Chapter 20
Trends in inputs of anthropogenic noise into the marine environment

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Keynote points

- The main anthropogenic noise sources in the ocean include vessels, industrial activity, including seismic exploration and renewable energy development, and sonar.
- Anthropogenic noise levels vary across space and time, the primary drivers being levels of human activity and propagation characteristics in the region. Noise does not persist once the sound source has been removed from the environment, although impacts can potentially persist.
- Areas with the highest levels of anthropogenic noise are those characterized by heavy industrial use, such as the Gulf of Mexico, the North Sea and the North Atlantic Ocean.
- Areas where anthropogenic noise is expected to increase include the Arctic, as the area opens up to shipping, and Africa, as investment in the region expands.
- Understanding of the impacts of anthropogenic noise on marine biodiversity is increasing, in parallel with a growing recognition of the need to monitor and possibly reduce the noise entering the marine environment.

1. Introduction

The last few decades have been characterized by an increased awareness of the importance of sound to marine life and a greater understanding of the potential impact of anthropogenic noise on such life. In the past 10 years, there has been an increased effort in some regions to develop guidelines and standards for monitoring and regulating the contribution of anthropogenic noise to the marine environment. While anthropogenic noise was not addressed as a stand-alone chapter in the first *World Ocean Assessment* (United Nations, 2017), it was the focus of a meeting of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea.[1] Increasing awareness of its impacts warrants specific consideration in the present Assessment. The current chapter therefore presents a broad overview, including a description of the main sources of anthropogenic noise in the marine environment and the current state of knowledge on the status of such anthropogenic noise. In addition, as the main contributors of anthropogenic noise include shipping, energy generation, and oil and gas exploration and extraction, the chapters of the first Assessment addressing those activities are relevant here.

The United States Navy was an early source of ocean ambient noise data, making recordings that offer insight into ambient sound at frequencies below several hundred hertz (Hz) from the 1950s onwards (Ross, 2005). In addition to individual or small group research efforts, over the last decade, acoustic data has begun to be collected by ocean observing systems on a regional scale, starting with Neptune Canada, now part of Ocean Networks Canada, and the Australian Integrated Marine Observing System. Those observing systems began deploying hydrophones and collecting acoustic recordings in 2008 and 2009, respectively. More recently, the development of metrics and guidelines has also led to advances in impact assessments and modelling of ambient sound using alternative data sources that serve as proxies for major sources of anthropogenic noise, such as Automatic Information System (AIS) and impulsive noise registry data (e.g.,

[1] See A/73/68.

Sertlek and others, 2019; United States National Oceanographic and Atmospheric Administration (NOAA) (2020) CetSound: Cetacean and sound mapping project).

At the same time, challenges remain in the measurement of ambient noise and modelling of acoustic propagation, as well as in the understanding of the impact that noise has on animal populations. Measurement challenges include the collection of calibrated data and the lack of standardization for both measurement and reporting. The American National Standards Institute/Acoustical Society of America and the International Organization for Standardization (ISO) have issued standards for measurement of underwater noise from ships, but the need for arrays of sensors to implement the standards has limited their application. The relatively high cost of deployment and recovery of underwater devices and even costlier installation of cabled systems are an additional impediment to data collection. From the modelling perspective, challenges include the lack of the fine-scale reliable data on environmental conditions needed for accurate models and the low spatial and temporal resolution of measured data for the validation of models. Finally, with regard to impact, work is under way to improve understanding of the hearing sensitivities of many species, in particular baleen whales, the cumulative effects of multiple noise sources and the impacts at the level of populations; however, practical difficulties remain.

2. Description of the environmental status

Sound is an efficient means of communication in the marine environment as sound waves travel very well through water, at speeds approximately five times higher than in the air. Nevertheless, the acoustic power is diminished as sound travels away from the source. Differences in absorption and spreading losses at different frequencies mean that lower sound frequencies travel further than higher frequencies. In addition, the properties of the environment affect sound propagation, ocean bottom and water properties affect the sound speed and bottom topography affects the direction of sound travel. In deep waters, special environmental conditions can result in the efficient propagation of sound in a deep channel or the convergence of sound at regular distances (Jensen and others, 2011). Unique propagation conditions, such as the waveguide effect or the Lloyd mirror effect, can contribute to the intensification of sound near the surface (Jensen and others, 2011), and bathymetric shielding can create large variability in sound intensity among nearby locations (McDonald and others, 2008).

Sound levels in the ocean, reported in units of decibels (dB), are calculated by referencing the measured sound pressure levels (in units of pascals) to one micropascal (dB re 1 μPa). Sound pressure levels are typically measured as instantaneous peak or peak-to-peak values or by calculating the root-mean-square of sound pressure for longer duration signals. Those differences in measurements result in sound pressure level differences of up to 4.5 dB. It should be noted that, since sound levels in air are calculated relative to 20 micropascals, ocean and air sound levels are not directly comparable. Higher acoustic impedance in water relative to air further contributes to a difference in measurements between those environments. As a result, a correction of 61.5 dB is required to compare airborne sound levels with those made underwater. When reporting noise levels, the calculation of power spectral density requires further normalization by the bandwidth of the signal and is thus typically reported in units of dB re 1 $\mu Pa^2/Hz$. Background ocean ambient sound levels in the absence of noise are not uniform across different frequencies, but range from 60 to 70 dB re 1 μPa^2/Hz at frequencies below 100 Hz and decrease to below 40 dB re 1 μPa^2/Hz at frequencies higher than 10 kilohertz (kHz) (Wenz, 1962). Particle motion, another component of sound waves, is more challenging to measure, but is an important consideration when evaluating the impact of sound on fish (Popper and Hawkins, 2019).

