

Potential impact of offshore human activities on gray whales (*Eschrichtius robustus*)¹

SUE E. MOORE* AND JANET T. CLARKE⁺

Contact e-mail: sue.moore@noaa.gov

ABSTRACT

Gray whale (*Eschrichtius robustus*) reactions to offshore human activities have been relatively well studied compared to those of other mysticetes. Studies of short-term behavioural responses to underwater noise associated with aircraft, ships and seismic explorations indicate a 0.5 probability that whales will respond to continuous broadband noise when sound levels exceed *ca* 120dB² and to intermittent noise when levels exceed *ca* 170dB, usually by changing their swimming course to avoid the source. Gray whales were 'startled' at the sudden onset of noise during playback studies, but demonstrated a flexibility in swimming and calling behaviour that may allow them to circumvent increased noise levels. Whales may be 'harassed' by noise from large commercial vessels, especially in shipping lanes or near busy ports. Gray whales sometimes change course and alter their swimming speed and respiratory patterns when followed by whalewatching boats. Conversely, some whales swim toward small skiffs deployed from whalewatching boats in breeding lagoons, seemingly attracted by the noise of idling outboard engines. Reported gray whale reactions to aircraft are varied and seem related to ongoing whale behaviour and aircraft altitude. Whale response to research involving tagging and biopsy sampling appears to be short term. Gray whales were seen swimming through surface oil from the *Exxon Valdez* oil spill along the Alaskan coast and showed only partial avoidance to natural oil seeps off the California coast. Laboratory tests suggest that gray whale baleen, and possibly skin, may be resistant to damage by oil, but spilled oil or oil dispersant in a primary feeding area could negatively affect gray whales by contaminating benthic prey. Gray whales are sometimes injured or killed in collisions with vessels or entanglement in fishing gear. Concern about the cumulative long-term impact of offshore human activities is particularly acute in the Southern California Bight, where many activities are often concurrent.

KEYWORDS: GRAY WHALE; NOISE; WHALEWATCHING; PACIFIC OCEAN; SHORT-TERM CHANGE; POLLUTANTS; ECOSYSTEM; LONG-TERM CHANGE; HUMAN IMPACT

INTRODUCTION

The coastal habits of gray whales (*Eschrichtius robustus*) often bring them into direct contact with offshore human activities. During their annual migration along the North American coast, the eastern North Pacific (California) gray whale stock passes through US oil and gas exploration/development areas, shipping lanes, military test ranges and near coastal cities, from which 'whalewatchers' embark. The western North Pacific (Korean) stock probably encounters similar offshore human activities during its migration along the Asian coast, especially near Korea and Japan (see review in Weller *et al.*, 2002). In a review of the impact of offshore human activities on gray whales along the migration route and in the breeding lagoons in the eastern North Pacific, Reeves (1977) suggested that additional research, enforceable management procedures and public education were needed to mitigate human harassment of whales. Responses to this suggestion in the ensuing years are summarised here.

This review of information regarding human activities that may affect gray whales is presented in three sections: (1) offshore oil and gas development; (2) commercial fishing and vessel traffic; and (3) whalewatching and scientific research (Fig. 1). Underwater noise from each of these activities is often regarded as the primary source of disturbance. Gray whale reactions to underwater noise associated with oil and gas development have been directly observed, resulting in documented responses to sounds from aircraft, a variety of classes of vessels, airgun pulses used in seismic exploration and oil drilling and production operations (summarised in Malme *et al.*, 1989; Richardson *et al.*, 1989; 1995).

Less attention has been focused on gray whale responses to oil on the sea surface (Kent *et al.*, 1983), on the potential fouling of the skin and baleen and on the contamination of prey by oil (Geraci and St. Aubin, 1985; 1990).

