Ocean Noise and Marine Mammals: A Summary Report of the U.S. National Research Council Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals

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The U.S. National Ocean Partnership Program, with leadership by the Office of Naval Research, requested that the U.S. National Academies examine the potential effects of noise in the sea on marine mammals. The report from an 11-member committee assembled to examine this issue provides information on natural and anthropogenic sources of ocean noise, the observed effects of noise on marine mammals, and reviews current modeling efforts and databases that seek to characterize ocean noise and its potential impact on marine mammals. The report's major conclusion is that the overall adverse impact of manmade sound on the marine environment is unknown, although there is cause for concern. Therefore, the committee report makes a series of recommendations designed to increase understanding of the characteristics of ocean noise, particularly from manmade sources, and their potential impacts on marine animals, especially those that may have population level consequences. These recommendations include establishing various measurement programs as well as numerical modeling, information gathering, coordination, and educational efforts. They build upon the recommendations made in the two previous NRC reports dealing with manmade sound in the ocean and marine mammals. [Work supported by the U.S. National Ocean Partnership Program.]

Impact of Manmade Sounds in the Context of the Natural Sounds in the Ocean

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Marine animals use sound in an environment with high and variable ambient noise from natural sound sources, and assessment of the impact of manmade sounds needs to be made in this context. Assessment of impact is difficult for many animals because of the limited knowledge of their hearing capabilities (as is the case for baleen whales). Some idea of the effect can, however, be obtained by comparing manmade sounds with the natural ambient sounds that the animals have always experienced and can be expected to have adapted to. Because of the relative isolation of Australian waters, many areas have low or negligible manmade noise and significant populations of whales and other marine animals, allowing reliable characterisation of the natural ambient noise. In particular, there are areas free of traffic noise, the noise from distant shipping that dominates low frequency ambient noise in much of the northern hemisphere. This paper discusses the characteristics of natural ambient noise and the inferences that can be made about impact of manmade sounds. For example, while traffic noise is widespread, natural ambient noise from the sea surface and biological choruses often reaches comparable levels and at times well exceeds the highest levels of traffic noise.

HARC: The Humpback Whale Acoustic Research Collaboration

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This is an international, collaborative research project including participants from the University of Queensland, Scripps Institution of Oceanography, Australia`s Defense Science and Technology Organisation and the Woods Hole Oceanographic Institution. The project concentrates on a field study of migrating Humpback whales along the eastern shore of Australia during the 2003 and 2004. HARC includes an intensive study of the physical and acoustic environment using a suite of instrumentation including digital-recording animal tags, simultaneous acoustic and visual tracking, propagation modeling of the noise field and recording of environmental metrics (surface wave field, meteorology, water column characteristics). HARC will attempt a rigorous study of the effects of ambient noise on baleen whale behavior in the presence and absence of anthropogenic sound sources on a migrating population that has received historical study over the last 25 years.

Pilot Studies for the Humpback Whale Acoustics Research Collaboration (HARC)

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The HARC project will build on studies of migrating humpback whales along the east cost of Australia which included passive acoustic and visual (theodolite) tracking, song analysis and behavioural observations. These provide base line data of "undisturbed" migrating humpback whales, important for determining how whales use sound to communicate and in determining the function of song. HARC will involve more active examination of the animals and their behaviours including the use of whale tags and biopsies, and playback experiments. Simultaneous real-time visual and acoustic tracking will allow a research vessel to be directed precisely to singing whales in the study area allowing behavioural interactions between singers and other whales to be observed at close quarters, complimenting data collected from the visual tracking station of behaviours over a much broader scale. Previous observations have suggested that singers reacted to surface active behaviours by females over scales of several kilometres. These interactions require further clarification. In 1997 there was a "natural" play back experiment in which a small number of singers introduced the western Australian song, which replaced the east coast song over the course of the next two years, providing a natural playback for comparison with those proposed in HARC.