Major contributors to the ocean soundscape include geophysical sources, such as wind, waves, ice, volcanoes and earthquakes; biological sources, such as marine mammals, fishes and invertebrates; and anthropogenic sources. There are multiple sources of anthropogenic noise in the marine environment; the main ones include vessels (e.g., merchant ships, fishing vessels and recreational and cruise ships), industrial activity (e.g., offshore energy generation, including seismic exploration activity, coastal development and mining operations) and sonar (e.g., sonars used for fishing and for military and scientific purposes). In some cases, the production of sound is intentional and critical for the activity in question, as with seismic exploration and sonar, while in others it is incidental, as with shipping and coastal development. Anthropogenic noise levels are variable across space and time, two primary drivers being levels of human activity present and acoustic propagation characteristics in the region.

An overview of the main anthropogenic contributors to ocean ambient sound, the level for each source and the main frequency range is provided in the table below. Following the approach taken in other reviews of ocean noise, seismic survey activity is considered separately from other industrial activities, as it is a major contributor at low frequencies over large scales, with impacts that are substantially different from those of other industrial noise sources. A review of the impacts of noise on marine life is also provided. Among possible impacts considered here are physiological and behavioural effects, as well as impacts on mortality, when that was reported in the past. An important extension of those studies on the impact of noise on individuals, however, is an understanding of the consequences of acoustic disturbance at the level of populations, including cumulative effects (National Academies, 2017).

2.1. Marine traffic as a contributor to ocean noise

The dominant sources of sound emanating from marine vessels are cavitation and turbulence generated by propellers, but machinery is also a substantial component of the acoustic energy contribution, transmitted and radiated through the ship's hull (Ross, 1976). The flow noise generated as a ship advances through the water adds, at a lower level, to the vessel's contribution to ambient noise. The levels of contribution from the various components depend on a series of physical variables, including the ship's dimensions, tonnage, draft, load and speed, as well as wind and sea conditions, in as far as they interfere with the ship's movement in the water.

Marine traffic covers merchant shipping, cruise liners, military vessels, ferries, fishing boats and coastal boating for recreational purposes. Merchant shipping includes container ships, oil tankers, dry bulk carriers, general cargo ships and passenger liners. Different ship classes have distinct noise signatures that also depend on ship speed and length (Ross, 1976; McKenna and others, 2013). For example, a modern commercial container ship at a typical operating speed of 12 metres per second (m/s) has sound levels of 195 dB re 1μPa at 1 m with most acoustic energy below 100 Hz (Gassmann and others, 2017). In the case of smaller vessels (e.g., those below 20 m long, such as passenger and fishing boats, recreational high-speed boats, jet skis, etc.), radiated sound levels are lower (128–142 dB re

1 μPa at 1 m; Erbe, 2013) with a power spectrum including acoustic energy above 1 kHz (Erbe, 2013), resulting in propagation ranges shorter than those of commercial shipping.

Merchant shipping noise is often the main anthropogenic contributor to ocean noise at frequencies below 200 Hz (Wenz, 1962; Frisk, 2012; Roul and others, 2019). Globalization of the economy has resulted in a steep increase in merchant shipping throughout the world in the past 30 years. The global volume of seaborne trade has steadily increased (except in 1985 and 2009), reaching 10.7 billion tons in 2017 (United Nations Conference on Trade and Development (UNCTAD), 2018). Mean annual growth of 3.8 per cent was projected for the period 2018–2023; however, that could be affected by the COVID-19 pandemic. In addition to a steady increase in the volume of trade, vessels are also spending more time at sea, with an increase of 5 per cent recorded in 2017 (UNCTAD, 2018). The total gross tonnage has also increased in line with the volume of trade. Overall increases in merchant shipping are highly correlated with increases in ocean sound pressure levels, which rose by approximately 3 dB re 1 μPa^2/Hz per decade over the 10–50 Hz band throughout the last decades of the twentieth century (McDonald and others, 2006). That increase appears to have plateaued since the start of the twenty-first century (Frisk, 2012, and references therein).

