Chapter 24
Input of Energy/Underwater Sound

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Abstract Underwater sound is ubiquitous throughout the world's oceans. Evaluating its impact and relevance for the marine fauna is highly complex and hampered by a paucity of data, lack of understanding and ambiguity of terms. When comparing sound (an energetic pollutant) with substantial pollutants (chemical, biological or marine litter) two notable differences emerge: Firstly, while sound propagates instantaneously away from the source, it also ceases immediately within minutes of shutting off the source. Anthropogenic noise is hence *per-se* ephemeral, lending itself to a set of *in-situ* mitigation strategies unsuitable for mitigation of persistent pollutants. Secondly, while pollution with hazardous substances can readily be described quantitatively with few parameters (concentration as the most important one), the description of sound and its impact on aquatic life is of much higher complexity, as to be evidenced by the issue's multifaceted description following hereinafter.

Keywords Underwater sound • Underwater acoustic environment • Marine life • Soundscape • Anthropogenic noise • Marine management

24.1 Introduction

This chapter's format prohibits a comprehensive discussion of the current state of knowledge and the provision of multifaceted guidelines that would do justice to the complexity of this topic. While hence having to refer the interested reader to comprehensive compilations on its specific aspects (i.a. Ainslie 2015; National Research Council 2003, 2005; Popper et al. 2014; Richardson et al. 1995; Southall et al. 2007b), we here present this topic's overarching concepts by presenting sets of

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contrasting terms as basis for a structured approach to its appraisal, while also highlighting some of its more common pitfalls. The succeeding chapters first introduce terms of the trade (printed bold) as required for the further discussion, followed by a generalized categorization of the effects of sound on marine fauna. Thereafter we provide a brief listing of the major anthropogenic sound producers, followed by short section on current mitigation approaches to conclude with a discussion of requirements for prudent management of underwater sound.

24.2 A brief Introduction to Underwater Acoustics: Concepts and Terms

Underwater ***sound***[1] is ubiquitous throughout the world's oceans. Nothing could be, or ever was, further from truth than the common notion of a quiet ocean, as stipulated by the title of Jacques-Yves Cousteau's and Louis Malle's influential movie from 1956 "*Le Monde du silence*". Until the late nineteenth century, when steamships became more common sights, the natural underwater ***acoustic environment***[2] was shaped by biotic (marine mammals, fish, invertebrates) and abiotic (waves and rain, undersea earthquakes, lightning strikes) sound sources, some of which match the source levels of today's loudest anthropogenic sources. Commencing with the mechanization of shipping, a multitude of additional anthropogenic sources emerged throughout the last century: ships, underwater explosions, sonars and seismic sources now produce acoustic sound signatures that contribute to the underwater acoustic environment year-round.

The underwater acoustic environment may be decomposed into ***discrete*** and ***diffuse***[3] components. Discrete contributions can be assigned to their respective acoustic sources, such as a ship passing nearby or a clicking sperm whale. Discrete sources are often of high intensity with significant mid- and high frequency components, yet local or regional in range and limited in time. Diffuse contributions (such as caused by distant storms or shipping lanes) cannot be assigned to a specific sound

[1] "***Sound***", as defined by ISO/DIS 18405.2 constitutes the "alteration in pressure, stress or material displacement propagated via the action of elastic stresses in an elastic medium and that involves local compression and expansion of the medium, or the superposition of such propagated alterations." The scientific meaning of sound therefore has no judgmental connotation, i.e. it is not used as the antonym of "noise", regardless of its origin or deliberateness of emission. Hereinafter, use of the term ***sound*** is strictly confined its physical meaning.

[2] The "***acoustic environment***" represents the sound at the receiver from all sound sources as modified by the environment (ISO 2014. ISO 12913-1:2014(E) Acoustics—Soundscape—Part1: Definitions and conceptual framework.) In marine acoustics it is currently used synonymously with the term "soundscape", which, however, in terrestrial acoustics represents a subjective perception, i.e. the acoustic environment as perceived by the listener.

[3] Sometimes called "ambient noise", a term we deprecate, due to the ambivalent meanings of the term noise. See also footnote #7.

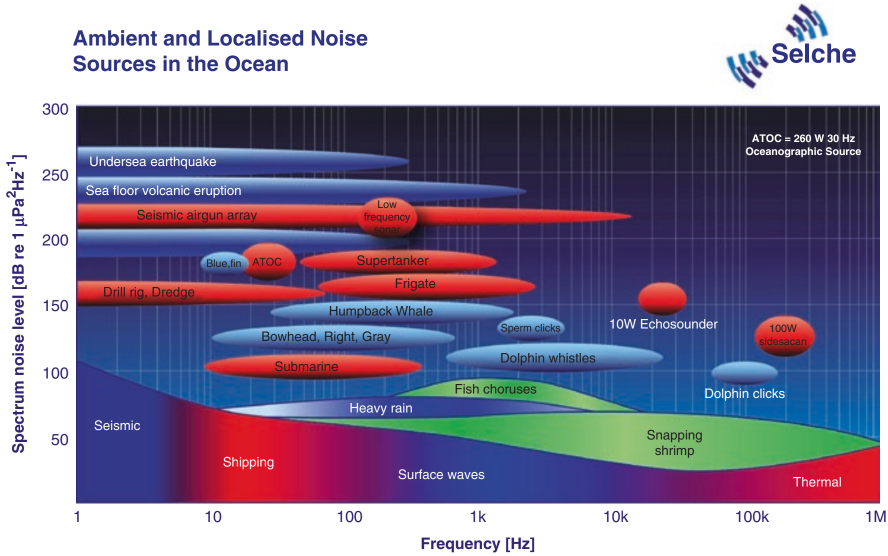

Fig. 24.1 (© Seiche Ltd. 2006) Spectral source levels versus frequency content of diffuse (called ambient in this figure) and discrete (called localized in this figures) sound sources in the ocean. Reproduced with permission by Seiche Ltd., The Advanced SONAR Course, Seiche (2002) ISBN 1-904055-01-X

source. They are usually of lower intensity and frequency, but far-reaching and often chronic.

