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* 120dB[2] 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 ensonification 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 μPa 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.*

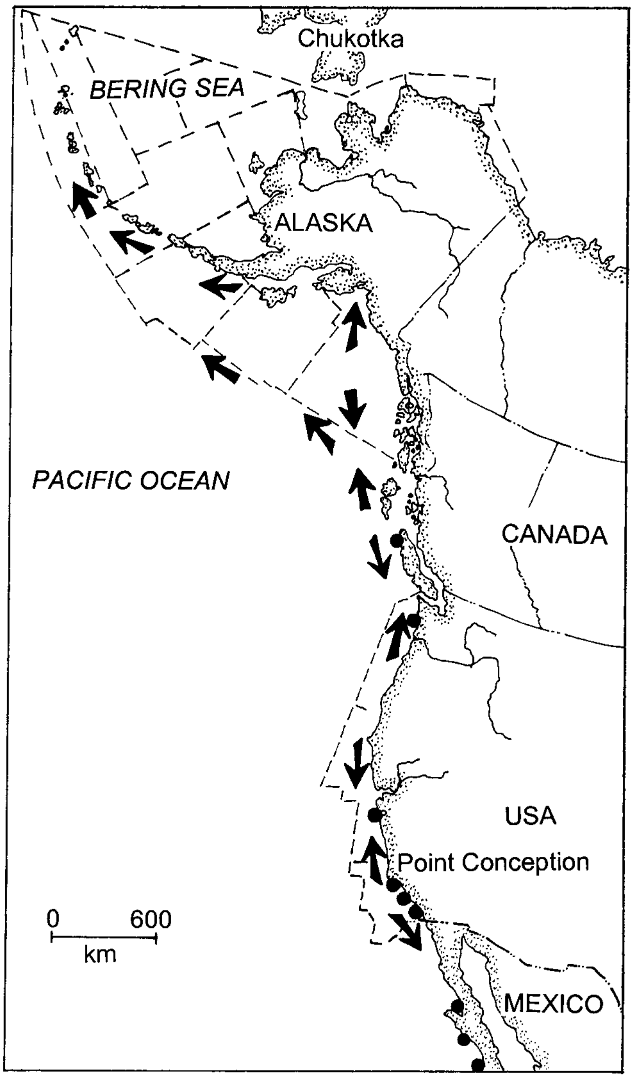

Fig. 1. US oil and gas planning areas (---), shipping lanes (→), and whalewatching centres (•) along the gray whale's northeast Pacific ranges.

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	164	0.10
(airgun array)	170	0.50
	>180	0.90
Feeding whales[1]	163	0.10
(single airgun)	173	0.50
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.

Table 2

Reports of gray whales associated with oil from the 1989 *Exxon Valdes* 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	
	1	Swimming through oil slicks	
Apr./May	*ca* 20 obs.	Whales swimming near or through oil	M. Dahlheim

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 damaged 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).

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 1μPa-m for the supertankers, to 169-180dB re 1μPa-m for medium sized ships, to *ca* 145-170dB re 1μPa-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 μPa-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 μPa-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 μPa-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 μPa-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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REFERENCES

Albert, T.F. 1981. Some thoughts regarding the possible effects of oil contamination on bowhead whales, *Balaena mysticetus*. pp. 945-53. *In:* T.F. Albert (ed.) Tissue structural studies and other investigations on the biology of endangered whales in the Beaufort Sea. Final report to the Bureau of Land Management, Anchorage, Alaska, from the Department of Veterinary Science, University of Maryland, College Park, MD. 953pp. [Available from National Technical Information Service, Springfield, VA 22161, USA as PB86-153582/AS].

Baird, R.W., Stacey, P.J., Duffus, D.A. and Langelier, K.M. 2000. An evaluation of gray whale (*Eschrichtius robustus*) mortality incidental to fishing operations in British Columbia, Canada. Paper SC/52/SD16 presented to the IWC Scientific Committee, June 2000, Adelaide. [Paper available from the Office of this Journal].

