller sea lions, Guenette et al. (2006) found that predation, prey availability, ocean climate changes, and interspecific competition all played a role in the drastic decline of the Alaskan stock of sea lions. They were also able to quantitatively weight the different factors in a modelling exercise. On the other hand, Ford et al. (2009) could link the decline of northern and southern resident killer whales off British Columbia and Washington State to the limitation of their most favourite prey, Chinook salmon (*Oncorhynchus tshawytscha*). In general, however, we are far from quantitatively weighting factors that affect whales and dolphins (see NRC, 2005). It should have become clear from this review that industry sound is only one factor impacting cetaceans and it might be not the most severe one in many cases. For example, Read et al. (2006) estimate that worldwide fisheries kill several hundreds of thousands of cetaceans as by-catch each year. It is therefore evident that the potential impacts of sound have to be looked upon in a wider perspective, addressing the consequences of acoustic disturbance on populations in conjunction with other factors (see NRC, 2005). This group of factors might be expanded to migratory species such as humpback, blue, and fin whales off California that are not only affected by human and other activities on their summer feeding grounds but also presumably during migrations and on their wintering grounds. Wright (2009) compiles some approaches to assess sound together with other human pressures. A comprehensive methodology for these cumulative impact assessments does not exist as of yet. However, mapping pressures against distribution of ecosystem components (e.g., marine mammals), as done for example by Halpern et al. (2008) and Schipper et al. (2008), might be an important first step in identifying potential problem areas where research and conservation effort should focus.

E. Regulation and Mitigation

A discussion of regulatory approaches and mitigation measures is not the primary concern of this review, and details can be found elsewhere (for overviews, see Richardson et al., 1995; Würsig

& Richardson, 2002; OSPAR, 2009). Here, we will only provide a general overview of regulation and mitigation of underwater sound which was the starting point of evaluation. One way to regulate activities generating underwater sound is to set criteria for sound exposure that should not be exceeded (Southall et al., 2007). It should again be noted that these values are based on very limited datasets with respect to sound-induced injury in marine mammals. In Europe, the EU Marine Strategy Framework Directive has defined descriptors for "good environmental status" (GES), which should be achieved by 2020. One of them deals with underwater noise and a first attempt at developing target indicators for low-frequency impulsive sound emission, and continuous low-frequency ambient sound has been made (Tasker et al., 2010). This work continues and will undoubtedly have a profound influence on regulation of underwater sound across Europe.

Another way for regulation to proceed is to set safety zones within which no marine mammals should be present during sound intensive activities. For example, for marine mammals, the UK Joint Nature Conservation Committee (JNCC) (2004) recommends an exclusion zone of 500 m for the start of seismic surveys (see also Weir & Dolman, 2007; Compton et al., 2008). Besides setting sound exposure criteria and safety zones, there are several other measures to mitigate potential impacts of underwater sound, both dealing with the source of sound as well as the receiver. Looking at the source, there are several mitigation options currently in place or proposed. The design of the equipment used in an activity can be altered so that noise is significantly reduced. There is also the option of a restriction of noisy activities during "critical" phases such as breeding in marine mammals. Operational procedures can also be applied to reduce noise—for example, "soft-start/ramp-up" procedures can be undertaken during pile driving by slowly increasing the energy of the emitted sounds and thereby alerting marine life to the sound. Looking at the receiver, acoustic harassment devices have been used both for seals and harbour porpoises and have proven to be effective in scaring the animals away from the source at close ranges (Yurk & Trites, 2000; Cox et al., 2001; Culik et al., 2001).

F. Future Areas of Research

Looking at the issue of effects of underwater sound in more general terms, Southall et al. (2007), Southall et al. (2009), and Inter-Agency Committee on Marine Science and Technology (IACMST) (2006) provide a detailed list of recommendations for future research. In our opinion, there are several areas where research on the effects of E&P industry sound on cetacean stocks should specifically focus in the future:

- *Better data on cetacean stocks (demographic data and long-term data on individuals) focussing in particular areas with high human pressures* – We have already highlighted the need for comprehensive datasets in certain areas. The combination of visual survey data with passive acoustic monitoring (PAM) (see Thomsen et al., 2005) could provide important insights into parameters governing cetacean distribution (Skov & Thomsen, 2008), and telemetry studies could help in identifying high density areas (see Teilmann et al., 2008).