Characteristics of sound differ widely between sources, with ***frequency*** and (nominal) ***source level***[4] being the most fundamental parameters (Fig. 24.1). Together they govern the range at which a specific sound will influence the acoustic environment. While louder sounds of course generally reach farther, sounds of different frequencies are subject to differences in absorption, diffraction, refraction and reflection. ***Low-frequency*** sounds *(<200 Hz)*[5] propagate much farther (hundreds of km) than ***mid-frequency*** (*200 Hz < f < 25 kHz*) sounds, which reach tens of kilometres, and ***high-frequency*** sounds *(>25 kHz*) which cover a few or even less than a kilometre.

Temporal characteristics of specific sounds vary across orders of magnitude. Impulse-like, ***transient*** signals from odontocetes (toothed whales) and sonars are of few to tens of milliseconds duration, followed by pauses on the order of seconds to tens of seconds until the next pulse is emitted. Grounding and colliding icebergs or

[4] "Nominal source levels" are used as parameter in far-field sound level calculations and must not be confused with true sound levels near the source. Note that Figure 1 depicts spectral source levels, not source levels, for discrete sources and spectral levels for diffuse sources.

[5] The terms, high-, mid- and low-frequency are associated by different stakeholders with rather different frequency ranges. Whenever using these terms, their definition should be provided for clarification. Here we follow the classification used by Hildebrand (2009) anthropogenic and natural sources of ambient noise in the ocean. Mar Ecol Prog Ser 395, 5–20.

marine vibrators emit minute-long sounds, while broadband sounds from storms and ships are audible for hours if not ***continuously*** for days to weeks.

Of similar variability is the duration of activities responsible for the sound generation. Anthropogenic activities might be rather ***short-term*** (e.g. a ship shock test or detonation of a naval mine), or last for an hour, like the passage of a ship. Other activities are ***long-lasting***, spreading over days (naval manoeuvres or ramming of a single wind farm foundation) to weeks and months (seismic surveys or ramming foundations of an entire wind park). Conglomerations of such activities might expose some regions to such sounds for the greater part of a year.

An important feature of seawater is its frequency-dependent absorption coefficient, allowing low frequency sounds in particular to remain discernible against the overall acoustic environment at rather large distances from the source. The frequency dependent nature of sound propagation thereby modifies the spectral composition of the propagating sound, similar to a lighting strike having a sharp, crisp characteristic when nearby but changing to a mere rumble when perceived from a distance. In addition to simple spreading loss and attenuation, the propagation of underwater sound is influenced by the characteristics of the bounding surfaces: depth, structure and composition of the seafloor, sea-state and ice cover as well as interior ocean stratification. Together these might promote (sound channels and sound ducts) or impede (e.g. sonar termination (Chambers and James 2005) and shadowing (Federation of American Scientists 2016)) the propagation of sound. All these aspects might be included in numerical sound propagation models, to obtain detailed predictions of sound levels around a given source.[6]

Underwater sound may be generated either ***intentionally*** or ***unintentionally*** (Table 24.1). Intentionally generated sounds (referred to as ***signals*** hereinafter) may be of biotic (e.g. echolocation clicks from toothed whales) or anthropogenic (e.g. chirps from naval sonars) origin. Unintentionally generated sound (referred to as ***noise***[7] hereinafter) can be of abiotic (e.g. breaking waves) or anthropogenic (ship noise) origin. The distinction is highly significant, as *anthropogenic signals* usually cannot be diminished without compromising their very purpose, while reduction of *anthropogenic noise* might be achievable without impairing the respective activity.

[6] However, overly ambitious efforts to provide precise sound level for risk assessments are often futile, as error estimates of even simple sound propagation estimates are dwarfed by the order of magnitude(s) bigger uncertainties associated with the estimation of probability and severity of contingent risks to the marine fauna.

[7] Alternatively, the term "***noise***" might also bear the connotation of being disturbing, however this is a rather subjective perception: Signals generated by marine animals may be experienced as distraction by a submarine's sonar operator, while the sonar pings of a submarine might disrupt the underwater communication of marine mammals. Additionally, noise sometimes is understood as all sounds of anthropogenic origin or it can bear special meanings in the context of measurement techniques.

Table 24.1 Characteristics of acoustic sources in the ocean

Acoustic source	Intention/application	Signal characteristics					
		Dominant frequency	Directionality	Signal type	Annual prevalence	Daily pattern	Acoustic footprint
Intentional, biotic							
Toothed whales	Echolocation	MF, HF	Forward	Broadband clicks	Year-round	Continuous	Local, mesoscale
Baleen whales (vocalizations)	Communication	LF, MF	Omni	Tonal (fm, am)	Seasonal/ year-round	Intermittent	Basin scale
Baleen whales (slapping, breaching)	Communication	LF, MF	Omni	Broadband pulses	Seasonal	Intermittent	Regional
Dolphins (whistles)	Communication	MF	Omni	Whistles	Year-round	Continuous	Local, regional
Snapping shrimps		MF	Omni	Broadband pulses	Seasonal	Diel cycle	Regional
Fish sounds	Communication, navigation	LF	Omni	Pulses, am-tonals	Seasonal	Diel cycle	Local, regional
Intentional, anthropogenic							
Fishing net pingers	Scare off marine mammals, position fishing net	MF,HF	Omni	Chirps, pings	Seasonal	Continuous	Local
(Simple) Echosounders	Navigation	MF, HF	Down	Ping, chirps	Year round	Continuous	Local
Fish finding sonars	Detecting fish	MF, HF	Down or sector	Ping, chirps	Seasonal	Intermittent	Local
Multibeam echosounders	Seafloor mapping	MF	Down	Pings, chirps	Occasional	Continuous	Local

