Cetaceans, bioindicators of noise pollution: understanding the changes of the marine environment

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Résumé
Le bruit dans la mer a toujours existé, sous forme naturelle ou biologique. Cependant, due à son caractère récent et non contrôlé, l'introduction massive de sources sonores artificielles s'est convertie en une menace pour son équilibre, plus importante que n'importe quelle autre pollution à laquelle se confronte aujourd'hui le milieu marin. Les cétacés, prédateurs supérieurs dans la chaîne alimentaire, ont évolué depuis des millions d'années autour de la perception acoustique de leur environnement et représentent des bio indicateurs naturels de l'équilibre acoustique des océans. Comprendre mieux la perception du milieu et les mécanismes de communication de ces mammifères marins signifie faire de la recherche pour la conservation des écosystèmes marins et le développement durable des activités humaines en mer.
Abstract
Ocean noise has always existed, both in natural and biological forms. Without any doubt, due to its recent and uncontrolled character, the massive introduction of artificial sound sources at a large scale has become a threat to its balance, more importantly than any other pollution found in the marine environment. Cetaceans, as top predators of the food chain, have evolved for millions of years on their acoustic perception of the environment and can be considered as bio-indicators of the acoustic balance in the oceans. Understanding how marine mammals perceive their environment and unravelling their communication methods means investigating for the conservation of the marine ecosystems and the development of sustainable human activities in the sea.

Sources of sound produced by human activities induce physical, physiological and behavioral effects on marine fauna: mammals, reptiles, fish and invertebrates; effects that can be diverse depending on the proximity to the signal source. These impacts, for example, include changes in cetacean behaviour and migration routes, and a distinct range of physical injuries in both marine vertebrates and invertebrate. There may be further long-term consequences due to chronic exposure and sound can indirectly affect animals due to changes in the accessibility of prey, which may also suffer the adverse effects of acoustic pollution. These damages could significantly impair the conservation of species already endangered which use acoustically contaminated areas for migratory routes, reproduction and feeding.

For many reasons, evaluating the acoustic impact of artificial sound sources in the marine environment is a complex and expensive proposition. Firstly, we face the relative lack of information on the sound processing and analysis mechanisms in marine organisms. Although we are capable of cataloging and recording the majority of these signals, we still do not know enough about the important role they play in the balance and development of populations. Secondly, the possible impact of sound emissions may not only concern auditory reception systems but might also interfere on other sensorial and systemic levels, possibly lethal for the affected animal. Even more complicating the situation is the fact that a prolonged or punctual exposure to a determined noise can have negative short, medium and long-term consequences that are not immediately observed. The lack of provision and research resources contributes to the greatest difficulty in obtaining objective data that will allow the efficient control of anthropogenic noise in the ocean.

In addition, we find ourselves with a most pressing problem, which relates to the homogenization of measurements. At the moment, there is no well-defined protocol for measuring marine acoustic pollution, nor any agreement on the enunciation of these measurements. While noise effects on the marine environment are increasing, the variability of the available parameters to measure these effects leads to heterogeneous or fragmented results that appear of little use in orientating preventive and precise management actions (André et al. 2010, http://www.lab.upc.es/research/downloads).

Finally, most studies lack information on long-term effects of noise sources on specific populations. There are very few data on current ambient noise levels in most regions, and even less on historical data. Information on trends is not available for any European waters. According to the Marine Mammal Commission (MMC 2007), underwater ambient sound levels will increase over time with more human activity (shipping, offshore construction) in the marine environment. It should be further noted that the potential increase in ambient sound levels will not affect all areas equally but specific regions where offshore activity is high, for example some of the Exclusive Economic Zones around North West Europe (see OSPAR 2009). Potential effects might not be proportionate to pollution levels due to variation in sound propagation and - most importantly - the distribution of marine life that is sensitive to sound.

Acoustic bioindicators

Cetaceans are acoustic bio-indicators. Marine mammals, notably cetaceans, depend on acoustic exchange for a great number of activities and vital behaviors such as communication, geographical orientation, habitat use, feeding and a wide range endeavors within the broader social group (cohesive action, warnings and maternal relationships). On account of their fundamental role in the balance of the marine food chain, cetaceans are considered as indicators of the interaction with anthropogenic noise.

A distinction must be made between "Sources of noise" and "Acoustic signals". The reason for this separation lies in the following: human activities in the ocean can generate residual noise that is associated with that activity but does not contain nor provide data. Shipping noise, oil and oceanographic platform construction, wind turbines or seabed drilling, for example, all fall into the category of "noise"; we are dealing with activities that "might" function without noise if they could rely on adequate available technology and practices. There are other activity groups which include military and industrial sonar, seismic and geographical surveys that are based on the usage of acoustic signals, i.e. sound sources introduced into the medium to extract information, and whose substitution would be very difficult, at the moment, to bring about. Lastly, we consider as acoustic signals the biological sources produced by marine organisms.

In the past hundred years the scale of anthropogenic noise introduced into the marine environment has grown to unprecedented levels. There is no doubt that in recent history, the larger oceangoing organisms, particularly cetaceans, have not yet developed the ability to adapt their auditory capacities to these powerful sound sources, whose impact on the functioning of their vital systems remains unknown.