Naval Noise and Disturbance of Cetaceans in West Scotland

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West Scotland is an important cetacean habitat, with 24 species recorded. The region also has several naval exercise grounds. In March, June and November, the military undertakes a joint services training exercise in the Minches and Sea of Hebrides and concerns have been raised over noise impacts on cetaceans. Military jets, submarines, warships, landing craft, sonar and sonobouys are utilized during these exercises. Decreased sightings of minke whales (*Balaenoptera acutorostrata*) and harbour porpoises (*Phocoena phocoena*) have been recorded in two areas of high activity (the Small Isles and Gairloch) during the June exercise, with subsequent recoveries after the exercise finished. Concerns over the significant decrease in minke whale sightings during a 1998 joint exercise (A NOVA on log transformed data: $F=4.6$; $p<0.005$) led to the formation of a forum for NGO and military representatives to discuss the impacts of military activities on cetaceans in West Scotland. One issue raised is the potential use of a new low frequency active sonar system (SONAR 2087), which operates with a source level of 200 dB (re 1µP@1m) in a frequency range down to 500 Hz. The legal cases surrounding the introduction of Low Frequency Active (LFA) sonar in the UK are pertinent to the situation in the UK, as disturbance of cetaceans would be in breach of UK and European law.

North Atlantic Right Whales (*Eubalaena Glacialis*) Ignore Ships But Respond to Alarm Signal

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We conducted tagging and controlled exposure experiments with right whales to determine their behavior/response in the presence of vessels to assist the design of ship strike mitigation measures. We exposed whales tagged with our multi-sensor acoustic recording tag (DTAG) to a combination of four stimuli: i) right whale social sounds as a positive control; ii) a negative control designed to be maximally alerting/alarming; iii) vessel noise as the test stimulus; and iv) silence. We exposed 14 whales to 24 playbacks, and then measured their response(s) with the DTAG and visual observations. In response to right whale social sounds, the whales often showed transient responses characterized by heading changes and cessation of fluking. We were unable to detect clear responses to the silent or the vessel noise exposures. In response to the alerting signal, however, 5 out of 6 whales showed a striking and identical response. They aborted their current dive, executed an uncharacteristically shallow-angle powered ascent, and remained at or near the surface until the exposure stopped. Not only were the ascents fully powered, but the whales also exhibited fluke stroke rates significantly above their individually rates. The 6th whale showed no response to the alert/alarm signal.

Responses of Whales to Anthropogenic Low-Frequency Sounds: Results From Field Research

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Baleen whales are low-frequency (<1000 Hz) specialists. They produce a great variety of sounds. Their ears are well adapted for low-frequency perception. Many species perform intense, hierarchically organized, acoustic displays referred to as songs. Calls and songs are assumed to be communicative and hypothesized to function over extensive ranges, but strongly influenced by propagation. These factors underlie the concern over behavioral disruption from anthropogenic sound exposures. Present levels of understanding on sound functions limit the ability to accurately assess behavioral risk. Integrated field research was conducted on multiple species to a) determine the sex of singers and their behaviors relative to oceanographic and ecological factors, b) document natural variability in vocal activity, and c) observe changes in behaviors under opportunistic and controlled exposure conditions. Results reveal high levels of variability under natural conditions. Factors influencing such variablity include ecological and social context, season, and locality. Techniques were sensitive enough to detect statistically significant changes in behavioral measures. The biologically correct interpretation of such changes relative to a source is not clear, but risk of significant behavioral disruption appears to be small. Potential impact from the aggregate increase in anthropogenic exposures remains uncertain.