(continued)

Table 24.1 (continued)

Acoustic source	Intention/application	Signal characteristics					
		Dominant frequency	Directionality	Signal type	Annual prevalence	Daily pattern	Acoustic footprint
Airguns	Hydrocarbon exploration	LF	Down	Pulses	Seasonal to year round	Quasi continuous	Regional to basin scale
Marine vibrators	Hydrocarbon exploration	LF	Down	Sweeps	Not yet in use		
Military sonars	Underwater reconnaissance	MF	Horiz.	Fm sweeps	Days to weeks	Intermittent	Regional
Unintentional, abiotic							
Precipitation	–	MF	Omni	Broadband pink noise	Occasional to year round	Intermittent	Regional
Breaking waves/surf	–	MF	Omni	Broadband pink noise	Seasonal to year round	Continuous	Local to regional
Lightning strikes	–	LF/MF/HF	Omni	Broadband	Seasonal	Sporadic	Local to regional
Marine earthquakes, volcanic eruptions	–	LF	Omni	Rumble, tremors	Year round	Intermittent	Basin scale to global
Sea ice and iceberg motion	–	LF, MF	Omni	Rumble	Seasonal	Intermittent	Regional to basin scale
Calving ice shelfs	–	LF	Omni	Cracking, rumble	Seasonal	Sporadic	Local to regional
Grounding and colliding ice bergs	–	LF, MF	Omni	Tremors, tonal sweeps	Occasional	Sporadic	Regional to basin scale

Shipping	–	LF, MF	Omni	Broadband, tonal	Year round	Continuous	Regional to global
Blasting of naval mines	–	LF, MF	Omni	Blast	Year round	Intermittent	Regional
Marine construction (ramming, vibrators)	–	LF, MF	Cylindric.	Pulses, tonal	Seasonal	Continuous	Regional
Marine renewable energies (operational phase)	–	LF, MF	Omni	Tonal	Year-round	Continuous	Regional
Small boats, jet skis	–	LF, MF	Omni	Broadband, tonal	Seasonal	Intermittent	Local to regional
Naval shock tests	–	LF, MF	Omni	Blast	Occasional	Rare	Regional to basin scale

Parameters given illustrate the typical range in areas of occurrence. Partially based on Hildebrand (2004a, b, 2009). LF (low frequency): 10–500 Hz; MF (mid-frequency) 500 Hz to 25 kHz; HF (high frequency) >25 kHz. A ping is a short, tonal pulse, a click is a broad-band pulse
fm frequency-modulated, *am* amplitude-modulated, *omni* omni-directional, *horiz* horizontal, *cylindric* cylindrical in horizontal plane

24.3 Impacts of Underwater Sound on Marine Life

Matching the diversity of sound sources, the potential impacts of sound are similarly manifold. Underwater sound is assumed to contingently affect the entire breadth of marine fauna, i.e. ***marine mammals, fish*** (including their larvae)***, sea turtles, birds, crustaceans, cephalopods and bivalves*** (including their larvae) at all levels, i.e. ***individuals***, ***populations*** and the ***ecosystem*** (Fig. 24.2), yet with widely varying severity and consequences. Unfortunately, while standing to reason, scenarios of specific consequences are mostly based on speculation or anecdotal reports and often are counterbalanced by no fewer reports noting a lack of observable effects. Quantitative assessments of a given scenarios likelihood and impact are, by contrast, sparse. Only recently, statistically robust descriptions of the effects of sound on individuals or populations have emerged (e.g. Solan et al. 2016), yet more than once revealing that further co-variates need to be included to fully understand the findings.

Exposure to sound may affect an individual's ***health***, ***hearing, fitness*** and ***behaviour***. Generally, it was assumed for long that the more distant the source, the less malign the impact: Exposure to sounds from high-intensity localised sources were

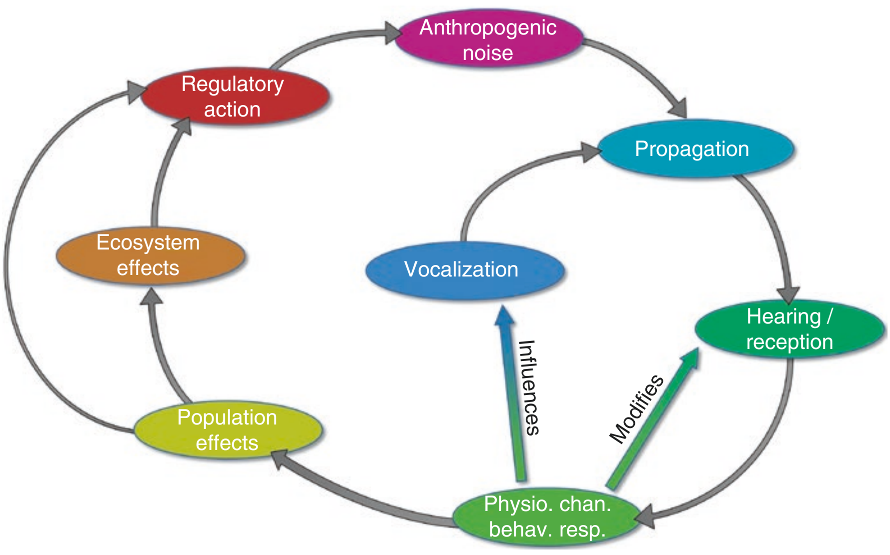

Fig. 24.2 Conceptual diagram of the contingent effects of (anthropogenic) sound on the marine fauna, including feedback mechanisms. Anthropogenic noise (top ellipse) is propagated to the receiving individual (hearing/reception), where it might elicit physiological changes (affecting hearing capabilities) or behavioural responses (motoric or vocal reactions such as louder or lesser vocalization). Individual responses may result in population effects when large numbers or critical members are affected, possibly resulting in ecosystem effects. Prudent regulatory action will modify anthropogenic emission as to avoid or at least minimize changes to populations and the ecosystem

presumed to result in acute effects such as mortal or recoverable injuries to individuals, while heightened diffuse sound levels were thought to elicit mainly transient behavioural interruptions. However, recent findings suggest that for some species/sound combinations initially merely behavioural responses may bear lethal consequences, requiring more differentiated evaluations.