The sources of marine noise pollution produced by human activity, includes, amongst others, maritime transport, oil and gas exploration and exploitation, industrial and military sonar, experimental acoustic sources, undersea explosions; military and civilian, engineering activities, supersonic aircraft noise and the construction and operation of sea-based wind farms.

These sound sources invade the acoustic and physical space of marine organisms (Figure 1) and there is no actual field of reference in which to foresee the negative consequences of these interactions on the ocean's natural equilibrium, and their short, medium and long term effects on marine biodiversity.

Even though land based environmental noise has been regulated since some time, only recently has marine acoustic pollution been introduced in legal international frameworks[1], becoming national regulations in countries such as the United Kingdom.

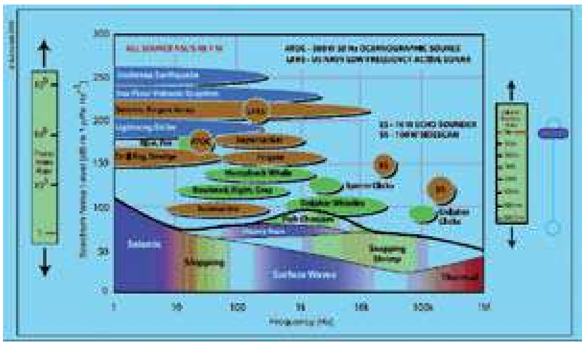

Fig. 1 : Sound levels and frequencies from anthropogenic and natural sound sources in the marine environment (Boyd et al. 2008)

The Council of the European Cetacean Society, a society of some 500 European scientists dedicated to cetacean biology research, considers that[2] :

- There is an urgent need for research into the effects of man-made acoustic pollution in the sea, research that must be conducted under the highest standards of scientific credibility, avoiding all conflicts of interest.
- Non-intrusive mitigation measures must be developed and implemented as soon a possible.
- There will have to be a limitation put on the use of powerful underwater sound sources until the short, medium and log term effects on marine mammals are known and the use of such sources is avoided in areas where concentrations of these animals are found.
- Legislative instruments must be developed with regard to marine acoustic pollution that will permit compliance of European and national policies on the protection of marine biodiversity.

Still even more recently, the Convention on Migratory Species (CMS), recognizing that…

… anthropogenic ocean noise constitutes a form of pollution which may degrade the marine environment and also have adverse effects on ocean fauna, even resulting in individual fatalities and reaffirming that the difficulty in determining the negative acoustic impact on cetaceans requires the drawing up of precautionary principles in cases where impact is possible,

… has just published among other resolutions[3], one that urges bodies whom exercise jurisdiction over any species of marine organisms listed in the appendices of the CMS, to…

… develop methods of control on the impact of acoustic emissions arising from human activities in susceptible habitats that serve as gathering points or places of passage of endangered species, and to carry out environmental impact studies on the introduction of systems that may produce noise and their derived risks to marine mammal species.

1- These regulations include articles 192, 194 (2.3), 206 and 235 of UNCLOS 1982 and UNCED 1992.
2- Conclusions from the 17th International Conference held in Las Palmas, Canary Islands in March 2003, under the main theme of Marine Mammals and Sound.
3- Ninth meeting of the parties, Rome 2008

TG11 Energy		
ATTRIBUTE	**Criteria** to assess the descriptor	**Indicators** to be measured
Underwater noise - Low and mid-frequency impulsive sound	High amplitude impulsive anthropogenic sound within a frequency band between 10Hz and 10 kHz, assessed using either sound energy over time (Sound Exposure Level SEL) or peak sound level of the sound source. Sound thresholds set following review of received levels likely to cause effects on dolphins; these levels unlikely to be appropriate for all marine biota. The indicator addresses time and spatial extent of these sounds.	The proportion of days within a calendar year, over areas of 15'N x 15'E/W in which anthropogenic sound sources exceed either of two levels, 183 dB re 1μPa2.s (i.e. measured as Sound Exposure Level, SEL) or 224 dB re 1μPapeak (i.e. measured as peak sound pressure level) when extrapolated to one metre, measured over the frequency band 10 Hz to 10 kHz
Underwater noise – high frequency impulsive sounds	Sounds from sonar sources below 200 KHz that potentially have adverse effects, mostly on marine mammals, appears to be increasing. This indicator would enable trends to be followed.	The total number of vessels that are equipped with sonar systems generating sonar pulses below 200 kHz should decrease by at least x% per year starting in [2012].
Underwater noise – low frequency continuous sound	Background noise without distinguishable sources can lead to masking of biological relevant signals, alter communication signals of marine mammals, and through chronic exposure, may permanently impair important biological functions. Anthropogenic input to this background noise has been increasing. This indicator requires a set of sound observatories and would enable trends in anthropogenic background noise to be followed.	The ambient noise level measured by a statistical representative sets of observation stations in Regional Seas where noise within the 1/3 octave bands 63 and 125 Hz (centre frequency) should not exceed the baseline values of year [2012] or 100 dB (re 1μPa rms; average noise level in these octave bands over a year).