Underwater Noise From Offshore Wind Turbines: Expected Impacts on Harbor Seals and Harbor Porpoises

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In order to fulfill the requiremnts of the Kyoto agreement, several large offshore windfarms are under construction in Denmark. The windfarms are placed in high-density areas for harbor porpoises and harbor seals. In this study, broadband underwater noise from four different wind turbines has been recorded, analyzed and compared with the auditory capabilities of harbor seals and harbor porpoises. The calculated source levels measured in 1/3-octaves as dB re 1 µPa2/Hz is converted into noise levels that are directly comparable witht the audiograms of harbor seals and harbor porpoises, using the "equal power method" first described in 1956. The noise is only measureable below 1000 Hz. The highest source level is 130 dB re 1 µPa2/Hz at 25 Hz (1/3-octave center frequency. The maximum noise level is 17-20 dB above the calculated hearing threshold of harbor porpoises, depending on masking bandwidth. This corresponds to a detection range of 50-100m. The behavior of harbor porpoises is not expected to be affected. The maximum noise level is 27-30 dB above the hearing threshold of harbor seals, corresponding to a detection range of 500-1000m. This is expected to have some negative impact on harbor seal communication within the windfarms. These effects are under investigation.

Tolerance of Ringed Seals (*Phoca Hispida*) to Sounds from Impact Pile Driving at a Oil Production Island

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During June and July 2000, observers documented underwater and airborne sounds from impact driving of conductor and insulator pipes for oil and gas wells at Northstar Island off Prudhoe Bay, Alaska. They documented reactions to these sounds of ringed seals in an open-water "moat" around the island and basking on landfast ice near the island. Individual pile-driving pulses were analyzed for their flat-weighted peak and rms sound pressure levels and sound exposure levels. Underwater, mean levels for these parameters reached 157 and 151 dB re 1 µPa and 145 dB re 1 µPa2 s, respectively. In air, the corresponding values were 112 and 96 dB re 20 µPa and 90 dB re (20 µPa)2 s, respectively. During seven days, observers saw twenty-one ringed seals within 2 km of pile driving. Seals exhibited little or no reaction to any industrial sound, even within 3 m of the island margin (46 m from the pile driving), except alert reactions to approaching Bell 212 helicopters. Adult and juvenile seals swam in open water near the island throughout the impact driving. Seals would not be expected to hear the pile driving sounds at distances >2 km underwater and >1 km in air. [Work supported by BP Exploration (Alaska) Inc.]

The Offshore Seismic Industry: Some Current Practices & Some Biological Research Efforts

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The current massively growing interest in sound in the oceans and its effects on marine mammals should make it incumbent on the various parties involved in this issue to become educated about the different types of sound and how they are created. The generators of anthropomorphic sounds in the oceans should be willing participants in this education process by creating materials that explain something about the sounds which they produce and why they produce them, and help determine what effects, if any, these sounds have on marine mammals. The characteristics of the sounds emitted from the air-gun arrays used by the seismic contractors who provide services to the global oil and gas industry are not particularly variable, and will be summarized. The basic operations followed when conducting 3D seismic surveys are to be described. The 5-pronged research program recommended by the International Association of Geophysical Contractors will be enumerated. Several oil companies and seismic contractors have been involved in numerous research projects concerned with studying the effects of ocean sound on marine mammals. A few comments will be made about one example of such a study, the current Sperm Whale and Seismic Study (SWSS) in the Gulf of Mexico being jointly conducted by the MMS, ONR, Oregon State University, Texas A&M University, Woods Hole Oceanographic Institution, five oil companies, and the International Association of Geophysical Contractors.

Impact Assessment by Monitoring Cetacean Sonar

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The sonar of toothed cetaceans can be monitored using self-contained loggers such as the 'POD'. This system uses a limited spectral analysis to identify tonal signals. The time of occurrence and duration of each signal are logged to 10 microsecond resolution. On retrieval the data is analysed by the software to detect trains and classify the sources of trains.

The POD has been used to assess the impact on porpoises and dolphins of fishing net pingers, marine windfarm construction and use, tidal power generation, pipeline blasting, synthesised predator calls and some natural events.

POD data can be collected consistently over long periods, day and night, in bad weather, and at a range of depths, and can be deployed unattended for up to 4 months. In all studies in which simultaneous visual observation has been made the POD data has given the same results but with equal or greater precision.