Furthermore, types of sound that might affect health or hearing may not affect behaviour, and vice-versa, or they might elicit different responses amongst different individuals or contexts, necessitating independent assessments of the affiliated risks. Systematic listing off all these aspects/co-variates (e.g. species, sex, level, impact type, sound characteristics, and behavioural context) would result into thousands of scenarios, each of which requiring dedicated experiments to obtain quantitative measures of their severity and probability. Noting the impossibility of such undertaking, the common approach is to use generalized categories to provide a conceptual framework facilitating discussion:

24.3.1 Effects of Sound on Individuals

Effects of sound on individuals may be classified into four categories (arranged below in order of decreasing sound levels as needed for their elicitation). It should be emphasized however, that only few scenarios have in fact been observed in the field and that some, such as seals fleeing under the ice shelf and drowning are mere speculation.

1. ***Primary injury:*** This category comprises mortalities and acute (mortal or recoverable) injuries caused directly by the energy of the acoustic wave, including barotrauma, permanent threshold shifts (PTS), lesions of interior tissues and clogging of blood vessels by bubbles. Such injuries might lead directly or indirectly to death, e.g. by starvation or disorientation when hearing is permanently compromised.

   Such effects require, probably for all species, exposures to the highest of physically possible sound levels as generated by nearby (order of tens to lower hundreds of meters) discrete sources, such as underwater blasts or ramming.
2. ***Significant auditory impairment***: This category describes temporary threshold shifts (TTS) of the hearing apparatus, i.e. the animal can hear less well for a certain (minutes to days, depending on severity) amount of time. TTS is most likely to be caused by sound from discrete sources, yet already at larger (order of hundreds to thousands of meters) radii than those at which primary injuries might occur. For marine mammals, TTS onsets have experimentally been determined by several studies, which are compiled systematically in e.g. Southall et al. (2007b).
3. ***Secondary injury***: This category comprises (potentially lethal) injuries triggered by the behavioural response of the animal to the sound. For marine mammals, an individual's behavioural response to sound has been suggested to possibly trigger

interior bubble formation (Jepson et al. 2003) or result in hyperthermia leading to cardiovascular collapse (Cox et al. 2006). Interior gas bubbles might also result in disorientation with possibly lethal consequences.

This class of effects has, in fact, been linked almost exclusively to beaked whales exposed to sound from naval mid-frequency sonars (D'Amico et al. 2009). Surprisingly, it appears to occur already at relatively low exposure levels, which implies a great impact range of tens of kilometres around the source. Dedicated experiments showed that the severity of elicited (behavioural) responses are influenced by signal characteristics, species and context.

4. ***(Significant) behavioural response***: This category includes motoric and acoustic responses of variable duration, ranging from mere startle effects to obvious flight response, yet without secondary injuries. Responses might be short term (evasion of noise source) or long term (abandonment of habitat), probably related to the duration of the stimulus. Responses usually have no immediately apparent effect on individual fitness. Whether or not they result in significant changes to animal fitness in the long term strongly depends on the behavioural context. Behavioural responses also include acoustic responses, such as modification of vocalizations (cessation, amplification, frequency shifts).

   Attempts to link occurrences and severity of behavioural responses to sound levels have with few exceptions not yet produced robust dose-response relationships. For example, fish responded more pronounced to an approaching quiet vessel than to a loud vessel (Ona et al. 2007; De Robertis and Handegard 2013). However, levels eliciting behavioural responses are generally assumed to be much lower than those causing primary injury or auditory impairment. This entails that not only discrete, loud sources, but also increased diffuse sound levels may cause behavioural responses.

24.3.2 Effects of Sound on Populations

Effects of sound on populations do, of course, not manifest themselves on their own, but are the consequence of the effects of underwater sound on individuals. Some population effects might relate linearly to the number of individuals affected, but others, such as population productivity, may exhibit more complex relationships, involving feedbacks resulting in non-linear responses. A comprehensive, quantitative assessment of population level effects would require a thorough understanding of how population parameters such as growth and reproduction are affected by underwater noise. This would require a complete mechanistic ecological model of the target species and its environment, a level of expertise far from the current level of knowledge for virtually all aquatic animals. Additional complications arise from the fact that many of the higher marine species are highly mobile and migratory, impeding predictions on potential local effects of underwater sound exposure as animals may abandon or circumvent affected areas.

A conceptual model of population effects of acoustic disturbance (PCAD) was developed under the auspices of the National Research Council (2005) and experiences continuous improvement and refinement by ongoing research (E & P Sound and Marine Live Programme 2016; Office of Naval Research 2016). The PCAD model links acoustic exposure of individuals to potential population effects via three intermediate stages, using transfer functions to relate a given stage to its consecutive stage. However, whether PCAD is the ultimate method for use in acoustic risk assessments across all species is a matter of debate, as its predictive power depends on a substantial level of knowledge on the species in question (e.g. habitat use, physiological parameters). Maybe simpler models, such as Productivity-Susceptibility Analysis, PSA (Milton 2001; Patrick et al. 2009; Stobutzki et al. 2001), might, by themselves or in combination with PCAD, serve to obtain at evaluations of acceptable robustness with much less detailed knowledge.