Beach, D.W. and Weinrich, M.T. 1989. Watching the whales: is an educational adventure for humans turning out to be another threat for endangered species? *Oceanus* 32(1):84-8.

Bogoslovskaya, L.S., Votrogov, L.M. and Semenova, T.N. 1981. Feeding habits of the gray whale off Chukotka. *Rep. int. Whal. Commn* 31:507-10.

Brown, M.W., Kraus, S.D. and Gaskin, D.E. 1991. Reaction of North Atlantic right whales (*Eubalaena glacialis*) to skin biopsy sampling for genetic and pollutant analysis. *Rep. int. Whal. Commn* (special issue) 13:81-9.

Brownell, R.L. 1971. Whales, dolphins and oil pollution. pp. 255-76. *In:* D. Straughan (ed.) *Biology and Bacteriology*. Vol. 1. *Biological and Oceanographical Survey of the Santa Barbara Channel Oil Spill, 1969-1970*. Allan Hancock Foundation, University of Southern California, Los Angeles, USA. 426pp.

Bryant, P.J., Lafferty, C.M. and Lafferty, S.K. 1984. Reoccupation of Guerrero Negro, Baja California, Mexico, by gray whales. pp. 375-87. *In:* M.L. Jones, S.L. Swartz and S. Leatherwood (eds.) *The Gray Whale, Eschrichtius robustus*. Academic Press, Inc., Orlando, Florida. xxiv+600pp.

Bursk, M. 1989. Response of whales to whale watching in southern California. p.11. *In*: Proceedings of the Workshop to Review and Evaluate Whale Watching Programs and Management Needs. 14-16 November 1988, Monterey, California. Center for Marine Conservation, Washington, DC, and the National Marine Fisheries Service, Silver Spring, MD. 53pp.

Center for Marine Conservation and National Marine Fisheries Service. 1989. Proceedings of the Workshop to Review and Evaluate Whale Watching Programs and Management Needs. 14-16 November 1988, Monterey, California. Center for Marine Conservation, Washington, DC, and the National Marine Fisheries Service, Silver Spring, MD. 53pp.

Cybulski, J. 1977. Probable origin of measured supertanker radiated noise spectra. *In: Oceans '77 Conference Record*. Institute of Electrical and Electronic Engineering, New York, 15C-1-8.

Dahlheim, M.E. 1987. Bio-acoustics of the gray whale (*Eschrichtius robustus*). Ph.D. Thesis, University of British Columbia. 266pp.

Dahlheim, M.E., Fisher, H.D. and Schempp, J.D. 1984. Sound production by the gray whale and ambient noise levels in Laguna San Ignacio, Baja California Sur, Mexico. pp. 511-41. *In:* M.L. Jones, S.L. Swartz and S. Leatherwood (eds.) *The Gray Whale, Eschrichtius robustus*. Academic Press, Inc., Orlando, Florida. xxiv+600pp.

Dohl, T.P. and Guess, R. 1979. Evidence for increasing offshore migration of the California gray whale, *Eschrichtius robustus* in southern California, 1975 through 1978. p.13. *In*: Abstracts of the 3rd Biennial Conference on the Biology of Marine Mammals, 7-11 October 1979, Seattle, WA. 64pp.

Engelhardt, F.R. 1983. Petroleum effects on marine mammals. *Aquat. Toxicol.* 4:199-217.

Gales, R.S. 1982. Effects of noise of offshore oil and gas operations on marine mammals - an introductory assessment. NOSC Technical Report 844 to the US Bureau of Land Management. 333pp.

Geraci, J.R. 1990. Physiologic and toxic effects on cetaceans. pp. 167-97. *In:* J.R. Geraci and D.J. St Aubin (eds.) *Sea Mammals and Oil: Confronting the Risks*. Academic Press, San Diego. xvi+282pp.

Geraci, J.R. and St. Aubin, D.J. 1982. Study of the effects of oil on cetaceans. Final report to the US Department of Interior, BLM contract AA551 CT9 29. 274pp.