The POD has been used to assess the impact on porpoises and dolphins of fishing net pingers, marine windfarm construction and use, tidal power generation, pipeline blasting, synthesised predator calls and some natural events.

The Influence of Underwater Acoustic Data Communication Sounds on the Behavior of Harbor Porpoises *(Phocoena Phocoena)* in a Floating Pen

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To prevent grounding of ships and collisions between ships in shallow coastal waters, an underwater acoustic data collection and communication network (ACME) is being developed. Marine mammals might be affected by ACME sounds because they use sounds of similar frequencies (around 12 kHz) for communication, orientation, and prey location. If marine mammals tend to avoid the vicinity of the sensors and transmitters, they may be kept away from ecologically important areas. Therefore, as part of an environmental impact study program for the North Sea, two captive harbor porpoises were subjected to sounds which may be used in the underwater acoustic data communication network. Each of the sounds could be made deterrent by increasing the amplitude of the sound. The porpoises reacted by swimming away from the sounds and by increasing their respiration rate. Discomfort zones for several source levels are calculated for the sounds. The discomfort zone is defined as the area around a sound source that harbour porpoises are expected to avoid. Based on these results source levels can be selected that have an acceptable effect on harbor porpoises in particular areas. The

discomfort zone of a sound depends on the selected ACME sound, the selected source level,

and the propagation characteristics of the area in which the system is operational.

Behavioral Responses to Low Frequency Broadcasts

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Acoustic and visual observations were used to study the responses of three species of baleen whale to low frequency acoustic broadcasts using the SURTASS LFA transmit system. Statistically significant responses were documented for several behavioral measures. The scale of these responses was within the range of variation observed when the source was off.

The Role of Song in Maintaining Spacing Between Singing Dwarf Minke Whales *(Balaenoptera Acutorostrata)*: Preliminary Results from Playback Experiments

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Blue, bowhead, fin, humpback, and minke whales all produce repetitive sound sequences (i.e.,songs) thought to be associated with reproduction. The specific functions of singing are still not known. This study on dwarf minke whales (*Balaenoptera acutorostrata*) has previously shown that these minke whales produce a distinct and repetitive song during their breeding season on the Great Barrier Reef. A sonobuoy array was used to localize and track multiple singing whales to test the role of song in maintaining spacing between singers. Nearest neighbor (NN) distances averaging 2.5km (n=22) were measured. All NN distances were greater than 1.2km, leading to a significant deficiency of small NN distances (Pielou test, $p<<0.01$) and indicating competition for space among singers. We actively tested song function for maintaining spacing by conducting playback experiments (10 trials to 11 whales). Upon initiation of song playback, 4 moving whales changed their direction of movement (3 directly away from playback source, 1 initially towards, then directly away), 3 whales stopped singing, 2 stationary

singers moved slightly (400-700m) away from the playback source, while 2 others had no immediately discernable reaction. These initial results support the hypothesis that song is used to maintain spacing between singing individuals.

Humpback Whale Acoustics

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The songs of eight male humpback whales were recorded at ranges varying from 20 to 40 m with both a single hydrophone and a vertical array of hydrophones that had a flat frequency response to 24 kHz. The songs consisted of bursts of sounds called units. Units were organized into phrases and phrases into themes. Most of the units had mean duration between 1 and 2 s and mean silent periods between units between 1 and 2 s. Many of the recorded songs contained units that had high frequency harmonics that extended beyond 22 kHz. These harmonic results suggest that humpback whale songs have a broadband quality not previously reported and may provide some insights on the high frequency limit of hearing in these whales. The source levels of the different songs were also estimated by considering the root mean square sound pressure level referenced to 1 m for the unit with the largest level for each different phrase within a song. Source levels varied between 171 to 189 dB re 1 µPa. Singing escorts have been regularly observed within two whale lengths of females and these observations and knowledge of source levels provide estimates of sound pressure levels that male humpback whales expose female whales too.