Gray whales are sometimes injured or killed by entanglement in commercial fishing gear (Heyning and Lewis, 1990). Commercial vessel traffic results in the ensouffication of shipping lanes and occasionally leads to collisions with whales (Heyning and Dahlheim, 2002). Finally, harassment of animals due to whalewatching and scientific research has become a focus of concern, particularly as more commercial recreation vessels, private boats and researchers converge to 'watch' whales near large cities along the North American coast. Gray whale reactions to vessel noise observed during studies of oil- and gas-related noise impact are referred to in both the 'Commercial Fishing and Vessel' and the 'Whalewatching and Scientific Research' sections of this paper, as appropriate.

OFFSHORE OIL AND GAS DEVELOPMENT

The potential impact of offshore oil and gas development on marine mammals was the focus of extensive research during the mid-1980s. Richardson *et al.* (1989) reviewed both acoustic and non-acoustic impacts of oil and gas exploration and development activities on marine mammals. Malme *et al.* (1989) used a modelling procedure to rank the impact of various petroleum-industry-related noise sources on gray whales and other marine mammals. Geraci and St. Aubin (1990) summarised the ecological and toxicological effects of oil on marine mammals. The potential impact of oil and gas development on gray whales is summarised in two

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² dB re 1 μ Pa throughout manuscript.

* Alaska Fisheries Science Center, National Marine Mammal Laboratory, 7600 Sand Point Way N.E., Seattle, WA 98115, USA.

⁺ SAIC, Bio Solutions Division, 14620 268th Ave. E., Buckley, WA 98321, USA.

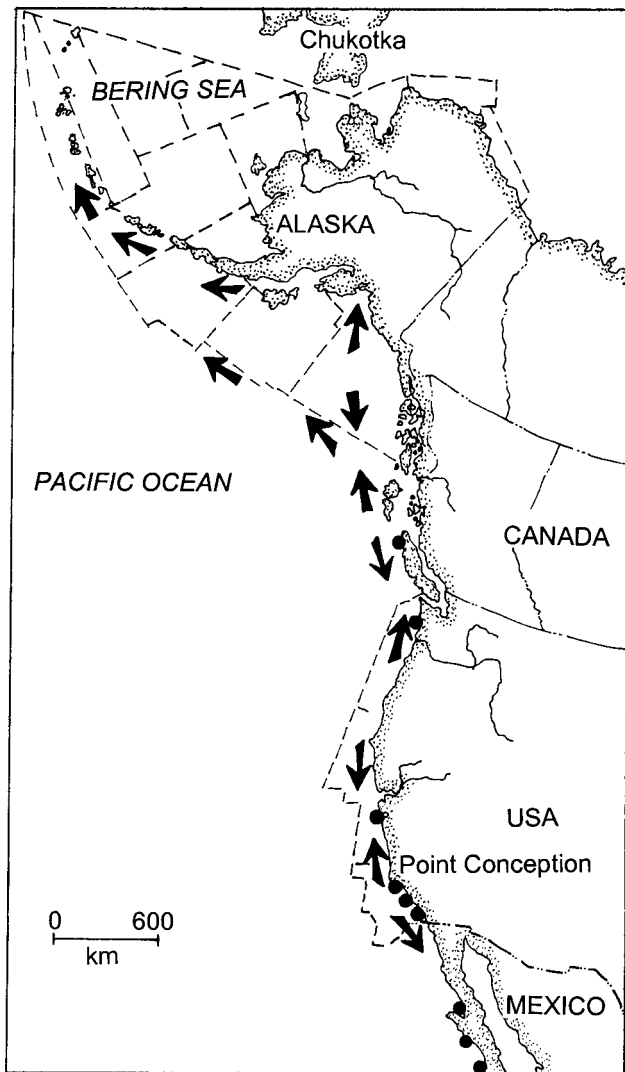


Fig. 1. US oil and gas planning areas (---), shipping lanes (→), and whalewatching centres (●) along the gray whale's northeast Pacific ranges.

sections, the first relating whale responses to noise associated with offshore operations and the second focusing on oil contamination of whales or their habitat.