Geraci, J.R. and St. Aubin, D.J. 1985. Effects of offshore oil and gas development on marine mammals and turtles. pp. 587-617. *In:* D.F. Boesch and N.N. Rabalais (eds.) *Long-term Environmental Effects of Offshore Oil and Gas Development*. Elsevier Applied Science, New York. 711pp.

Geraci, J.R. and St. Aubin, D.J. (eds.). 1990. *Sea Mammals and Oil: Confronting the Risks*. Academic Press, San Diego. xvi+282pp.

Graham, W.C. 1990. Southbound migrations of the gray whale near San Clemente Island. Paper SC/A90/G15 presented to the IWC Scientific Committee Special Meeting on the Assessment of Gray Whales, Seattle, April 1990 (unpublished). 4pp. [Paper available from the Office of this Journal].

Hansen, D.J. 1985. The potential effects of oil spills and other chemical pollutants on marine mammals occurring in Alaskan waters. MMS 85-0031. US Minerals Management Service, Alaska OCS Region, Anchorage, UK.

Harvey, J.T. and Mate, B.R. 1984. Dive characteristics and movements of radio-tagged gray whales in San Ignacio Lagoon, Baja California Sur, Mexico. pp. 561-89. *In:* M.L. Jones, S.L. Swartz and S. Leatherwood (eds.) *The Gray Whale, Eschrichtius robustus*. Academic Press, Inc., Orlando, Florida. xxiv+600pp.

Heyning, J.E. and Dahlheim, M.E. 1990. Strandings, incidental kills and mortality patterns of gray whales (*Eschrichtius robustus*). Paper SC/A90/G2 presented to the IWC Scientific Committee Special

Meeting on the Assessment of Gray Whales, Seattle, April 1990 (unpbulished). [Paper available from the Office of this Journal].

Heyning, J.E. and Lewis, T.D. 1990. Entanglements of baleen whales in fishing gear off southern California. *Rep. int. Whal. Commn* 40:427-31.

Hubbs, C.L. and Hubbs, L.C. 1967. Gray whale censuses by airplane in Mexico. *Calif. Fish Game* 53(1):23-7.

International Whaling Commission. 1990a. Chairman's Report of the Forty-First Annual Meeting. *Rep. int. Whal. Commn* 40:11-37.

International Whaling Commission. 1990b. Report of the Scientific Committee, Annex N. Biopsy sampling: its effect on individual animals. *Rep. int. Whal. Commn* 40:171.

International Whaling Commission. 2002. Report of the Scientific Committee. *J. Cetacean Res. Manage. (Suppl.)* 4:1-78.

Jones, M.L. and Swartz, S.L. 1984. Demography and phenology of gray whales and evaluation of whale-watching activities in Laguna San Ignacio, Baja California Sur, Mexico. pp. 309-74. *In:* M.L. Jones, S.L. Swartz and S. Leatherwood (eds.) *The Gray Whale, Eschrichtius robustus*. Academic Press, Inc., Orlando, Florida. xxiv+600pp.

Jones, M.L. and Swartz, S.L. 1990. Abundance and distribution of gray whales in the Channel Islands National Marine Sanctuary during the southward migration in January 1986 and 1987. Paper SC/A90/G17 presented to the IWC Scientific Committee Special Meeting on the Assessment of Gray Whales, Seattle, April 1990 (unpublished). 21pp. [Paper available from the Office of this Journal].

Kasamatsu, F. and Ishikawa, H. 1990. Current sightings and stranding of gray whale in the adjacent waters and coast of Japan. Paper SC/A90/G31 presented to the IWC Scientific Committee Special Meeting on the Assessment of Gray Whales, Seattle, April 1990 (unpublished). 5pp. [Paper available from the Office of this Journal].

Kent, D.B., Leatherwood, S. and Yohe, L. 1983. Responses of migrating gray whales, *Eschrichtius robustus*, to oil on the sea surface - results of a field evaluation. Final Report, Contract P-0057621, to the Department of Pathology, Ontario Veterinary College, University of Guelph, Guelph, Ontario, Canada N16 2WA. 63pp.

Leatherwood, J.S. 1974. Aerial observations of migrating gray whales, *Eschrichtius robustus*, off southern California, 1969-72. *Mar. Fish. Rev.* 36(4):45-9.