The "distant shipping" component of ambient noise, which arises when signatures from individual vessels are indistinguishable in the data, but appear as increased acoustic energy at frequencies below 100 Hz (Wenz, 1962) at a given location and time, strongly depends on ship distribution at that moment. Shipping is unevenly distributed by latitude, with higher densities in the northern hemisphere along heavily used shipping lanes. As a result, high levels of ambient sound (80–90 dB re 1 μPa^2/Hz or more) at frequencies dominated by shipping (10–100 Hz) are typically found in the North Atlantic Ocean and the North Pacific Ocean (Ross, 2005; McDonald and others, 2006; Širović and others, 2013; 2016). In the Arctic, where shipping traffic is substantially lower, ambient noise at low frequencies is largely driven by environmental factors, such as sea ice cover and wind conditions (Roth and others, 2012). In coastal waters, near busy harbours and beaches, small and medium-sized fishing vessels, recreational boats and small ferries can also be important contributors to anthropogenic noise (Samuel and others, 2005; Merchant and others, 2012).

Ambient noise levels from distant shipping have not been linked to lethal, tissue-damaging or other direct physical injury in marine mammals (although see chap. 6D for other threats to marine mammals caused by shipping). Shipping and small craft noise has been associated with wide-ranging impacts on the survival, physiology and behaviour of individuals, with potential consequences for the survival of populations and communities across a number of marine taxa. In marine mammals, those include increased stress levels in North Atlantic right whales (*Eubalaena glacialis*) (Rolland and others, 2012); changes in the foraging behaviour of humpback whales (*Megaptera novaeangliae*) and their vocalizations during the breeding season (Blair and others, 2016; Tsujii and others, 2018); changes in harbour porpoise (*Phocoena phocoena*) behaviour (Dyndo and others, 2015); and changes in calling behaviour and the masking of or reduction in communication space (Parks and others, 2010; Putland and others, 2018). In other taxa, the impacts include increases in stress levels for a number of fish species (see, for example, Nichols and others, 2015; Simpson and others, 2016a), potentially resulting in an increased predation risk in some species (Simpson and others, 2016a), a reduced ability of fish and coral larvae to select suitable habitats (Simpson and others, 2008; 2016b) and the masking of and reduction in communication space (Putland and others, 2018; Weilgart, 2018 and references therein).

2.2. Seismic exploration as a contributor to ocean noise

The use of sound to image sub-sea floor geological structures is the predominant marine geophysical technique employed by the offshore oil and gas industry. Seismic reflection profiling provides information about potential oil and gas deposits several kilometres below the sea floor. To generate the high levels of sound needed to penetrate the solid earth, large arrays of airguns are towed behind survey vessels. Each airgun releases a volume of air under high pressure, creating a high intensity sound pressure wave. Typically, an array of airguns used in the seismic industry will include from 25 to 50 individual guns (Dragoset, 2000). The acoustic pressure signal of airgun arrays is focused vertically, producing a signal 12–15 dB stronger in the vertical direction for most arrays. The peak source level for those arrays is impossible to calculate at a standard 1 m reference but, according to a simplified estimate, if it is considered as a single source, it can reach 260 dB_{peak} re 1 µPa at 1 m (Turner and others, 2006). Seismic operations can be limited in duration (weeks to months) but, depending on bathymetry, can affect entire ocean basins as low frequency signals propagate over significant ranges.

Seismic surveys can also be conducted for research purposes, including outside of areas that are subject to commercial surveys, such as in the Southern Ocean. High resolution geophysical surveys are also conducted in coastal areas for the construction of critical infrastructure, such as bridges, ports and, more recently, offshore wind farms. Those surveys employ sound sources such as sparkers and Uniboom that are less powerful (210–230 dB re 1 µPa at 1 m) than airguns and operate in a higher frequency band (0.5–2.5 kHz; Gontz and others, 2006). While those surveys tend to be localized in both time and space, their impact may be relevant for sensitive inshore species and ecosystems.

Marine areas of all continents except Antarctica are undergoing active seismic exploration. The Gulf of Mexico has among the highest levels of activity in the world, with deepwater exploration the dominant source of low frequency ambient noise in that region (Wiggins and others, 2016). High activity has also occurred in the North Atlantic (Nieukirk and others, 2004), the South Atlantic (Miksis-Olds and Nichols, 2016; Haver and others, 2017) and the North Sea (Hildebrand, 2009). Seismic survey activity was increasing in the late 2000s and early 2010s owing to increasing prices of crude oil, in particular in such areas as the South Atlantic and the Mediterranean Sea (Maglio and others, 2016). The global average number of active seismic vessels increased from 40 in 2004 (Hildebrand, 2009) to 75 by 2014 (based on seismic crew records), with the highest levels of activity recorded in the Gulf of Mexico, Europe, Asia Pacific and Africa. However, following a decline in crude oil prices in 2015 and 2016, the number of active vessels had decreased to 58 by mid-2018 (GeoTomo, 2018).