Noise

Short-term responses of gray whales to playback of noise associated with oil and gas development were studied during the migration past the central California coast in 1983-1984 (Malme *et al.*, 1984), near feeding whales in the Bering Sea in 1985 (Malme *et al.*, 1988) and in San Ignacio Lagoon, Baja California, Mexico in 1981-1984 (Dahlheim, 1987, summarised in Richardson *et al.*, 1995). Underwater noise sources recorded and used during playback trials included helicopter overflights, drillship operations, drilling and production platforms, a semi-submersible drilling rig and tripping operations (withdrawing drills from exploratory wells). In addition, Malme *et al.* (1984; 1988) conducted experiments using airgun arrays and single airguns as sources. It is important to recognise that although playback studies provide valuable information on specific responses of whales to a controlled noise source, they are hampered by the limitations of the sound projector and rarely fully simulate noise from the source, especially at low (<100Hz) frequencies.

Gray whale responses to noise playback and airgun blasts included: changes in swimming speed and direction to move away from the sound source, termed 'avoidance' (Malme *et al.*, 1984); abrupt behavioural changes from feeding to avoidance, with a resumption of feeding after exposure (Malme *et al.*, 1988); changes in calling rates and call structure (Dahlheim, 1987); and changes in surface behaviour, usually from travelling to milling. A 0.5 probability of avoidance was calculated for migrating gray whales exposed to continuous noise at levels ranging from 117-123dB (Table 1). When migrating or feeding gray whales were exposed to airgun pulses, a 0.5 probability of avoidance was calculated at levels of 170dB and 173dB, respectively. Overall, Malme *et al.* (1988) concluded that a 0.5 probability of avoidance occurred when continuous noise levels exceeded *ca* 120dB and when intermittent noise levels exceeded *ca* 170dB. While these values provide some useful baseline information on the levels of industrial noise to which gray whales respond, the distance from the source at which these levels occur varies with geographic region and sea condition.

Table 1

Gray whale response to various levels of playback of noise associated with offshore oil and gas development. Data from Malme *et al.*, 1984, except: ¹ from Malme *et al.*, 1988; and ² from Dahlheim, 1987. Tripping operations = sound of drillstring being drawn out of exploratory well hole.

Source	Noise level (dB re 1µ Pa)	Response (avoidance probability)
Helicopter	115	0.10
	120	0.50
	>127	0.90
Drillship	110	0.10
	117	0.50
	122	0.90
Semi-submersible	115	0.10
	120	0.50
	>128	0.90
Drilling platform	114	0.10
	117	0.50
	>128	0.90
Production platform	120	0.10
	123	0.50
	>129	0.90
Airgun pulses		
Migrating whales (airgun array)	164	0.10
	170	0.50
	>180	0.90
Feeding whales ¹	163	0.10
	(single airgun)	173
Tripping operations ²	110-130	'increased milling'

Malme *et al.* (1989) subsequently prepared a disturbance ranking scheme for oil and gas noise sources in outer continental shelf (OCS) planning areas of offshore Alaska, based on a model of noise contribution and exposure rating. The ranking scheme indicated that gray whales had a high probability of being influenced by noise from oil and gas operations, particularly from large tankers, dredges and airgun arrays. The authors cautioned that the noise contribution and exposure rating models used in ranking were based upon several untested hypotheses regarding the properties of sound transmission in specific locales and the ability of gray whales to hear frequencies produced by offshore oil and gas operations.

Dahlheim (1987) studied the effects of man-made noise, including ship, outboard engine and oil-drilling sounds, on gray whale calling and surface behaviours. Statistically

significant increases in gray whale calling rates and changes in calling structure, swimming direction and surface behaviours were associated with artificially-increased noise levels during playback experiments in San Ignacio Lagoon, Mexico. For example, when tripping noise was played back, gray whales decreased their calling rate and level and a greater proportion of whales milled near the playback transducer compared to the control periods. Whale responses varied with the type and presentation of the noise source. In general, as noise levels increased there was a corresponding increase in calling rates, level of calls received, number of frequency-modulated calls, number of pulses produced per pulsed-call series and call repetition rate. Whales responded more dramatically ('startled') to the sudden onset of sound compared to sound played back over a longer time period. Dahlheim (1987) emphasised that flexibility in swimming and calling behaviour may allow gray whales to circumvent increased noise levels in their environment, but cautioned that the combined effects of various disturbances could pose a problem.