Table 1 : Noise Descriptor of Good Environmental Status under the EU's Marine Strategy Framework Directive (MSFD)

In January 2010, a report concerning the Descriptor of Good Environmental Status under the EU's Marine Strategy Framework Directive (MSFD) for inputs of energy and noise was released (Table 1). The main output of the report concentrated in the definition of three indicators that are presented in the following table:

Cetacean Acoustic Signals

As was explained before, the choice of cetaceans as bio-indicators of oceanic acoustic pollution is not coincidental. The marine environment, as with all environments, is organized on the basis of the balance of organisms inhabiting them; each one is positioned on a specific trophic level that allows the development of higher levels. Disruption in any of these levels unbalances the chain, in both senses. Faced with a problem of conservation, the challenge of scientists is to find an organism, sufficiently representative, that's to say, whose balance and development may have an influence on the balance and development of the rest of the food chain, and use it as a bio-indicator against a contaminating source. Cetaceans, for their vital dependence and almost exclusive relationship with sound information, represent, up until now, the best bio-indicators of marine acoustic pollution.

The auditory system of cetaceans is characterized by a series of unique morphological adaptations: one of the most interesting ones is the capacity to select frequencies in order to distinguish acoustic images across auditory channels, which act as frequency filters.

In a healthy organism, this frequency selectivity of the ear (and of the acoustic signals which are produced and received therein) is evolvable and directly in relation with the specific use of its habitat, and as such, characterizes each cetacean species. On the other hand, within this frequency selectivity, the sensitivity of the ear in some species allows the measurement of the physiological or pathological condition of the auditory system in a predetermined individual, and to estimate its auditory capacity to use its habitat.

Each of the 80 species of cetaceans relies on a complex acoustic repertoire (see Table 2). This diversity of acoustic signals, intra and interspecies, complicates any analysis we make and considerably limits our capacity to adequately estimate the effects of a polluting sound source.

Each of the species that make up the order of cetaceans offers a unique acoustic repertoire in direct relation with the habitat where it has evolved over millions of years (Table 2). It is understood, that in order to detect prey, a coastal species will need to extract precise short distance details of the surrounding relief, while the absence of such relief will require pelagic cetaceans (those living in the open sea) to obtain information over medium and long distances to the presence of fish shoals or plankton blooms. Notwithstanding, all toothed cetaceans share the same acoustic production mechanism, which includes the projection of air across nasal air ducts and its exit by vocal lips, situated on the top of the head. Throughout immersions or dives, this air is recycled and permits them to vocalize, with the aim of echolocation or communication depending on the social context at that time.

Functional groups according to auditory characteristics	Estimated Bandwidth	Genus represented
Low frequency	7Hz to 22 kHz	*Baleana, Caperea, Eschrichtius, Megaptera, Balaenptera* (13 species/subspecies)
Mid frequency	150 Hz to 160 kHz	*Steno, Sousa, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcaella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon* (57 species/subspecies)
High Frequency	200 Hz to 180 kHz	*Phocoena, Neophocaena,Phocoenoides, Plaanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus* (20 species/subspecies)

Table 2 : Functional groups according to the auditory characteristics of cetaceans, the estimated bandwidth and the genus that represents each group[4]

Another peculiarity along with the absence of vocal chords, also unique in mammals, is the non-use of the external auditory channel for hearing purposes. Auditory vibrations are received across fatty tissues situated at lower jaw level that direct information to the middle and inner ear where it is processed before arriving to the brain.

Best Practices in management, assessment, and control of underwater noise pollution

Based on the above and before addressing activities that can cause noise pollution in the sea, within the framework of its authorization system (Environmental Impact Assessment), or by mean of its introduction in management systems of Marine Protected Areas, it is important to carry forth the following activities :
- Noise pollution measurements that the activity might provoke, like Sound Pressure Levels, Equivalent Sound Level (Leq), Sound Exposure Level (SEL), Energy Flux Density and Power Spectral Density.
- Comparison of results obtained from the measurements with tolerance thresholds of the different species present in the area, according to currently available scientific data.
- Description of the need to adopt some of the reduction measurements of the sound source.
- Description of the need to adopt some of the mitigation measurements from the produced impact.

Once the activity is authorized (in its case with its reduction or mitigation Measurements), the following must be adopted and implemented :
- Monitoring systems by means of sound propagation modeling and acoustic cartography.
- Monitoring by means of Passive Acoustic Monitoring techniques.

Special attention will be paid to the necessity of addressing the following within the monitoring framework of the activity :

4- Even though the range of frequencies embrace a considerable bandwidth that makes classification in different groups difficult, we consider here the central energy to the auditory spectrum of the species studied.

- The electrophysiological examination of stranded individuals in order to reveal the different acoustic sensitivities of different species (Auditory Evoked Potentials, AEP).
- The postmortem study of acoustic reception channels to establish possible injuries related to artificial sound source exposure.
- Comparative postmortem study of injuries in non-auditory organs.

References

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