The impacts on marine life of sound produced during seismic exploration surveys have been documented across a number of taxa, ranging from zooplankton to marine mammals. McCauley and others (2017) reported zooplankton depletion immediately following seismic operations, concurrent with an increase in dead zooplankton comprising a variety of species. Controlled experiments on scallop larvae showed that they exhibit significant developmental delays and developmental malformations if exposed to seismic airgun pulses (Aguilar de Soto and others, 2013), while adult scallops were observed to have disrupted reflexes (Day and others, 2016). Seismic operations may also be implicated in the stranding of giant squids (Guerra and others, 2004). Fish have been observed to exhibit behavioural and physiological changes as a result of seismic operations (Weilgart, 2018 and references therein), with changes in fish catch rates also reported (Løkkeborg, 1991; Løkkeborg and others, 2012). Seismic operations have been observed to have a negative impact on baleen whale communication (Di Iorio and Clark, 2009; Cerchio and others, 2014). While a number of impacts of seismic exploration on marine life have been observed, controlled exposure experiments have reported no observable impacts on the development and survival of southern rock lobster (*Jasus edwardsii*) embryos and Dungeness crab larvae (*Metacarcinus magister*) (Pearson and others, 1994; Day and others, 2016) and a limited effect on the copepod *Calanus finmarchicus* (Fields and others, 2019).

2.3. Industrial activity as a contributor to ocean noise

A comprehensive review of underwater noise from industrial activity was completed in 2003 by the National Research Council (NRC) of the United States of America. Below is a summary of the main findings of that report and of the research in the area of ocean industrial noise published since 2003. For the purposes of the present chapter, non-seismic oil and gas industry contributions have been separated from other industrial activity that contributes to marine noise.

2.3.1. Industrial noise from the oil and gas industry

As well as through seismic surveys, the purpose of which is to explore for oil and gas, the oil and gas industry also contributes noise during the drilling and production phases. Oil and gas industrial activities occur worldwide from latitudes 72° north to 45° south. Activities associated with seismic surveys and oil and gas production are present along the coastlines of all the continents of the world except Antarctica (NRC, 2003). The noise levels associated with oil and gas production and associated activities, such as the installation of pipelines, the generation of energy on platforms, pipeline flow and support vessel activity, are typically much lower than those associated with seismic surveying (Richardson and others, 1995). The impacts of that production noise can be restricted to areas near facilities, but persist during the active life of the facility, which can last for years (ibid.). Based on data collected along the North Slope of Alaska and the adjoining coast of Canada, ships actively engaged in drilling activity have high radiated sound levels with a maximum broadband source pressure level calculated from the root-mean-square of pressure across the 10 Hz–10 kHz band of about 190 dB_{rms} re 1 μPa at 1 m (Richardson and others, 1995).

2.3.2. Other industrial and construction contributions to ocean noise

The range of activities in this category is extremely broad. Pile-driving and power-generating wind turbines are often found in deeper waters, while dredging, coastal development and associated construction, shipyards and daily harbour functions located near the shore contribute noise in shallow waters. Deep seabed mining is still largely limited in scope because of prohibitive costs (Miller and others, 2018; Thompson and others, 2018), but may expand in future. The compound impact of various industrial activities, for example, a combination of terrestrially based, shoreline or nearshore sound sources, on the marine environment is poorly understood. Nevertheless, that broad range of industrial activities produces a range of source levels and acoustic patterns described in detail below.

Pile-driving typically consists of thousands of impacts by large hammers occurring about once a second to drive stabilizing structures for above-water structures into the seabed. Pile-driving noise source levels are substantial, with peak source levels ranging from 226 to 248 dB_{peak} re 1 μPa at 1 m (Bailey and others, 2014; Miller and others, 2017). There are a number of techniques for reducing propagated noise levels from pile-driving, including the use of freely rising bubble screens (Würsig and others, 2000), fixed air bubble screens (Rustemeier and others, 2011) and Helmholtz resonator screens (Lee and others, 2012). Deployment of those techniques has the potential to reduce received sound levels away from the activity by up to 20 dB, although average reductions are in the order of 5 dB (Buehler and others, 2015).

Operating offshore wind farms produce noise levels of about 150 dB re 1 μPa at 1 m (Nedwell and Howell, 2004; Hildebrand, 2009). That can represent a 5–25 dB increase in overall ambient sound levels at nearby locations (within approximately 1 km) (Norro and others, 2011). As with oil and gas facilities, the noise associated with wind farm construction, largely stemming from pile-driving activities, is limited in duration, but can affect large areas of the ocean. Once the wind farms are operational, noise generated by the operation will affect a smaller area, but will last throughout its exploitation.

In recent years, there has been renewed interest in commercial operations for extracting economically valuable metals from the deep sea, including in hydrothermal vent locations worldwide, with exploration undertaken in the Mid-Atlantic Ridge area around the Azores (see also chap. 18). The levels of sound those activities contribute to the deep sea are unknown.

Anthropogenic noise from dredging consists of sound from ship-borne machinery and mechanical motion, for example from suction and earth-moving devices, as well as the possible use of explosives. Noise levels recorded during dredging range from approximately 163 dB to 190 dB re 1 μPa at 1 m, depending on the type of dredging operation (Greene, 1985; Nedwell and others, 2008; Robinson and others, 2011; Reine and others, 2012; McQueen and others, 2020).