The 'noisiest' period of offshore oil and gas operations occurs during exploration and site establishment (Richardson *et al.*, 1995). Many interrelated activities during these periods require support from aircraft, a variety of vessels, dredges and sometimes even explosive operations (University of California, 1990). Conversely, production activities are generally quieter and require fewer support operations. Gray whales have been migrating past oil exploration and production activities in the Santa Barbara Channel off California for decades, suggesting that they habituate to, or at least tolerate, noise associated with these activities (Richardson *et al.*, 1995). Although there are no published accounts of gray whale disturbance caused by production platform noise, Gales (1982) hypothesised that this noise could be detected by a mysticete from 37m to over 5km away, depending on propagation conditions in the Santa Barbara Channel and the hearing thresholds of the individual whales.

Oil contamination

The effect of surface oil on gray whales has been the topic of more speculation than study (Geraci and St. Aubin, 1985; 1990). It is unclear whether gray whales can detect surface oil. Gray whales were observed lying in or swimming through oil slicks from the 1989 *Exxon Valdez* oil spill along Alaska's south-central coast (Table 2). Similarly, gray whales migrating past areas of natural oil seeps near Santa Barbara, California, often swam through oil (Kent *et al.*, 1983). In general, gray whales swimming through oil offshore of California swam faster, stayed submerged longer and took fewer breaths than whales that did not pass through

oil. Whales sometimes changed direction to swim around surface oil, but it was not clear that the direction change was in response to the oil. Reactions of migrating gray whales to the 1969 Santa Barbara Channel oil spill were not documented (Brownell, 1971), but no deaths were attributed to the effects of oil pollution (Reeves, 1977). Six gray whale carcasses were recovered after the 1969 Santa Barbara spill and 25 after the 1989 *Exxon Valdez* spill (Geraci, 1990). Although the tally of dead whales was higher than previously recorded for both areas, researchers concluded that the higher counts were due to increased survey effort.

Gray whales probably experience irritation to their eyes and tactile hair follicles upon contact with oil, but lasting effects on skin tissue may be less likely (Geraci, 1990). Although exposure of discrete areas of captive bottlenose dolphins' (*Tursiops truncatus*) skin to crude oil and gasoline for 0.5-1.25hrs initially resulted in 'small blisters' (Geraci and St. Aubin, 1982; 1990), normal colour returned within 2hrs. Geraci and St. Aubin (1985) concluded there was 'no evidence of damage or loss of integrity,' possibly because dolphins do not exhibit a vascular reaction to contact with petroleum products. Similarly, although the mid- and outer layers of the skin of a live-stranded sperm whale (*Physeter macrocephalus*) were damaged by a 7-12hr exposure to oil and gasoline, the basal layer and underlying dermis were undamaged. Geraci and St. Aubin (1985) also reported no difference in healing between two shallow epidermal wounds in uncontaminated dolphin skin and two wounds contaminated with oil for 0.5 or 1hr, suggesting that oil contamination did not seriously impair the healing process.

Geraci (1990) concluded that cetacean skin impeded the penetration of petroleum compounds by 'tight intercellular bridges, the vitality of the superficial cells and the extraordinary thickness of the epidermis.' However, there have been no laboratory tests of oil contamination of gray whale skin and inferences drawn from small sample-size studies on other species must be interpreted with caution. Specifically, Albert (1981) suggested that rough or caudated skin (such as the barnacle-covered skin of a gray whale) may be more susceptible to oil contamination and subsequent bacterial infection than the smooth skin of the majority of other cetaceans. This suggestion will probably remain untested for the foreseeable future, as funding for studies related to oil and gas impacts on marine mammals has diminished substantially in recent years.