- *Transformation of activities into quantities of sound exposure by area* – The question of how activities such as the kilometre transect of seismic surveys can be transformed into area-wide "noise budgets," providing units that are quantifiable is a very important issue that is still in its infancy. Yet, without noise budgets, the exposure that animals face is not quantifiable and, therefore, comparing effects can only be done in broad terms (see Hildebrand, 2005; Miller et al., 2007).

- *Development of finer impact analysis methodology* – As mentioned earlier (see Chapter 1), NRC (2005) developed a population consequence of acoustic disturbance model (PCAD model) that involves different steps from sound source characteristics through behavioural change, life functions impacted, and effects on vital rates to population consequences. Yet, most of the quantitative variables of the PCAD model are currently unknown. Challenges to fill gaps can come in many ways due to uncertainties in population estimates for several species/regions, difficulties in weighting sound against other pressures, difficulties in quantifying sound impacts etc. (see NRC, 2005, for a detailed discussion). Despite the uncertainties, models like the PCAD are essential to understanding the possible impacts of anthropogenic sound and should be further developed. This will probably have to be closely tied to methodologies looking at cumulative impacts (see Wright, 2009).

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Appendix

Table 22. Overview of E&P industry and cetacean stocks; a: Number of platforms (BERR, 2007; GESAMP, 2007; MMS, 2008), b: Average active drilling rigs per month current (2007 year average) activity (Baker Hughes rig count 2008), c: Average active drilling rigs per month – Historical Peak during 1982 to 2007 (Baker Hughes rig count 2008), d: Current Rig Fleet (RIGZONE, accessed January 2008), e: Current rig utilisation (RIGZONE, accessed January 2008)

Area	E&P activity							Number of species	Most abundant stocks (N)	Source for cetacean stocks	Data assessment
	Activity started	a	b	c	d	e	Seismic				NS/S
Africa – West Coast	1938 – seismic exploration 1958 – production	~380 (2000)	15	54 (1982)	69	89.9%	Seismic vessel count – 9 (1995)	> 20	Gulf of Guinea: bottlenose dolphins and humpbacks All coast: Atlantic humpback dolphin	Picanço et al., 2006	NS
Nigeria			6				21,000 km 2D seismic lines 21,500 km 3D seismic lines (1993-1998) Nigerian National Petroleum Corporation (NNPC) (www.nnpcgroup.com), 2008				
Angola			3				94,758 km 2D (~2007) Western Geco	21	Sperm and humpback whale	Weir, 2006a, 2006b, 2006c, 2007	
Gabon			1				47,429 km 2D (~2007) Western Geco				
Congo			1				2,426 km 2D (~2004) Western Geco				
Overall		~ 950 (2000)	107	109 (2006)	219	42.5%	Seismic vessel count – 29 (1995)				