Those various industrial activities can have differing impacts on marine life. Impulsive noise such as that created by pile-driving has been observed to disrupt harbour porpoise habitat use (Carstensen and others, 2006) and has the potential to cause hearing impairment in marine mammals and fish close to the noise source (Madsen and others, 2006; Casper and others, 2013). The noise generated by pile-driving has been observed to increase metabolic rate in some fish and mussel species (Spiga and others, 2016; Bruintjes and others, 2017), as well as to alter fish swimming and schooling behaviour (Mueller-Blenkle and others, 2010; Herbert-Read and others, 2017) and elicit responses in squid (Jones and others, 2020). Vibrations of the seabed resulting from experiments designed to simulate pile-driving have also been observed to have a negative impact on the growth and body condition of bottom-dwelling mussels (Roberts and others, 2015). While fish and marine mammals can detect sounds from operating wind farms at distances of a few kilometres, it is not known if those sounds cause any disruptions to their biological functioning, although they were shown to disrupt crab settlement (Pine and others, 2012).

2.3.3. Ocean noise from sonar

Different types of sonars are used for mapping the ocean bottom and detecting and localizing various objects in the water column (e.g., plankton, fish or submarines). Sonar is used by the military, the commercial, charter and recreational fishing communities, and the scientific research community, among others. The type of use is different within each of those groups.

Sonar use in the military is primarily focused on anti-submarine warfare and involves two types of sonar: low-frequency active (LFA) sonar and mid-frequency active (MFA) sonar. LFA sonar operates in the 100–500 Hz band, with an overall source level of 230–240 dB re 1 μPa at 1 m, allowing detection over long ranges (hundreds of kilometres). MFA sonar operates at frequencies of 2–8 kHz, has a source level of 235 dB re 1 μPa at 1 m (Hildebrand, 2009) and operates over ranges of tens of kilometres. The

United States Navy has four ships dedicated to LFA sonar use, and there are approximately 300 MFA sonars in active service in the world's navies (Hildebrand, 2009).

In non-military uses, the sonars most frequently encountered on vessels include "fish finders" and other echo sounders, called multibeam sonars and side-scan sonars, operating at single or multiple frequencies. Sonars not used for military purposes generally operate at lower source levels than military sonars and, in most cases, their beams are directed downwards under the vessel track, or across the track in the case of multibeam sonars. The typical operating frequency of a fish finder is between 15 and 200 kHz. The multibeam mapping sonars typically used by the research community operate at frequencies ranging from 12 kHz for deepwater systems to 400 kHz for shallow-water systems, with narrow directional beams (approximately 1 degree) and source levels between 232 and 245 dB re 1 μPa at 1 m (Hildebrand, 2009).

The use of LFA sonar has been restricted by some countries owing to concerns about its impact on divers and marine mammals (Miller and others, 2000), although it has been reported that LFA sonar does not affect the behaviour of herring (Doksæter and others, 2012). The use of MFA sonar has been implicated in the stranding of multiple species of cetaceans (Balcomb and Claridge, 2001). Beaked whales appear to be particularly sensitive to that type of sonar, which has been associated with both physiological damage (Fernández and others, 2005) and behavioural changes in several beaked whale species (Tyack and others, 2011; DeRuiter and others, 2013; Moretti and others, 2014). Overall, however, responses vary by population, and there is some indication that beaked whales regularly exposed to MFA sonar may acclimate to the sound (Bernaldo de Quirós and others, 2019). Presence of MFA sonar has been observed to alter the behaviour of baleen whales (Goldbogen and others, 2013) and multiple odontocete species (Sivle and others, 2012). Beaked whales also appear to be sensitive to other forms of sonar, with observed changes in their behaviour documented in the presence of an echo sounder deployed for scientific purposes (Cholewiak and others, 2017).

Main sources of anthropogenic noise

Industry/sector	Sound source	Sound type	Source level (dB re 1 μPa at 1 m)	Frequency of main energy (kHz)
Commercial shipping				
Medium-sized ships (50–100 m)	Propeller/cavitation	Continuous	165–180[a]	< 1
Large vessels (e.g., supertankers and container ships)	Propeller/cavitation	Continuous	180–219[a]	< 0.2
Resource exploration and exploitation				
Oil and gas	Seismic airgun	Impulsive	220–262[c]	0.05–0.1
	Drilling	Continuous	124–190[a]	0.1–1
Renewable energy	Impact pile-driving	Impulsive	220–257[c]	0.1–2
	Operational wind farm	Continuous	144[a]	< 0.5
Navy	Low-frequency sonar	Impulsive	240[b]	0.1–0.5
	Mid-frequency sonar	Impulsive	223–235[b]	2.8–8.2
	Explosions (e.g., ship shock trials and exercises)	Impulsive	272–287[a]	0.006–0.02
Fishing	Propeller/cavitation	Continuous	160–198[a]	< 1–10
	Deterrent/harassment device	Impulsive	132–200[b]	5–30
	Sonar (echo sounder)	Impulsive	185–210[b]	20–260
Dredging	Propeller/cavitation, cutting, pumping, grabbing and digging	Mainly continuous	163–188[a]	0.1–0.5
Marine scientific research (e.g., research vessel)	Propeller/cavitation	Continuous	165–180[a]	< 1
Recreational activities (e.g., recreational craft and speedboat)	Propeller/cavitation	Continuous	160–175[a]	1–10
Tourism (e.g., whale and dolphin watching and cruise ships)				
Vessels (<50m– >100m)	Propeller/cavitation	Continuous	160–190[a]	< 0.2–10
Harbour construction	Impact pile-driving (e.g., sheet piling)	Impulsive	200[b]	0.1–0.5

Source: United Nations document A/73/68, annex.