Effects of Pile Driving Hydroacoustic Noise on Fish

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Pile driving results in powerful pulsed hydroacoustic pressure waves that cause the swim bladder to contract and then expand resulting in injuries to internal organs including the kidneys, cardiovascular system, and inner ear. The swim bladder of fish very close to the pile being driven may rupture, releasing the swim bladder gas into the body cavity where it expands and the stunned fish float up to the surface where they are quickly taken by piscivorous birds. Pile driving also injure the sensory membranes of the semicircular canals in the fish`s inner ear resulting in disorientation and wild whirling behavior. These fish are easy targets for larger predatory fish. Pile driving injuries tend to be cumulative. The longer the exposure the more severe the injury to the extent that after a period of time the internal organs may be completely homogenized. The radius of delayed mortalities for large pile drivers is greater than 300 meters. A systematic study of the effects of duration and distance on delayed mortalities for two species of fish will be conducted in the summer of 2003. The effectiveness of different types of bubble curtains in reducing mortality will be discussed.

Listening to Fish: Proceedings of the International Workshop on the Applications of Passive Acoustics to Fisheries

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On April 8-10, 2002, MIT Sea Grant hosted an international workshop on the application of passive acoustics in fisheries funded through the Office of Naval Research. The workshop succeeded in bringing together an outstanding group of over 40 international researchers to exchange research results, knowledge and ideas, and demonstrated the high potential of passive acoustics as a research tool, not only in fisheries, but in the census of life and exploration of the seas. Some of the most important research initiatives identified by the workshop participants were 1) developing a national data base of historic underwater sound archives, 2) establishing a national/international reference library of fish sounds, guided by an international panel of scientists, 3) establishing an international research and training center for passive acoustics applications to fisheries and marine census, 4) establishment of regional "listening-posts" to monitor fish sounds and promote passive acoustics research, and 5) the active promotion of the technology through publication of the workshop proceedings and related activities. The workshop has been an important catalyst in the development of cooperative research activities of scientists across North America and Europe and has helped to increase funding opportunities in the United States.

Locating Cod and Haddock Spawning Areas Using Low-Cost Underwater Recorders

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The gadoids Atlantic Cod (Gadus morhua) and haddock (Melanogrammus aeglefinus) are commercially important fish in the northeastern United States. Their management includes measures to protect spawning aggregations from fishing pressure, therefore identifying spawning times and locations are essential to the sustainability of the stocks. Since both species are known to be soniferous during spawning, a program of acoustically monitoring historical spawning locations in the Gulf of Maine is being conducted. The work is being done as cooperative research with commercial fishermen who deploy bottom mounted acoustic recording devices much like passive fishing gear. Low cost underwater listening devices have been developed expressly for the project and are built around Nomad digital recording units. We use 10 GB versions that provide over 2 days of continuous recording at a 11kHz sampling rate. Six units are used by the two boats involved in the project. The total cost of each, including polyethylene housings, external hydrophone, and gel batteries was less than $1,000. The Nomad

recorders are used as data shuttles between the boats and the laboratory where they are uploaded for analysis and archiving. Spawning vocalizations are identified by automated and manual comparisons with sounds recorded from cod and haddock in tanks. Histograms of vocalization occurrence vs. time for each deployment reveals the patterns of spawning activity. Data and sample sounds are portrayed on a project Web site.