Area	E&P activity							Number of species	Most abundant stocks (N)	Source for cetacean stocks	Data assessment
	Activity started	a	b	c	d	e	Seismic				NS/S
Indonesia	1962 – Joined OPEC		20				15,854 km 2D seismic lines 2,877 km 3D seismic lines (2003) MIGAS, 2007 (www.migas-indonesia.com)	Indonesia: 29 (sperm whales); Sulawesi: sperm whales Kalimantan: 10 species, mostly Delphinidae	Not sufficient information; potentially sperm whales (regional) and Delphinidae	Indonesian oceanic cetacean program; Kalimantan: Kreb & Budiono, 2005	NS
Malaysia & Philippines			15				3,524 km² 3D (1997-1998) 5,740 km 2D (2002) Western Geco	Philippines: 21		Alava et al., 1993	
Thailand & Vietnam			15					Vietnam Gulf of Tonkin: ~6; mostly Delphinidae	Delphinidae	Smith et al., 2003	NS
West Australia			11		21	90.5%	23,875 km 2D (1996-1997) CGG Veritas Seismic vessel count – 6 (1995)		Humpback and blue whale	Jenner & Jenner, 1992, 1994; Jenner et al., 2001	Sufficient for humpback whale LFC
South Asia (India)			29		51	88.2%					
China			19								
Middle East											
Overall	1960 – Arabian Gulf and south Caspian Sea		30	66 (1982)			Seismic vessel count – 12 (1995)	Western tropical Indian Ocean, incl. Gulf of Oman: 21 species, spinner dolphins and sperm whales; Arabian Peninsula: 23 (6 mysticetes) All areas 28 species; all groups with regional differences	Regional differences; mostly small odontocetes, less mysticetes	Ballance & Pitman, 1998; Baldwin et al., 1998, 1999, 2000, 2002; WDCS, 2002; Oman 2003, 2004	NS

Area	E&P activity							Number of species	Most abundant stocks (N)	Source for cetacean stocks	Data assessment
	Activity started	a	b	c	d	e	Seismic				NS/S
Caspian Sea					25	68.0%					
Persian Gulf (UAE, Qatar, Saudi Arabia)			27		16	73.8%		3 + unidentified	Indian Ocean: bottlenose dolphin	Preen, 2004	NS
Red Sea (Egypt)			11		16	100.0%		~10	Bottlenose dolphin	Baldwin et al., 1999	NS
Russia Offshore activity confined to areas of Sakhalin Island and Barents Sea	1998 – Shakalin Island construction 1999 – Production 1982 – O&G discovered in the Barents Sea	3 – Shakalin Island					Seismic vessel count – 13 (Commonwealth of Independent States – 1995)	Barents Sea: 15 (marine mammals): minke whales and humpbacks white whales Sakhalin: ~23	Barents Sea: minke whales, humpback whales Sakhalin: killer whales, minke whales, gray whales (identified individuals)	Barents Sea: Schweder & Volden, 1994; Lindstrøm et al., 1999, 2001; Lindstrøm & Haug, 2001; Haug et al., 2002; Skaug & Oien, 2005; Zabavnikov et al., 2005 Sakhalin: Kato et al., 2005; Burdin et al., 2007	Barents Sea: Sufficient for minkes and humpbacks Sakhalin: Sufficient for killer whales and gray whales
South America											
Overall		~340 (2000)	71	87 (1982)			Seismic vessel count – 10 (1995)				
Venezuela	1920 – Offshore activity around Lake Maracaibo		17		46	89.8%		21	Bryde's whale and common dolphin wintering; humpback whales	Romero et al., 2001; Oviedo & Silva, 2005; Silva et al., 2006	NS
Brazil	1967 – Offshore activity began		22		49	67.4%	27,531 km 2D (~1999) CGG Veritas 21,000 km 2D 27,000 km^2 3D Fugro Reprocessed	43 (35 odontocetes; 8 mysticetes)		IWC progress reports; Freitas Netto & Barbosa, 2003; Parente & De Araújo, 2005; Parente et al., 2006	Only presence/ absence data