[a] Root-mean-square sound pressure level.

[b] Peak sound pressure level.

[c] Peak-to-peak sound pressure level.

3. Description of economic and social consequences and other economic or social changes

During the discussions of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea on anthropogenic underwater noise in 2018, the importance of addressing the socioeconomic impacts of such noise was stressed. It has been shown, for example, that the presence of seismic airgun surveys reduces catches of gadid and sebastid fishes (Hirst and Rodhouse, 2000). That may result in short-term economic loss for concerned fisheries during seismic surveys. The impacts of noise on species that are of particular social, economic and cultural relevance may have socioeconomic effects on coastal communities, in particular if they alter the availability of commercially or recreationally important marine species. A similar decline of social and economic benefits may be expected in association with the displacement of marine mammals that are the focus of tourism activities. In addition, the displacement of marine animals may affect traditional and cultural practices of indigenous communities that rely on artisanal fishing and subsistence hunting. The area of interactions between anthropogenic noise and its impact on social and economic factors has not been well studied in the past, but an increased interest in anthropogenic noise in the ocean may lead to a greater focus on the human consequences of the increase in noise.

While anthropogenic underwater noise may be most obviously connected to the achievement of Sustainable Development Goal 14 (Conserve and sustainably use the oceans, seas and marine resources for sustainable development), it is also linked to a number of other Goals.[2] Ensuring access to affordable, reliable, sustainable and modern energy for all (Goal 7) is likely to lead to localized, short-term increases in anthropogenic noise levels in the ocean during the construction of offshore wind farms, but could result in an overall reduction in anthropogenic noise associated with a decrease in the need to exploit fossil fuels. The successful implementation of Goal 11, on sustainable cities and communities, and Goal 12, on responsible consumption and production, could ultimately affect overall anthropogenic noise in the ocean if the achievement of those goals results in changes in global shipping.

4. Key region-specific changes and consequences

4.1. Arctic Ocean

The opening up of shipping channels in the Arctic as a result of decreases in sea ice caused by climate change has started to result in increased ship traffic through the Arctic Basin (Eguíluz and others, 2016). While it is still a rather uncommon path, the Arctic is likely to become a more common shipping and tourism route in the future, as sea ice continues to recede (Smith and Stephenson, 2013). The consequences for local Arctic communities and marine animals of changes in shipping and, in particular, associated changes in soundscapes to more anthropogenically driven ones are largely unknown (Ho, 2010). Oil exploration in the Chukchi Sea began in the mid-2000s, but further exploration and development were abandoned when the region's reserves were found to be insufficient to warrant additional investment (Shell, 2015). Offshore oil and gas development in the Canadian Arctic is

[2] See General Assembly resolution 70/1.

currently not allowed, with a review of the ban due in 2021 (Nunatsiaq, 2016).

4.2. North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

The North Atlantic is a busy shipping route all year round (Vettor and Soares, 2015). Seismic exploration noise is seasonally present in the polar areas of the North Atlantic (Klinck and others, 2012; Haver and others, 2017). A rapid expansion of offshore wind farm development in the North and Baltic Seas has resulted in the presence of nearly 90 operational wind farms, as of 2018, and continued development in the future is predicted (Xu and others, 2020; Rusu, 2020), which will result in substantial increases in noise during the building phase (Miller and others, 2017). The main noise hotspots in the Mediterranean are the areas around major harbours. In addition, the Ionian Sea and the Adriatic Sea, as well as coasts along north-western Africa and in the eastern Mediterranean, have seen a recent increase in oil and gas exploratory surveys (Maglio and others, 2016). An increase in seismic activity in the Black Sea is also a possibility (Broad, 2014).

4.3. Gulf of Mexico, South Atlantic Ocean and Wider Caribbean

The number of vessels conducting seismic surveys has decreased in the Gulf of Mexico, but expanded off the Atlantic coast of South America (GeoTomo, 2018; United States Energy Information Administration (USEIA), 2020), potentially increasing noise levels at low frequency over the past decade. Large discoveries of offshore oil by Guyana (Cummings, 2018) may lead to higher levels of seismic exploration and industrial activity in the area. Noise associated with vessel traffic is ubiquitous throughout the Caribbean (Heenehan and others, 2019).

4.4. Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Development in Africa, including an increased number of new ports, is contributing to a rapid expansion in shipping in the region (Tournadre, 2014), which is in turn increasing anthropogenic noise in areas that were previously relatively noise-free. Seismic exploration continues offshore from Australia (Paumard and others, 2019).

4.5. North Pacific Ocean

New offshore wind projects are being developed off Japan, the Republic of Korea, Taiwan Province of China, and China (Yang and others, 2018; Li and Yuan, 2019). As part of that process, Japan is also starting to define acoustic monitoring parameters. Similarly, offshore wind projects have been proposed, but not yet permitted or constructed, off the west coast of the United States (Bureau of Ocean Energy Management, 2020). Some areas along the west coast of the United States, as well along the Hawaiian island chain, are designated as marine sanctuaries and could be protected from direct development.