24.3.3 Effects of Sound on the Environment and Ecosystems

Effects of sound on the environment may occur directly through modifying the acoustic environment itself or indirectly via impacts on the region's (acoustic) ecology. Four categories are identified to facilitate discussion:

5. ***Masking effects*** consider the subjective ability of the receptor (listener) to discriminate a signal of relevance against the overall acoustic environment (Erbe et al. 2016). Usually, masking effects are considered as detrimental for the listener, when for example prohibiting timely detection of a predator (Simpson et al. 2015), but they also might redound to another species' advantage, when, for example, baleen whale mother-calf communication is masked from detection by waylaying killer whales. Scenarios of the effects of chronically increased acoustic background levels are highly speculative. In some cases increases might not even be perceived by the animals, while in other contexts changes to the level of the acoustic environment might significantly reduce the range over which marine mammal vocalizations are audible. Ranges at which masking occurs are most variable across species and contexts, depending on e.g. frequency and signal characteristics and directionality, with numerous mechanisms by which relieve from masking can be achieved.
6. The ***acoustic ecology*** of a region might alter due to changes to the acoustic environment. Biotic use of acoustic time-frequency space is believed to be the result of an evolutionary process attempting to optimize the use of acoustics for each species (Van Opzeeland 2010). For example, seal vocalizations in the Antarctic are so unique in their characteristics that calls from different species remain recognizable even if concurrent. Introducing new sounds into this acoustic environment might change biotic usage patterns, similar to songbirds changing frequencies and source levels of their calls when residing in cities or next to highways (Brumm and Slabbekoorn 2005).

7. ***Biological services*** may alter through population effects with consequences for the (local) ecosystem. The great whales have been proposed to act as lateral (North/South) and vertical biological pumps, redistributing nutrients from the polar to the subtropical and from deep to shallow realms (Roman et al. 2014). Should acoustic exposure lead to changes in habitat usage, entire ecosystems might restructure. Behavioural responses of sediment-dwelling invertebrates to sound, on the other hand, have been shown to bear the potential to affect benthic nutrient recycling (Solan et al. 2016).
8. ***Prey distribution*** and ***predator pressure*** might change to a species' advantage or disadvantage due to the prey's or predator's response to acoustic exposure (Slabbekoorn et al. 2010), presumably shifting their habitat to less exposed locations.

24.4 Anthropogenic Sources and Emission Trends

Underwater sound is produced by nearly all anthropogenic marine activities. Emitters include, amongst others, the shipping industry, oil and gas producers, renewables, navies and marine research. While Hildebrand (2004b) already provides a comprehensive description of anthropogenic sound sources, the most notable sound emitters, along with their key features, are listed hereinafter.

Shipping, with the advent of steam engines, was probably the first human activity to introduce notable levels of noise into the ocean (see also Chap. 6). Source levels increased with growing numbers of ships which mainly followed tracks between major ports. Shipping noise is mainly caused by machinery and cavitating propellers. Both contributions increase with ship size, yet efforts to minimize fuel consumption for economic reasons instigated optimized propeller designs which reduce cavitation and hence noise levels (Chekab et al. 2013). Shipping is presumed to primarily elicit (significant) behavioural responses, as sound levels of ships are considered relatively benign. The near continuous chain of ships along some shipping routes imply a quasi-permanent broadband increase of sound levels in their vicinity. Shipping is, with regard to its noise emissions, currently unregulated.

Marine seismic exploration started with refraction and reflection surveys in the 1960 (Sternlicht 1999) and grew in momentum in the wake of the digital revolution and the development of non-explosive seismic sources. Today, seismic surveying is carried out on a regular basis mostly on the shelves and along the continental margins, with nearly 140 open-ocean going ships (Kliewer 2014) being operated by some 30 companies worldwide. In some areas, seismic operations are audible for much of the year. Airguns emit high acoustic level with the potential to cause primary injuries and auditory impairment in their direct vicinity. Marine seismic exploration is regulated under a number of jurisdictions, yet regulations vary widely between different states.

Naval activities since long introduced significant levels of underwater noise through explosions (torpedoes, water bombs) and the naval vessel's machinery, particularly during wartime. Interestingly though, in spite of the increased marine noise levels during World War II (WW II), whale stocks recovered notably during the concurrent decline in whaling (Muscolino 2012), putting the potential negative effects of noise into perspective. Today, controlled underwater detonations of lost mines and bombs from WW II occur regularly throughout the Baltic and North Sea.

Regular use of SONAR (SOund Navigation And Ranging) in submarine warfare started with WW II, and has received continuous advancement ever since. Currently, tactical mid-frequency sonars are deployed on order of 100 ships (Hildebrand 2004b), while low frequency sonar is used only in experimental settings.[8] While wartime activities are usually not subject to environmental regulations, use of sonars during naval exercises received increasing regulatory attention, particularly after the atypical strandings of beaked whales in the Bahamas (Jepson et al. 2003) was associated with the concurrent use of tactical mid-frequency sonars.

Marine construction includes a wide breath of noise sources: Dredging, ramming and vibrating of piles and runners (sheet piles) has originally been confined to coastal and estuary settings but now moved offshore with the construction of offshore windfarms, deep oil and gas installations and deep-sea mining (see also Chaps. 8, 9 and 11). Deep-sea mining requires operation of machinery on the sea-floor for extended periods of time, emitting sound levels comparable to those of large ships. Noise of highest levels is produced during the construction phase of structures (but drop by order of magnitude during the operational phase), with the potential to inflict primary injuries and significant auditory impairment. Some activities (ramming) are already subject for regulation based on noise emissions, yet others (e.g. dredging), where primary injury from noise exposure is less likely, are currently not.