Using a Towed Hydrophone Array to Survey Red Drum Spawning Sites in the Western Gulf of Mexico

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A towed hydrophone array was used to survey for red drum (*Sciaenops ocellatus*) spawning sites in the coastal region of the Texas coast in the western Gulf of Mexico. The array was towed at approximately 3.5 kts. during the known spawning time (both season and daily) of red drum. Red drum produce a characteristic drumming sound during courtship and spawning. Although the pulse pattern of the call is variable, the fundamental frequency is consistently around 140-160 Hz. The occurrence of red drum spawning activity was determined by listening to the tapes for characteristic sounds and by examination of spectral analysis of the data stream. We estimated that clearly identifiable calls of individual red drum could be heard over a distance of 80-100m and convergent sounds of numerous red drum over greater but undetermined distances. Individual red drum were heard regularly along the tow track but were seldom heard in close proximity to each other. Drumming occurred over a relatively wide area of the shallow coastal waters. The temporal nature of spawning activity (red drum only spawn during a few hours in the evening) and our limited knowledge of the exact reproductive strategies of red drum make data interpretation somewhat problematic.

Use of Passive Acoustic Sensing to Establish Spawning Areas and Monitor Responses of Fishes in the Drum Family *(Sciaenidae)* to Cetacean-Generated and Anthropogenic Underwater Sounds

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The use of passive acoustics to study fish communication sounds is becoming well established. Fishes produce sounds while mating, in response to disturbance or predation (alarm calls), and in aggressive encounters with other fishes. By listening and recording these fish sounds, we can infer much about their spawning patterns, habitat use, seasonal and long-term abundance patterns, and predator avoidance behaviors. The work we have been doing in Pamlico Sound has shown that particular areas are used for spawning by sciaenid fishes at certain seasons, specifically, weakfish and silver perch near inlets in the spring, spotted seatrout in the summer throughout the Sound, red drum at river mouths in the fall. We have also demonstrated that the silver perch, while producing a spawning chorus, are acoustically sensitive to signature whistle sounds produced by bottlenose dolphins, shutting down their chorus when dolphin are producing whistles nearby or when recorded whistles are experimentally played back to them. They do not respond to a 700-Hz pure tone, however. The sounds produced by a vessel (NC Ferry) have similar frequency components and greater sound pressure levels than a nearby vocalizing red drum, suggesting the potential for interference from anthropogenic sounds.

Human Induced Sound Interference with Spawning Call Performance in Estuarine Fishes

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Historical sound recordings made during field acoustic surveys from 1990 to 2001 documented a variety of human induced underwater sounds as well as a variety of fish and invertebrate sounds. Surveys were conducted along 235 km of the Florida east coast from 29̊ 00` N to 26&#778; 58` N latitude within the Indian River Lagoon estuarine system. Twenty five years of monitoring underwater calls of resident soniferous fishes has demonstrated call site residency during ephemeral call periods. Call periods and sites were highly predictable. Sound produced by passing boats, autos over bridges and trains passing along the Lagoon margin were demonstrated to silence calling males of the spotted seatrout, Cynoscion nebulosus, and the Atlantic toadfish, Opsanus tau. Call analyses indicated that the diagnostic fundamental frequencies along with sound intensity overlapped substantially with certain ephemeral human induced sounds thus silencing the caller. This acoustic interference has the potential to interfere with species reproductive behaviors and thus spawning site choice and fisheries production.

Patterns of Fish Sound Production Measured with Passive Acoustics

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In order to understand the potential impacts of noise on soniferous marine fishes, it is important to understand their patterns of sound production and how sound is used in communication. Passive acoustics was used to measure sound production in damselfish, toadfish, spotted seatrout, and other fishes on seasonal, daily, and subdaily time scales. Most sounds fishes produce are related to courtship and spawning behavior. Sound production ranges from highly coordinated behavior between individual neighboring toadfish to uncoordinated chorus behavior in spotted seatrout. Differences in coordination of sound production can be related to differences in territoriality and modes of reproduction. Toadfish and damselfish are territorial fishes in which males guard benthic eggs laid in nests. Croakers and drums spawn planktonic eggs, and form temporary aggregations of calling males. Many species have increased sound production at dawn and dusk, while others call mainly during the night. Boat noise is the main source of man-made noise in the coastal environment, and mainly occurs during daylight hours. Thus, the effects of masking during courtship behavior may be minimal, but other effects, such as temporary threshold shifts, could affect the ability of fish to hear each other.