4.6. South Pacific Ocean

Seismic exploration continues offshore from Australia and New Zealand (e.g., Cheong and Evans, 2018; Urosevic and others, 2019). Otherwise, the South Pacific remains relatively free from anthropogenic noise sources, with little shipping and industrial development.

4.7. Southern Ocean

The Southern Ocean has seen an increase in cruise ship traffic in recent years, both in the Antarctic Peninsula region, which has had some cruise ship traffic in the past, and in Eastern Antarctica and the Ross Sea, both previously unexplored (Sánchez and Roura, 2016). Overall, however, the region has had few anthropogenic noise sources, with little shipping and industrial development (Dziak and others, 2015).

5. Outlook

Anthropogenic noise in the ocean is largely driven by shipping, oil and gas exploration, and, at the more local or regional level, coastal development. Population growth, migration to coastal areas, increased industrialization and tourism and other developments will result in an increase in activities that contribute to anthropogenic noise, unless accompanied by mitigation efforts. A number of such efforts have been initiated. The Scientific Committee of the International Whaling Commission (IWC) has endorsed the goal of reducing ocean ambient sound by 3 dB in the next decade and 10 dB over the next 30 years. IWC is actively engaged with the International Maritime Organization (IMO) on discussions regarding strategies to achieve those reductions. One step may be to reduce noise from shipping, a major anthropogenic noise contributor at low frequencies in the open ocean (Wenz, 1962; Frisk, 2012; Roul and others, 2019). Shipping noise can be reduced by modifying propeller blades to make them quieter and by isolating engines and other noise contributors on the vessel so that the noise generated by them does not propagate through the ship into the ocean. Those technologies already exist but need wider implementation. Alternative measures being considered that can be implemented without technological advancements include decreasing ship speed or diverting ship traffic away from sensitive areas for marine life, such as marine sanctuaries, parks or reserves. In the oil and gas industry, new alternatives to the use of airguns in exploration surveys, such as marine vibrator technology, are being investigated. Even with new technological advances, adequate protection of the marine environment cannot be reached without a consensus on a global approach that fills the knowledge gaps related to anthropogenic noise impacts. Taking those considerations into account, for example, in 2014, IMO adopted the Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life.

The importance of anthropogenic noise has been acknowledged by various United Nations entities. In June 2018, anthropogenic noise was the main topic of the nineteenth meeting of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea. The presentations and discussions during the meeting covered, inter alia, a review of the sources of anthropogenic noise, the effects and socioeconomic impacts of noise, and cooperation and coordination among States to address anthropogenic noise. Among other things, it was noted that the application of a precautionary approach to the management of noise impacts had been proposed at both the regional and global levels and that cross-sectoral cooperation was needed for identifying and mitigating impacts.[3]

Given that sound is a form of energy, its introduction into the marine environment is regarded by many as a form of contamination, owing to its potentially deleterious effects. In its resolution 12.14, the Conference of the Parties to the Convention on the Conservation of Migratory Species of Wild Animals recognized the impact of anthropogenic underwater noise on marine species and encouraged further study and mitigation of such noise. It also endorsed guidelines on environmental impact assessment for marine noise-generating activities

[3] See A/73/124.

that had been developed in collaboration with the secretariats of the Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and contiguous Atlantic area and the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas. Furthermore, it welcomed related technical support information (Prideaux, 2017).[4]

A number of States have been developing their own guidelines for managing ocean noise. The European Union has a mandate from its member States to measure and report anthropogenic noise under descriptor 11 of the Marine Strategy Framework Directive adopted in June 2008. The aim of the Directive is to achieve good environmental status by 2020, with each member State determining how that might be achieved. Under the Directive, there has been a proliferation across the region of ocean noise-targeted projects, including noise registers or databases with specifications on impulsive noise activity. Examples of those registers include the Baltic Marine Environment Protection Commission impulsive noise register and the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and neighbouring Atlantic Area noise register for the Mediterranean and Black Seas. Canada is building the Marine Environmental Research Infrastructure for Data Integration and Application Network,[5] a database on underwater acoustics and vessel tracking, including visualization and analytical tools to provide information to managers, the public and researchers. In the United States, measures for comprehensively managing the impact of noise on marine species are set out in the National Oceanographic and Atmospheric Administration Ocean Noise Strategy (Gedamke and others, 2016), which also includes the use of mapping tools to assist in evaluating the impacts of anthropogenic noise on cetaceans (NOAA, 2020). Those national efforts to document noise sources should result in an increased ability to map variability in sound levels across the region. At the same time, such initiatives are leading to increased efforts to standardize data collection and measurements. For example, the International Quiet Ocean Experiment, a collaborative international science programme aimed at promoting research, observation and modelling to improve the understanding of ocean soundscapes and the effects of sound on marine organisms, has established working groups on data collection and data management standardization.