Nautical safety and sovereign responsibilities require detailed knowledge of the sea-floor topography (bathymetry), which is obtained using multi-beam echosounders and side-scan sonars. Regions along coastal shipping lanes require continuous monitoring, as sediments are constantly repositioned, particularly in tidal seas. Delineation of exclusive economic zones under the United Nations Convention on Law of the Sea (UNCLOS) as based on e.g. the "foot of the slope" criteria recently led to increasing numbers of bathymetric surveys seaward of the continental shelves, particularly in regions of dispute between neighbouring states. So far, these activities remain unregulated, raising little concern of posing risks of primary injury or auditory impairment.

Commercial fishing employs sound to both find and track fish (fish sonars), to control the position of their fishing gear and to deter marine mammals (acoustic deterrent and harassment devices) from (drift-) gillnets. Fishing is unregulated with regard to noise, in fact use of sound producing marine mammal deterrence devices is encouraged in some countries.

Recreational boating, particularly motorboats and jet skis, might subject coastal settings to extended periods of noise, however, activities so far have not been regulated on basis of their sound pollution. Underwater noise related regulations may exist locally, yet are not known to the authors.

[8] Note that the terms "low" and "mid" frequency are used differently by different navies, creating ambiguities. Discussion should specify the frequency range in Hertz.

24.5 Current Management and Mitigation Approaches

Protective goals vary both with regard to target species as well as ecosystem level, i.e. whether individual animals, populations, or the ecosystem is to be protected. While facing great gaps in understanding on existence, type and magnitude of effects of sound on these various ecosystem levels, recommendations regarding management of sound have nevertheless been sought and developed throughout the past two decades. Two mitigation approaches have developed: ***operational*** and ***strategic***.

Operational management is primarily used to mitigate against primary injuries and significant auditory impairment, which may occur – probably across all taxa with acoustic perception – in the proximity of loud, discrete sources such as marine seismic, naval activities and marine construction: within tens to low hundreds of meters for primary injuries and hundreds to low thousands of metres for auditory impairment. Suitable metrics to regulate such risks have been investigated extensively in the past years and were first summarized in the seminal paper by Southall et al. (2007a), building the basis for a recently issued technical memorandum on this issue by the National Oceanic and Atmospheric Administration (NOAA 2016a, b). Recent advances in operational mitigation technologies (e.g. Zitterbart et al. 2013) facilitate an effective 24/7 implementation of mitigation measures.

Strategic management aims at alleviating risks caused by distant, discrete sources, i.e. secondary injuries and significant behavioural responses (which both are presumed to possibly occur up to tens of kilometres from the source), but also of diffuse sources which may change a region's (acoustic) environment and ecology including prey and predator distribution, and biological services rendered by resident species. While currently still a rather uncommon approach, the EU Marine Strategy Framework Directive aims at achieving a coherent management approach for European waters across national boundaries, also with respect to underwater sound, employing acoustic monitoring and registration of major noise emitters (Tasker et al. 2010). Further guidance on how to address managing these risks might also be taken from regulatory approaches concerning persistent substantial pollutants.

Managing diffuse sources, however, is difficult as it requires tracking a large number of dispersed sources, eventually located in different or even outside regulatory regimes. Contrasting the management options for persistent substantial pollutants, the underlying principle here is to shift anthropogenic activities – if possible – to areas and times when relevant marine fauna is less likely to be present. This approach requires *a priori* knowledge of species distribution and habitat use and/or operational mesoscale surveying. While implementation of the latter operational capabilities are rather costly, *a priori* information on habitat suitability is more easily obtained and might already provide reasonable guidance to at least avoid activities being conducted during peak presence (e.g. Bombosch et al. 2014).

24.5.1 Shortcomings of Current Implementations

Currently, a broad variety of regulatory procedures exists. Depending on the regulatory regime, mitigation requirements during seismic surveys range, for example, from none at all to continuous visual and passive acoustic observations for marine mammals and shutdown of sources should an animal enter a rather large mitigation zone. Such discrepancies likely reflect more on the subjectivity of the respective guideline than on underlying scientific uncertainties, particular when guidelines and regulatory documents make use of ambiguous terms. Unspecified legal terms, such as "harassment", "molestation", "disturbance" or "injury" allow for a wide range of interpretation when trying to determine whether such incidents might manifest themselves or not, resulting in rather divergent assessments of potential risks and hence mitigation requirements.

The situation worsens when documents are translated in different languages, e.g. during the national ratification of international agreements. Then, even presumably objective technical terms might attain ambiguity as manifest in the EU parliament's resolution (European Parliament 2016) on the environmental effect of "*high intensity active naval sonars*". The latter, i.e. the subject of the resolution, was translated as "sonars navals actifs à haute intensité" in the French and "*hochleistungsfähige[r] active[r] Unterwassersonare*" in the German versions of this resolution, terms of the trade which pertain to rather different types of sonar systems and stakeholders affected.[9]

Hence the use of unspecific terms in legal and regulatory documents, together with an imprecise use of the terms of the trade particularly in the "grey" literature on this topic, currently allows for a wide range of interpretation when trying to employ these terms in concrete assessments of risks as caused by specific activities, a shortcoming that future documents and discussions urgently need to resolve.

24.6 Challenges and Requirements of Prudent Management

Prudent management requires a solid understanding of the impacts it attempts to mitigate and the ability continuously adjust regulations to changes in our current state of scientific knowledge. This will require sustained science-based stakeholder dialogues as well as a management model governed by dynamic processes which continuously adapt and update regulations whenever scientific progress is made.