In laboratory tests, water flow through gray whale baleen contaminated with various grades of oil was relatively unaffected (Geraci and St. Aubin, 1985; Geraci, 1990). Most of the oil (70%) was removed from the test baleen within 30 minutes of continuous flushing with sea water. Geraci and St. Aubin (1985) concluded that oil impact on baleen was slight and short term, but added that oil-coated baleen fibres could contaminate ingested food. Baleen fibres could remain oiled if an animal was feeding in an area so blanketed by oil that fouling outpaced the rate of cleansing, such as in the centre of a spill (Geraci, 1990). Ingested oil is toxic to marine mammals (Engelhardt, 1983). Although no cases of ingestion have been reported, gray whales could consume oil from fouled baleen, by engulfing floating tar balls (Geraci, 1990) or from contaminated bottom sediments (Hansen, 1985). Stranded gray whales, examined after the *Exxon Valdez* spill, had oil on their baleen but not in their digestive tracts, suggesting that the baleen was fouled after the animals died (M. Dahlheim, pers. comm.).

Oil and chemical dispersants, used to break up surface oil and cause it to sink, could impact gray whales by contaminating benthic prey (Neff, 1990; Würsig, 1990).

Table 2

Reports of gray whales associated with oil from the 1989 *Exxon Valdez* oil spill.

Date	No. whales	Behaviour	Pers. comm.
6 Apr.	1	Lying still in large oil slick <100m from shore	B. Morris
	5-6	Swimming through oil slicks ca 1km from shore	
12 Apr.	4	Swimming in and out of oil slicks	
	2	Swimming through oil slicks	
Apr./May	1	Swimming through oil slicks	M. Dahlheim
	ca 20 obs.	Whales swimming near or through oil	

Although gray whales probably feed opportunistically throughout their range, they return annually to primary feeding areas in the northern Bering Sea and Chukchi Sea (e.g. Nerini, 1984; Moore *et al.*, 1986; Weller *et al.*, 1999). Any large-scale contamination by oil or oil dispersants of a primary feeding area could negatively impact the population. Increased activity by the oil and gas industry in offshore waters and recent large oil spills motivated the Scientific Committee of the International Whaling Commission to recommend the development of 'measures to prevent and mitigate the impact of petroleum exploration, development and transportation' (IWC, 1990a). As yet, plans on paper have not resulted in an effective clean-up of any offshore oil spill, leaving real the possibility of large-scale contamination somewhere within the gray whale range.

COMMERCIAL FISHING AND VESSEL TRAFFIC

Many different classes of commercial fishing and transport vessels regularly transit shipping lanes and frequent busy marine ports along the North American coast. Gray whales are exposed to the combined noise from these vessels along their migration route and in feeding and breeding areas. Further, gray whales are sometimes struck by vessels and occasionally become entangled in fishing gear. As summarised in the subsequent two sections, potential negative impacts of commercial fishing and vessel traffic on gray whales include collisions, entanglement and noise harassment due to the ensonification of coastal waters by intense vessel traffic.

Collisions and entanglement

Information on gray whale mortality or injury incidental to vessel traffic or fishing operations must be inferred from stranding records, which are not uniformly available for the species' entire range. Heyning and Dahlheim (2002) summarised instances of gray whales being struck by ships and stated that there are 'several documented cases of dead, stranded gray whales with cuts from the propellers of large ships', although they could not estimate ship collision-related mortality. Gray whale mortality due to entanglement in fishing gear is also difficult to substantiate because stranded animals often exhibit little or no evidence of entanglement (Baird *et al.*, 2002; Heyning and Dahlheim, 2002). Often stranded whales cannot be examined for cause of death because of geographic location (see, e.g. Kasamatsu and Ishikawa, 1990).