Ljungblad, D.K., Moore, S.E. and Van Schoik, D.R. 1983. Aerial surveys of endangered whales in the Beaufort, eastern Chukchi and northern Bering Seas, 1982. NOSC Technical Document 605 to the US Minerals Management Service, Anchorage, AK. NTIS AD-A134 772/3. 382pp. [Available from *http://www.mms.gov*].

Ljungblad, D.K., Moore, S.E., Clarke, J.T. and Bennett, J.C. 1987. Distribution, abundance, behavior and bioacoustics of endangered whales in the Alaskan Beaufort and Eastern Chukchi Seas, 1979-86. OCS Study MMS 87-0039, NOSC Technical Report 1177 to the US Minerals Management Service, Anchorage, AK. NTIS PB-88-116470. 391pp. [Available from *http://www.mms.gov*].

Malme, C.I., Miles, P.I., Clark, C.W., Tyack, P. and Bird, J.E. 1984. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior - Phase 2: January 1984 migration. Final Report No. 5586 report prepared by Bolt, Beranek and Newman Inc., Cambridge, MA for the US Minerals Management Service, Anchorage, AK. BBN, Inc. NTIS PB-86-218377. 297pp. [Available from *http://www.mms.gov*].

Malme, C.I., Würsig, B., Bird, J.E. and Tyack, P. 1988. Observations of feeding gray whale responses to controlled industrial noise exposure. pp. 55-73. *In:* W.M. Sackinger, M.O. Jefferies, J.L. Imm and S.D. Treacy (eds.) Vol. 2. *Port and Ocean Engineering under Arctic Conditions*. University of Alaska, Fairbanks, AK. 111pp.

Malme, C.I., Miles, P.R., Miller, G.W., Richardson, W.J., Roseneau, D.G., Thomson, D.H. and Greene, C.R. 1989. Analysis and ranking of the acoustic disturbance potential of petroleum industry activities and other sources of noise in the environment of marine mammals in Alaska. Final Report No. 6945 to the US Minerals Management Service, Anchorage, AK. BBN Systems and Technologies Corp. [Available from *http://www.mms.gov*].

Marine Mammal Commission. 1993. US Marine Mammal Commission Annual Report to Congress, 1992. Marine Mammal Commission, Washington, DC. xii+226pp.

Mathews, E.A., Keller, S. and Weiner, D.B. 1988. A method to collect and process skin biopsies for cell culture from free-ranging gray whales (*Eschrichtius robustus*). *Mar. Mammal Sci.* 4(1):1-12.

Moore, S.E., Ljungblad, D.K. and Van Schoik, D.R. 1986. Annual patterns of gray whale (*Eschrichtius robustus*) distribution, abundance and behavior in the northern Bering and eastern Chukchi Seas, July 1980-83. *Rep. int. Whal. Commn* (special issue) 8:231-42.

Neff, J.M. 1990. Composition and fate of petroleum and spill-treating agents in the marine environment. pp. 1-33. *In:* J.R. Geraci and D.J. St Aubin (eds.) *Sea Mammals and Oil: Confronting the Risks*. Academic Press, Inc., San Diego. xvi+282pp.

Nerini, M. 1984. A review of gray whale feeding ecology. pp. 423-50. *In:* M.L. Jones, S.L. Swartz and S. Leatherwood (eds.) *The Gray Whale, Eschrichtius robustus*. Academic Press, Inc., Orlando, Florida. xxiv+600pp.

Reeves, R.R. 1977. The problem of gray whale (*Eschrichtius robustus*): harassment at the breeding lagoons and during migration. Final report to US Marine Mammal Comnmission, MMC-76/06. 60pp.

Rice, D.W. and Wolman, A.A. 1971. *The Life History and Ecology of the Gray Whale (Eschrichtius robustus)*. American Society of Mammalogists, Special Publication No. 3, Stillwater, Oklahoma. viii+142pp.