Sound has also recently been identified as an Essential Ocean Variable by the Biology and Ecosystems Panel of the Global Ocean Observing System (GOOS) (GOOS, 2020). Ocean sound is recognized as a cross-disciplinary variable as it includes such geophysical sources as wind, bubbles, ice, earthquakes and volcanoes. That global recognition and incorporation of observing systems into new initiatives should contribute to an increase in monitoring of anthropogenic noise, as well as to a better understanding of its contributions to ambient sound and of possible changes in soundscapes over time, in particular in relation to changing ocean use and climate change.

High levels of noise in the ocean can have a variety of consequences for marine life. A theoretical framework to evaluate the consequences of acoustic disturbances at the level of populations is available for marine mammals, but should be applicable to other taxa as well (Pirotta and others, 2018). Such an approach can be used for management purposes, but also offers a framework to investigate the proximate mechanisms of phenomena that induce changes at the individual level and guide future data collection and

4 Detailed information on the *CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-generating Activities* is available at www.cms.int/guidelines/cms-family-guidelines-EIAs-marine-noise.

5 See https://meridian.cs.dal.ca.

model development. Considering that those consequences occur among commercially and recreationally important species, as well as those that are relied on for subsistence, there is potential for negative social and economic impacts. For example, a reduction in the recruitment of commercially important fishes (Simpson and others, 2008) may lead over time to a reduction in catches, and higher mortality may decrease fishery yields. For species that are the focus of tourism activities, those activities themselves, for example whale watching, may result in increased noise and can cause impacts (Erbe, 2002; Holt and others, 2009).

6. Key remaining knowledge gaps

Several challenges remain in evaluating the relative increases and possible impacts of anthropogenic noise in the ocean. A fundamental problem is the lack of knowledge regarding baseline ocean ambient noise. Given that no recordings are available from time periods prior to human activities, there is limited understanding of the marine soundscapes that marine life evolved with or the extent to which they might have adapted to anthropogenic noise inputs. The best proxy are regions outside the influence of human development and activity, which may exist in isolated basins, such as areas of the Southern Ocean, or were present until recently in parts of the Arctic. However, on the basis of best estimates, many regions of the ocean have ambient noise levels at low frequency (10–200 Hz) at least 20–30 dB higher than primordial levels.

Another major gap is in the understanding of the impact of noise on marine ecosystems. To date, most work has been focused on the impact of a single stressor on a particular species, the result of which may not be directly applicable to populations (Gill and others, 2001). It is unclear, and very difficult to study, how the combination of noise and other stressors (e.g., shifting food webs, changing water temperatures and habitat destruction) affect marine populations. A framework has been developed to assess the consequences of disturbance on populations, but often too many key parameter values are missing to enable an evaluation at the population level (King and others, 2015). For example, very little is known about the hearing response of large baleen whales. In addition, environments can be subject to multiple sources of noise over large scales, with the potential to affect multiple species at the same time, which can compound any effects (Shannon and others, 2016). At the current stage, the precautionary approach has been followed in many regulations that are based on insufficient data. However, it will be essential to expand the ability to integrate effects and impacts across different scales and sources in order to allow for a realistic assessment of the impact of anthropogenic noise on marine animals.

Finally, substantial effort is needed to standardize monitoring approaches, measurements and archival frameworks or systems for acoustic recording approaches and associated collected data. The American National Standards Institute/Acoustical Society of America standard (2009) and the ISO standard (2016) for measurement of underwater noise from ships in deep water require multiple sound measurements by arrays of sensors and, in practice, have been rarely applied. Among other work currently under way, ISO is developing standards on soundscape measures and monitoring, which will include underwater data, and standards are being developed through the Acoustical Society of America standards procedures regarding towed array systems and data archiving. In future, standards for other parts of the acoustic monitoring effort, such as fixed recordings, calibrations and ambient sound data, should also be developed.

7. Key remaining capacity-building gaps

Thus far, the monitoring and modelling of anthropogenic noise have been concentrated in areas of North America and Europe, with some concentrated monitoring also taking place off the coast of Australia. However, across-the-board capacity-building in the area of the Indian Ocean and its adjacent seas, including monitoring, impact assessment and development of management frameworks, would help to increase understanding of the changes taking place in the environment. Since sound travels broadly across ocean basins, and anthropogenic noise sources are found worldwide, there is a need for increased collaboration and cooperation across all States and regions, as well as greater sharing of information and technology. One example of differences in technological availability relates to AIS for ship tracking. Knowledge of ship positions is essential for accurate mapping of underwater noise. AIS is a localization and identification system developed for ship collision avoidance that, over time, has been adopted and mandated across vessels of a broad range of sizes. Ships are most comprehensively monitored in the developed world, owing to relatively good spatial coverage by AIS receivers. The move to satellite-based AIS that is under way will enable broader data coverage, and timely international collaboration to use those data might be an opportunity to bridge some capacity gaps in modelling across States. Enhanced cooperation and collaboration activities with developing States would facilitate the sharing of best practices and best available technologies necessary to build national and regional programmes, not only to monitor the effects of anthropogenic underwater noise, but also to provide the information needed for well-informed policy decisions.

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