Gray whale mortality incidental to offshore fishing operations in British Columbia was estimated at 27% of all stranded whales, or roughly two gray whales per year (Baird *et al.*, 2002). The authors cautioned that biases in survey methods and stranding records may have resulted in under-representation of the actual number of whales taken incidentally. Gray whales were the species most frequently documented (94% of all records) as entangled, usually in set gillnets, off southern California (Heyning and Lewis, 1990). Of the 61 animals entangled, most were 3yrs of age or younger (<10m in length). Many of the 41 live entanglements were released alive; however, it is unknown whether there are any long-term effects of entanglement on live-released whales.

Ensonification

Commercial vessels range from cargo supertankers (>250m) to small sports-fishing boats (*ca* 30m). Noise levels for these vessels range from *ca* 185-190dB re 1 μ Pa-m for the supertankers, to 169-180dB re 1 μ Pa-m for medium sized ships, to *ca* 145-170dB re 1 μ Pa-m at frequencies from

ca 50-300Hz (Richardson *et al.*, 1995). Cybulski (1977) reported a maximum source level of 205dB at 2Hz for an oil tanker, but noted that measurement of such long wavelength sounds was highly dependent on water depth. The noise field from the combined output of several vessels has not been documented, but would be expected to be greatest near ports and along busy shipping lanes (Malme *et al.*, 1989).

Reactions of gray whales to vessels are summarised in Richardson *et al.* (1995) and Malme *et al.* (1989). Most accounts describe relative movements of whales and vessels, with little or no specific information on concomitant underwater noise. On the summer feeding grounds, gray whales fled when Soviet catcher vessels approached within 350-550m, but generally they paid no attention to vessels at distances >550m (Bogoslovskaya *et al.*, 1981). Wyrick (1954) reported that migrating gray whales changed course at distances of 200-300m to avoid vessels. Although many whalewatching and private boats routinely approach within 200m of whales, there are no published accounts of the whales' responses at these distances. Vessels moving erratically or at high speeds in the breeding lagoons sometimes caused whales to swim rapidly away, but there was little or no whale response to slow-moving or anchored vessels (Swartz and Jones, 1979).

Evidence that vessel traffic can cause gray whales to abandon an area is equivocal. Gray whales stopped using Guerrero Negro Lagoon, Baja California, Mexico during a period of increased dredging and commercial shipping activity (1957-1967), but reoccupied the lagoon in later years after ship traffic abated (Bryant *et al.*, 1984). Conversely, Jones and Swartz (1984) reported no evidence that whales moved out of San Ignacio Lagoon when whalewatching vessels were present and suggested that gray whales became less sensitive to boats in the lagoons as the winter progressed. Notably, whalewatching boats remained at anchor in the seaward one-third of the lagoon with only their generators running while tourists made excursions in small outboard-powered skiffs to watch whales. Jones and Swartz (1984) noted an increasing tendency for whales to approach rather than flee from these skiffs since the late 1970s. Dahlheim *et al.* (1984) also reported that some whales were attracted to noise from idling outboard engines and that each whalewatching vessel and outboard-powered skiff in San Ignacio lagoon had a distinctive acoustic spectrum profile.

WHALEWATCHING AND SCIENTIFIC RESEARCH

Whalewatching

Whalewatching has become an important recreational industry in several communities along the North American coast from British Columbia, Canada, to the breeding lagoons of Baja California, Mexico, especially in the Southern California Bight (waters south of Point Conception, California, to the Mexican border) where day cruises are launched from at least 14 landings from Morro Bay to San Diego and hundreds of private vessels launch from the large metropolitan areas (Reeves, 1977). In addition, some expeditions sail from southern California ports to observe gray whales in the breeding lagoons. The Mexican government has designated the lagoons as a sanctuary and strictly controls the number and location of vessels in the lagoons. Whalewatching along the migration route is not as well regulated and it has been suggested that this activity, in combination with commercial fishing and vessel operations, may cause gray whales to migrate further offshore (Wolfson, 1977).