Area	E&P activity							Number of species	Most abundant stocks (N)	Source for cetacean stocks	Data assessment
	Activity started	a	b	c	d	e	Seismic				NS/S
Mexico			28		68	76.5%					
Other & Caribbean			4		14	71.4%			Humpback whales (regional)	NOAA	NS
North America											
Overall		~3,889 (2008)	75								
Gulf of Mexico	1947 – Production began	3,847 (MMS, Feb 2008)	71	231 (1981)	276	54.7%	1,800,144 km CDP (2D) 234,590 km High Res. 269,962 km 258,202 km CDP Interpretation 549,277 km^2 3D DST 3 wells 1968-2002, OCS Report	19	Sperm whale; bottlenose dolphin	IWC; NOAA (1995-2005), SWSS (2002-2006)	Sufficient for sperm whales (MFC)
North Atlantic Shelf (U.S. Waters)	1976 – Exploratory drilling		3		3	100.0%	127,788 km CDP (2D) 0 km^2 3D 1968-1997, OCS Report				
Eastern Canada – Scotian Shelf and Labrador – Newfoundland Shelf	1960 - Seismic exploration began	8 (July 2007 – Deloitte Petroleum Services)					400,034.33 km 2D 29,511.86 km^2 3D	11	White beaked, white sided dolphin, harbour porpoise, minke whales The Gully: northern bottlenose whales	NOAA (1995-2007); Hooker et al., 1997, 1999, 2001, 2002; Hooker, 1999; Hooker & Baird, 1999; Gowans et al., 2000; Hooker & Whitehead, 2002	The Gully: Sufficient for Northern bottlenose whale, MFC

Area	E&P activity: Activity started	a	b	c	d	e	Seismic	Number of species	Most abundant stocks (N)	Source for cetacean stocks	Data assessment NS/S
Offshore California, Washington, to Oregon		23 (MMS, Feb 2008)	2				246,022 km CDP (2D) 56,638 km High Res. 78,460 km CDP Interpretations 867 km^2 3D 1968-1997, OCS Report	23	Humpback whales, blue whales	NOAA (1995-2007)	Sufficient for Humpback whales Blue whales Fin whales and perhaps others (odontocetes, small) LFC
U.S. Alaska (Beaufort Sea)		11 (August 2007 – Deloitte Petroleum Services)			4	25.0%	815,212 km CDP (2D) 110,851 km High Res. 156,833 km CDP Interpretations 550 km^2 3D DST 14 wells 1968-2002, OCS Report		Beluga whale, bowhead whale	NOAA (1995-2007); Fraker & Bockstoce, 1980; Richardson et al., 1986; da Silva et al., 2000	Sufficient for bowhead whales LFC
Cook Inlet							38,892 km CDP (2D) No 3D surveys 1968-2002, OCS Report	15	Gray whale, humpback whale Cook Inlet Beluga	NOAA (1995-2007)	Beluga Gray whale (with reference to seismic) LFC / MFC
Northwest Europe											
Overall		~562 (2008)	48	89 (1985)	160	98.1%					
UK	1964 – First E&P licences 1967 – Production began	284 (BERR, 2008)	25				23,582 km (2D) 29,708 km^2 (3D) 1997-2007 ASCOBANS, 2005	25	Harbour porpoise, whitebeaked dolphin, and minke whale	Hammond et al., 2002; Reid et al., 2003; Hammond, 2006a, 2006b, 2007	Sufficient for harbour porpoise and minke whale HFC/LFC

Area	E&P activity							Number of species	Most abundant stocks (N)	Source for cetacean stocks	Data assessment
	Activity started	a	b	c	d	e	Seismic				NS/S
Norway		96 (OPL, 2001)	18					Diverse Southern Norway up to Trondheim: SCANS II T&M: harbour porpoise, minke whale, whitebeaked dolphin Northern Norway, North of Nordkap: harbour porpoises, sperm whales, killer whales	Southern Norway: harbour porpoise Northern Norway: harbour porpoises	Bjørge & Øien, 1995; Hammond et al., 2002; Hammond, 2006a, 2006b, 2007	Southern Norway: Sufficient for harbour porpoise HFC Northern Norway: Insufficient
Netherlands		135 (OPL, 2001)	3					Harbour porpoises		Hammond et al., 2002; Hammond, 2006a, 2006b, 2007	
Other Europe North Sea		47 (OPL, 2001)									

Table 23. Results of the measurement of McQuinn & Carrier (2005) on seismic airguns in different distances