Richardson, W.J., Greene, C.R., Hickie, J.P., Davis, R.A. and Thomson, D.H. 1989. Effects of offshore petroleum operations on cold water marine mammals: a literature review. Final Report to the American Petroleum Institute, Washington, DC. LGL Ltd, King City, Ontario. 385pp. [2nd Edition].

Richardson, W.J., Greene Jr, C.R., Malme, C.I. and Thomson, D.H. 1995. *Marine Mammals and Noise*. Academic Press, San Diego. 576pp.

Southwest Research Associates. 1988. Results of the 1986-1987 gray whale migration and landing craft, air cushion interaction study program. USN Contract No. PO N62474-86-M-0942. Final Report to Nav. Fac. Eng. Comm., San Bruno, CA. Southwest Research Associates, Cardiff by the Sea, CA. 31pp.

Sumich, J.L. 1983. Swimming velocities, breathing patterns, and estimated costs of locomotion in migrating gray whales, *Eschrichtius robustus*. *Can. J. Zool.* 61(3):647-52.

Sumich, J.L. and Show, I.T. 1990. Aerial survey and photogrammetric comparisons of southbound migrating gray whales in the southern California Bight, 1988-1990. Paper SC/A90/G8 presented to the IWC Scientific Committee Special Meeting on the Assessment of Gray Whales, Seattle, April 1990 (unpublished). 24pp. [Paper available from the Office of this Journal].

Swartz, S.L. and Jones, M.L. 1979. The evaluation of human activities on gray whales, *Eschrichtius robustus*, in Laguna San Ignacio, Baja California, Mexico. Final report to US Marine Mammal Commission MMC-78/03. NTIS PB-289737. 34pp.

Swartz, S.L., Jones, M.L., Goodyear, J., Withrow, D.E. and Miller, R.V. 1987. Radio-telemetric studies of gray whale migration along the California coast: a preliminary comparison of day and night migration rates. *Rep. int. Whal. Commn* 37:295-9.

Tyack, P. 1989. Long-term effects of whale watching on whales. pp.13-14. *In*: Proceedings of the Workshop to Review and Evaluate Whale Watching Programs and Management Needs. 14-16 November 1988, Monterey, California. Center for Marine Conservation, Washington, DC, and the National Marine Fisheries Service, Silver Spring, MD. 53pp. [Available from *http://www.mms.gov*].

University of California. 1990. Oil and gas project newsletter for fisherman and offshore operators. Marine Advisory Program, University of California, Sea Grant Program Vol. 7(3):1-10.

Watkins, W.A. 1986. Whale reactions to human activities in Cape Cod waters. *Mar. Mammal Sci.* 2(4):251-62.

Weinrich, M.T., Lambertsen, R.H., Baker, C.S., Schilling, M.R. and Belt, C.R. 1991. Behavioural responses of humpback whales (*Megaptera novaeangliae*) in the Southern Gulf of Maine to biopsy sampling. *Rep. int. Whal. Commn* (special issue) 13:91-7.

Weller, D.W., Würsig, B., Bradford, A.L., Burdin, A.M., Blokhin, S.A., Minakuchi, H. and Brownell, R.L. 1999. Gray whales (*Eschrichtius robustus*) off Sakhalin Island, Russia: seasonal and annual patterns of occurrence. *Mar. Mammal Sci.* 15(4):1208-27.

Weller, D.W., Burdin, A.M., Würsig, B., Taylor, B.L. and Brownell, R.L. 2002. The western North Pacific gray whale: a review of past exploitation, current status, and potential threats. *J. Cetacean Res. Manage.* 4(1):7-12.

Wolfson, F.H. 1977. Gray whale behavior. *Science* 195(4278):534-5.

Würsig, B. 1990. Cetaceans and oil: ecologic perspectives. pp. 129-65. *In:* J.R. Geraci and D.J. St Aubin (eds.) *Sea Mammals and Oil: Confronting the Risks*. Academic Press, Inc., San Diego. xvi+282pp.

Wyrick, R.F. 1954. Observations on the movements of the Pacific gray whale *Eschrichtius glaucus* (Cope). *J. Mammal.* 35:593-8.