A Workshop to Review and Evaluate Whalewatching Programs and Management Needs was convened by the Center for Marine Conservation (CMC) and the National Marine Fisheries Service (NMFS) in Monterey, California, November 1988 (Center for Marine Conservation and National Marine Fisheries Service, 1989). Bursk (1989) reported that gray whales often changed speed and deviated from their course in the presence of whalewatching boats. In another evasive behaviour, 'snorkelling,' whales came to an almost complete halt to breathe in an inconspicuous manner. Similarly, migrating gray whales disturbed by vessels tended to exhale underwater and surface only long enough to inhale, making it difficult to see them (Hubbs and Hubbs, 1967). Because estimates of energy expenditure based on breathing patterns indicated that fast-moving whales breathe and use energy more rapidly than slow-moving whales (Sumich, 1983), Bursk (1989) suggested that these vessel-induced practices may increase gray whale energy consumption and thereby reduce migrating efficiency.

At the CMC/NMFS meeting, a distinction was made between commercial whalewatching vessels and private recreational boats. The general consensus was that commercial operators were effectively limiting their approach distances to whales, but private boaters often 'harassed' gray whales by approaching closely or by cutting in front of their path. The NMFS established whalewatching guidelines for all boat operators, effective during the 1990-1991 gray whale migration season (J. Lecky, pers. comm.). The guidelines stipulate that boaters maintain a 100yd (90m) distance from whales, avoid sudden changes in course or speed, not cross a whale's path or separate a whale from a calf, and not restrict whale movements or behaviour (University of California, 1990).

Observations of gray whales migrating further offshore in the Southern California Bight have been interpreted as either a response to increased human activities along the coast or a reoccupation of routes historically used by an increasing whale population (Rice and Wolman, 1971; Dohl and Guess, 1979). The route of the southbound migration along the North American coast bifurcates at Point Conception. Some whales (*ca* 20-35%) turn east and continue to follow the coast, while the others (*ca* 65-80%) swim south across open water to the northern Channel Islands (Leatherwood, 1974; Kent *et al.*, 1983). Most whales (*ca* 94%) pass the northern Channel Islands within 3 n.miles (5.5km) of shore and tend to cluster at points, reefs, headlands and inter-island passages (Jones and Swartz, 1990). The route between the northern and southern Channel Islands is poorly documented. Whales tend to pass the southern Channel Islands along the western shore, then turn southeastward, joining coastal migrants near the USA/Mexican border (Sumich and Show, 1990). Counts of whales passing San Clemente Island, the southernmost of the Channel Islands, indicate that there is broad interannual variability in the number of whales using that route (Graham, 1990). However, such variation is not necessarily related to human activities and Sumich and Show (1990) suggest that the use of offshore routes along the Channel Islands may reflect whale migration patterns established during the last glacial maximum.

Scientific research

Research often requires observers to approach gray whales closely in aircraft or boats. Reported gray whale reactions to aircraft are varied and seem related to ongoing whale behaviour and aircraft altitude. For example, cow-calf pairs in the northern Chukchi Sea seemed particularly sensitive to

a turboprop aircraft at 305m altitude; calves swam under adults and were subsequently hard to see (Ljungblad *et al.*, 1983). Conversely, a group of mating gray whales did not react to the arrival of the same aircraft, nor to its circling at 320m altitude for over 10 minutes (Ljungblad *et al.*, 1987). Malme *et al.* (1984) played back underwater noise recorded from a Bell 212 helicopter (estimated altitude = 100m), at an average of three simulated passes per minute, to migrating gray whales. Whales changed their swimming course and sometimes slowed down in response, but proceeded to migrate past the transducer. Migrating gray whales did not react overtly to a Bell 212 helicopter at >425m altitude, occasionally reacted when the helicopter was at 305-365m, and usually reacted when it was below 250m (Southwest Research Associates, 1988). Reactions included abrupt turns or dives or both.