Station	Recording date (dd-mm-yyyy)	Latitude N (deg.dec)	Longitude W (deg.dec)	Distance to source (km)	Hydrophone deployment depth (m)	Bottom depth (m)	Sound speed (ms^{-1})	No. of seismic pulses	Peak	SPL_{rms} (dB re 1 µPa)	SEL	Interpulse difference Mean (dB)	Interpulse difference Max. (dB)	Pulse time window (s)
A1	05-07-2003	44.0967	59.2807	64.5	50	60	1,463.3	47	138.2	121.3	122.6	3.9	10.4	2.6
A2	14-07-2003	44.1656	59.1917	96.1	90	230	1,456.4	28	134.0	117.9	123.0	6.6	11.7	6.3
A3	05-07-2003	44.1884	59.0216	71.2	90	190	1,454.9	27	131.0	117.0	126.1	3.3	9.8	7.2
A4	05-07-2003	44.2244	58.8934	90.9	45	56	1,458.3	103	144.5	134.3	134.6	3.9	12.1	1.4
B1	06-07-2003	44.0057	59.2232	51.7	35	43	1,463.0	150	144.1	137.6	135.4	3.2	8.4	0.6
B2	06-07-2003	44.0454	59.0843	50.9	90	300	1,447.3	4	139.1	123.3	128.5	2.4	3.1	3.6
B3	14-07-2003	44.0896	58.9681	67.2	90	230	1,453.6	20	142.6	131.2	129.7	3.3	8.0	0.8
B4	05-07-2003	44.1368	58.8318	101.3	75	90	1,455.6	91	147.3	134.4	133.8	3.7	12.2	1.8
C1	06-07-2003	43.9176	59.1649	53.9	45	59	1,456.0	66	150.7	136.1	140.6	2.7	7.4	3.7
C2	06-07-2003	43.9589	59.0428	74.7	90	292	1,448.8	145	147.7	131.8	131.0	4.1	8.8	1.2
C3	14-07-2003	43.9967	58.9147	70.9	90	193	1,447.9	79	145.3	134.6	136.0	3.2	10.9	2.7
C4	14-07-2003	44.0329	58.7862	89.1	90	106	1,450.3	105	148.6	138.8	132.8	5.3	13.7	1.4
D1	07-07-2003	43.8273	59.1138	66.7	85	91	1,449.4	95	149.9	131.5	130.9	4.5	11.4	2.1
D2	13-07-2003	43.8696	58.9862	75.7	90	550	1,452.3	36	151.7	138.4	131.5	5.7	14.1	1.1
D3	13-07-2003	43.9045	58.8528	--	90	252	1,449.3	--	--	--	--	--	--	--
D4	06-07-2003	43.9447	58.7299	82.8	90	196	1,448.0	82	152.0	132.6	139.5	1.7	5.5	5.2
E1	07-07-2003	43.7341	59.0547	50.7	90	309	1,446.0	159	154.7	133.6	138.3	3.3	7.4	3.1
E2	07-07-2003	43.7727	58.9339	50.9	90	1,300	1,447.5	104	155.9	145.1	137.6	4.3	14.6	0.3
E3	13-07-2003	43.8171	58.8014	58.9	90	1,100	1,447.0	156	156.5	145.1	136.9	3.3	13.3	0.2
E4	08-07-2003	43.8538	58.6877	79.6	90	1,220	1,447.8	154	153.7	139.5	135.6	2.7	9.2	1.7
F1	08-07-2003	43.6420	59.0143	30.8	90	1,250	1,473.4	161	160.5	140.2	143.7	1.0	2.5	2.2
F2	13-07-2003	43.6893	58.8891	50.2	90	1,300	1,462.4	150	150.8	132.9	138.1	1.8	10.5	3.9
F3	08-07-2003	43.7247	58.7593	60.3	90	2,500	1,452.5	74	155.2	139.1	138.9	1.3	4.7	1.1
F4	08-07-2003	43.7655	58.6283	72.1	90	2,000	1,448.0	163	153.1	136.8	134.6	4.0	14.8	1.5
Min				30.8				4	131.0	117.0	122.6	1.0	2.5	0.2
Mean				67.9				96	152.2	137.7	136.3	3.4	9.8	2.4
Max				101.3				163	160.5	145.1	143.7	6.6	14.8	7.2