[9] "Naval" in English implies "belonging to the Navy", i.e. a military context, whereas the French "naval" implies "nautical", i.e. all seagoing activities including civil. The German text version simply refers to highly powerful (or efficient, the German term is ambivalent in this regard) active underwater sonars, including e.g. fishing sonars.

Future management of ambient noise should also employ a holistic approach, involving knowledge on ecoacoustics, i.e., how sounds reflect ecosystem processes. By increasing the awareness that acoustic environments are dynamic systems and products of adaptation, this can lead to alternative strategies to manage anthropogenic sound sources. The goal would be to minimize anthropogenic noise input particularly at times and frequencies relevant to the marine fauna. The temporal dimension hereby includes seasonal and diel cycles as well as call shapes, different temporal scales which all may be employed to minimize interference.

Mariners, on the other hand, will perceive regulatory requirements only as reasonable if implemented with a sense of proportion. Regulation of anthropogenic underwater sound is likely to impact considerably on marine anthropogenic activities: Activities will be prolonged (e.g. less wind farms built per year, longer seismic surveys due to shut downs, longer shipping routes), or involve higher risks for personnel and gear (e.g. longer times at sea or lack of situational awareness due to shutdowns of hydroacoustic sensors systems). Such consequences of mitigation measures, which might counter the original conservation goal, require careful balancing against the requirements' presumed benefits. Effects of sound also need to be put into perspective with other, potentially cumulative, anthropogenic disruptions (fishing, bycatch, ship-strikes) to allocate effort and funds to those mitigation measures benefitting the marine ecosystem most. For marine mammals, bycatch, whaling and ship strikes by far exceed the number of immediate mortalities (or takes) known to have been caused by sound exposure, and similar ratios apply in all likelihood for fishing versus acoustically mediated lethal takes of commercial fish.

Hence, to come to effective while at the same time economically viable, socially desirable, environmentally prudent and operationally realistic mitigation, regulations need to heed the insights and expertise of different scientific and societal actors and incorporate their knowledge bases. Flexibility will need to be an inherent and key feature of management for it to be truly effective, continuously facilitating implementation of new scientific insights into existing regulation. Some of the necessary prerequisites for an effective management are discussed hereinafter.

24.6.1 Understanding the Natural Environment

Guidance regarding a prudent setting of thresholds, e.g. for acceptable ambient noise levels, may be derived from an understanding of the natural levels and their variability (NOAA 2016a, b), as it can be assumed that species have evolved under like conditions and hence are capable of coping with them. Pristine areas, like the Southern Ocean, might serve to establish the *status quo ante*[10] acoustic state. As

[10] With recovering whale stocks, acoustic levels are expected to rise in their respective vocalization bands. For Antarctic Blue Whales, which already produce the most powerful signal in the Southern

many natural signals wax and wane on seasonal time scales, baseline acoustic recordings should be continuous and broadband, covering at least one, preferably multiple years for a meaningful analysis.

Proper calculations of sound levels are essential when aiming for an evaluation of long-term trends. While decadal trends between the sixties and nineties are estimated for some locations to be on the order of 3 dB per decade, this growth apparently stalled or reversed since the mid-nineties (Andrew et al. 2011). However, measurement uncertainties are of similar magnitude as the observed decadal changes. Hence thorough pre- and post-calibration for each recorder is mandatory to allow attaining robust results. Resolving long term trends furthermore requires multiple, successive recorder deployments which in most cases will employ different instruments, necessitating cross-recorder calibrations and meticulous management of recorder meta-data (Roch et al. 2016).

24.6.2 Understanding the Effects of Sound

Research questions are structured according to risk type (see above) and of course by the species concerned. They are hence at least as multifaceted as the number of categories listed under “effects of sound” times the number of species. Studies on the direct impact of sound on the organism (e.g. Kastelein et al. 2012; Mulsow et al. 2014) appear most advanced, whereas those concerning behavioural responses of individuals (e.g. Cato et al. 2013; Southall et al. 2012) are only emerging. Particularly, questions concerning the consequences of potential stress responses are difficult to address, at least for marine mammals, as monitoring biochemical levels and physiological changes in a meaningful, natural setting, is rather difficult for this group of species. Finally, studies of population and ecosystem level effects are the least progressed due to their complexity.

It is difficult to develop a universal ranking of research needs, as advancement is needed on all levels. However, among researchers there is a general consensus, that studies in a natural environment involving wild and unconfined animals will provide the most meaningful results, while, at the same time, being with few exceptions the most complex and expensive approach. At the same time, scientific progress is urgently needed regarding our understanding the impacts of chronic noise exposures on population and ecosystem health, which likely involves studying large sample sizes to attain statistically robust results (Boyd et al. 2011).

Ocean at 27 Hz when estimated at only about 1–2% of their pre-whaling population, acoustic levels might rise by up to 20 dB should the population fully recover. Estimates of natural levels should hence be based on the pre-whaling (*status quo ante)* acoustic state of the ocean.

24.6.3 Understanding Acoustic Metrics and Terms of the Trade

Creation of a judicious regulatory framework requires correct and unambiguous use of technical terms. However, the field of marine/hydro acoustics has not yet quite settled on an unambiguous language. Fortunately, recent efforts to standardize metrics (and language to some extent), are advancing rapidly (ISO 2014, 2016). One particular complication arises from the common use of "***levels, L***" together with the pseudo-unit "***decibel (dB)***" when describing acoustic properties. In fact, "deciBel" does not represent a physical metric (unambiguously traceable to SI units), but merely indicates that the preceding numerical number is proportional to the decadal logarithm of the ratio of the property and a reference value (Table 24.2). Hence, any proper use of levels requires declaration which field or power quantity is being considered, which frequently happens only implicitly by indicating the reference value. Equally often reference values are missing or incomplete and it is left to guessing to relate the numeric values to the physical property they describe. Particularly when measurements are compared between different stakeholders, this difficulty becomes evident.