Gray whale tracking and biopsy studies necessitate approaching whales (to within 10-25m) by boat and attaching tags or firing projectiles into them (e.g. Harvey and Mate, 1984; Swartz *et al.*, 1987; Mathews *et al.*, 1988). Gray whales sometimes responded to tag attachment by fluke slapping and rapid swimming, but usually returned to pre-tagging behaviours soon after the event (Harvey and Mate, 1984). The response of gray whales to biopsy darts was not described (Mathews *et al.*, 1988), but disruption of ongoing behaviours in other mysticetes has been brief, if sometimes dramatic (Brown *et al.*, 1991; Weinrich *et al.*, 1991). The long-term benefit of these activities to the population is generally accepted to outweigh the short-term discomfort to the subject whales (IWC, 1990b), although caution should be exercised for small populations such as the western gray whales (see IWC, 2002).

Oceanographic research often requires the use of low frequency sounds to investigate transmission loss and water mass properties. Specifically, during long-range acoustic tomography and acoustic thermometry studies, sounds to 190-220dB re 1 μ Pa-m are commonly broadcast at 20-200Hz (Richardson *et al.*, 1995). Responses of gray whales to these sources are largely unknown. However, in August 1996, the US Navy began preparation of an Environmental Impact Statement (EIS) to support use of a low frequency active (LFA) sonar, which transmits signals as intense as 205dB re 1 μ Pa-m in the 100-500Hz frequency range. Research to investigate the effect of this source was conducted offshore central California during the 1998 southbound gray whale migration (P. Tyack, pers. comm.). Preliminary results showed that gray whales avoided exposure to transmissions from this source at levels of 170 and 178dB re 1 μ Pa-m by deviating their swimming path at ranges of 'several hundred meters', similar to avoidance behaviours described during playback of oil and gas-related sounds (Malme *et al.*, 1984). When the LFA source was transmitting at 185dB re 1 μ Pa-m in the path of the migration (i.e. roughly 2km from shore), gray whales deviated their swimming path at significantly longer ranges (> 1km) than when the source was broadcast farther offshore and out of the migration path. These results, and those of Malme *et al.* (1984), indicate that gray whales alter their behaviour to avoid exposure to loud low-frequency sounds.

SUMMARY

When Reeves (1977) suggested that additional research, management and education were needed to mitigate human harassment of gray whales there were few quantitative accounts of whale responses to specific human activities. Much has been accomplished in the ensuing years. Overall,

there is little evidence that gray whales disturbed by human activities travel far as a result of, or remain disturbed long after, the causal event. However, most research, management and educational efforts have focused on short-term responses by gray whales to single-stimulus trials. An example of event-related management is the warning given to spectator boats that were harassing migrating gray whales during the 1992 International America's Cup Regatta off San Diego, California (Marine Mammal Commission, 1993).

Assessing the cumulative, long-term effects of offshore human activities on gray whales should be the focus of future research. Specifically, Tyack (1989) suggested that management based on assessing long-term impacts of human activity on whale populations should take precedence over attempts to regulate individual acts of whale harassment. Gray whales often encounter stimuli from human activities simultaneously or sequentially, not in isolation. A case in point is the Southern California Bight, where gray whales are exposed to offshore oil and gas operations, a myriad of commercial shipping and fishing activities and various whalewatching and whale research efforts. The cumulative effects of several stimuli can be purely additive, or can lead to synergistic effects that result in changes greater than the sum of changes from individual stimuli.

Assessment of cumulative, long-term effects requires consistent data collection and analyses of multiple environmental factors over many years. A long-term (1957-1982) assessment of the effects of research vessels in Cape Cod Bay suggested that mysticete species differed in their response to vessels and there was no evidence that vessel interactions exerted a long-term negative impact on any population (Watkins, 1986). Similarly, an overview of the effects of whalewatching activities on mysticetes off Cape Cod suggested few negative impacts, provided that commercial vessels maintained safe guidelines for the approach and watching of whales (Beach and Weinrich, 1989). The recovery of the gray whale population in the face of long-term exposure to human activities along the North American coast suggests a strong degree of tolerance to such activities. Long-term research should be directed at investigating whether there is a limit to such tolerance by examining changes in relative abundance and migration routes near centres of human activities over a number of years.

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