Two further particular pitfalls need to be emphasized. Firstly, the definition of "root-mean-square sound pressure levels" needs to be augmented by the period and frequency band over which the acoustic signal is averaged, particularly when used in the context of pulsed sounds. This length should be chosen in accordance with the (biological) effect that is to be regulated through this metric, e.g. if behavioural responses are to be described, the averaging time should relate to the time period at which the auditory system processes sounds. Secondly, the definition of sound exposure levels requires the integration period over which sound levels are accumulated and/or the definition of an effectively quiet sound pressure level. Otherwise, even the lowest natural levels would accumulate to SELs exceeding any threshold. Currently, a comprehensive international standard is in preparation by the International Organization for Standardization, providing a catalogue of underwater acoustics terms, definitions and concepts (ISO 2016). It is highly advisable that terminology and standards as described therein are adopted stringently throughout all legal and regulatory proceedings.

No less important is the realization of obscured differences in the use of biological terms by different communities when formulating regulatory threshold levels. For example, the marine mammal scientific community considers a threshold shift of 40 dB to be prone of eliciting a permanent noise-induce hearing loss (National Oceanic and Atmospheric Administration (NOAA) 2016a, b). Recent studies on mice applied similar threshold shifts of up to 40 dB to study the long-term consequences of what they term initially "*moderate, but completely reversible threshold elevation*" (Kujawa and Liberman 2009). Hence, what is still considered a TTS (temporary threshold shift) in lab-based experiments with mice, is already considered the onset of PTS (permanent threshold shift) by the marine mammal community.

Table 24.2 Examples of metrics expressed in terms of the pseudo-unit "dB", including ancillary parameters as needed for their proper definition

"Unit"	Metric	Reference	Reference value	Ancillary parameters	Applications
dB	• Mean-square sound pressure level; • Sound pressure level • SPL	ISO/DIS 18405.2 2.2.1.1	1 μPa² (sic!)	Averaging time, frequency range	Characterizing pings in sonar technology
dB	• Peak sound pressure level • Zero-to-peak sound pressure level	ISO/DIS 18405.2 2.2.2.1	1 μPa	Time interval and frequency range	Description of pulsed sounds in geophysics; evaluate impact of sound on marine mammal hearing (dual criteria in NOAA 2016a, b)
dB	• Peak to peak sound pressure level		1 μPa	Time interval and frequency range	Description of pulsed sounds in bioacoustics
dB	• Mean-square sound pressure spectral density level	ISO/DIS 18405.2 2.2.1.10	1 μPa² Hz^{-1}	Averaging time, frequency range	Description of broad band sounds, e.g. from airguns
dB	• Band averaged sound pressure level • Band level		1 μPa²	Time duration and frequency range	Description of acoustic emissions of ships
dB	• Band averaged sound pressure level per Hertz	ICES 209	1 μPa (1 Hz band)	Time duration and frequency range	Description of acoustic emissions of ships
dB	• Sound exposure level • Sound pressure exposure level • SEL	ISO/DIS 18405.2 2.2.1.5	1 μPa² s	Time duration and frequency range	Metric used to evaluate impact of sound on marine mammal hearing (dual criteria in NOAA 2016a, b)
dB	Frequency weighted sound exposure levels	NOAA (2016a, b)	1 μPa² s	Weighting function, integration time	Metric used to evaluate impact of sound on marine mammal hearing (dual criteria)
dB	• Source level • SL	ISO/DIS 18405.2 2.3.2.1	1 μPa² m² 1 μPa² @ 1 m	Time interval and frequency range	A nominal value used as descriptor of sound source characteristics

24.6.4 Promoting Technical Progress

With shipping being a major contributor of anthropogenic sound to the acoustic environment, regulations and technical solutions should be sought for this industry with priority. Currently, most ships lack equipment to monitor their acoustic state. At comparably little cost such systems could be integrated in the hull during construction of new vessels, allowing crews to observe and control their acoustic state. Setting design goals (ICES 1995) and requiring independent verification of acoustic emissions for newly launched ships, maybe coupled to financial incentives (e.g. like the Port of Los Angeles Environmental Ship Index Program to reduce airborne emissions), could provide an incentive for shipbuilders and shipping companies to develop, acquire and implement quieter propulsion systems and codes of conduct to reduce their acoustic footprints.

24.7 Further Reading

Apart from the comprehensive *in-depth* reviews listed in the Foreword, www.dosits.org provides an illustrative background on the issue, with their "Facts and Myths" page (http://www.dosits.org/factsandmyths/) giving informative examples of common misconceptions and pitfalls. JASCO Applied Sciences published a most helpful booklet (http://oalib.hlsresearch.com/PocketBook%203rd%20ed.pdf) for the practicing acoustician. Glossaries of terms are provided by a number of institutions, with examples given below. However, in case of conflict, preference should be given to the documents provided by ISO.

- Appendix F of the NOAA DRAFT Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing.
- The Journal of Cetacean Research and Management's guide to authors providing a list of recommended keywords and species names.
- HTI, providing a web page with terms related to sonar technology—http://htisonar.com/glossary.htm
- The list of terms and abbreviations in the recent paper by Erbe et al. (2016) on masking.
- Several stakeholders have initiated dedicated research programs, funding independent, scientifically sound studies. Calls for proposals and publications of current results may be accessed via their webpages:
  - http://www.onr.navy.mil/Science-Technology/Departments/Code-32/All-Programs/Atmosphere-Research-322/Marine-Mammals-Biology.aspx
  - http://www.lmr.navy.mil/Preproposals.aspx
  - http://www.soundandmarinelife.org/
  - http://www.esrfunds.org/abopro_e.php

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