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Threats Posed by Ocean Noise to Marine Mammals and Implications for Management

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Abstract. With the increasing frequency of human activities in the ocean, marine noise pollution has become a significant environmental stressor threatening the survival of marine mammals. This paper systematically reviews the primary sources of marine noise (such as vessel navigation, underwater pile driving, and offshore engineering) and its propagation mechanisms in complex marine environments. It focuses on analyzing the adverse effects of noise on the auditory perception, behavioral patterns, and ecological functions of marine mammals like cetaceans and pinnipeds. Research indicates that marine mammals rely on sound for communication, navigation, reproduction, and foraging. Anthropogenic noise not only risks causing hearing damage but also disrupts echolocation and social behaviors, potentially leading to severe consequences like strandings. Regarding governance, the paper reviews the progress and limitations of existing technical measures (such as bubble curtains) and legal frameworks. It proposes a systematic governance approach encompassing source control, propagation mitigation, and intelligent monitoring. The study emphasizes the need for enhanced interdisciplinary collaboration and international coordination to advance the implementation of dynamic adaptive management strategies, thereby achieving effective protection of the marine soundscape and sustainable management of marine ecosystems.

Keywords: Marine Noise, Marine Mammals, Noise Management

1. Introduction

With the population becoming larger than ever before, the resources on the land could barely meet human needs. Human expansion into the ocean area, correspondingly, aggravated the invasion of the habitats for those marine creatures. Many activities will produce different types of noise, such as subsea piling, ship noise, etc. Besides, a series of engineering subjects ranging from offshore wind power generation to subsea drilling, etc, will generate different types of noise as well. According to various marine creatures, a number of them rely on acoustics to survive, especially the marine mammals, which use voices to carry out conversations, breeding, individual recognition, echo location, setting the social order, etc.

Different mammals have different sensitive frequency ranges to sound and different auditory threshold ranges. Up to now, there has been some research on the auditory systems of marine mammals, but mostly on seals, and little on cetaceans, so the issue of how marine noise affects marine mammals. There has been a group from Xiamen University conducting research on how

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subsea piling and ship noise affect seals [1]. Meanwhile, there has been plenty of research on ocean noise. Su et al. analyzed the spectral characteristics of pile-driving and vessel noise and compared them with the hearing sensitivity range of spotted seals, indicating that both types of noise may interfere with their habitat and communication [1]. Hastie et al. conducted a pre- and post-construction study using GPS/GSM collars on 12 harbor seals, finding that for every 1 dB increase in vessel noise, the probability of seals remaining in core habitat areas decreased by 3% [2]. Kastelein et al. confirmed that pile-driving noise can cause temporary hearing loss (TTS) in harbor seals and discussed the potential risk of permanent hearing loss (PTS) [3].

Marine mammals, including Cetacea, Pinnipedia, and Sirenia. This article is going to focus on cetaceans and seals as examples to discuss the impact of ocean noise on marine mammals and provide some inspiration for governing the marine noise by reviewing the relevant literature.

2. Sources and propagation of ocean noise

According to the definition given by the National Oceanic and Atmospheric Administration, ocean noise refers to sounds generated by human activities that can disrupt or mask marine animals' ability to perceive natural oceanic sounds. It is obvious that ocean noise has a severe impact on the creatures relying on acoustics to survive or communicate. The noise can be divided into two categories: one with long duration but low intensity and the other with short duration and high intensity [4]. The former is normally regarded as the burst pulse, which is mainly produced by seismic engineering and sonar, while the latter is mainly produced by some transportation and industry engineering, such as ship engineering.

It has been indicated that several factors can affect the direction of noise propagation, which are the noise sources, seawater, and the seabed. In terms of noise sources, they include the sound frequency, the distance range of the noise sources, and the underwater depth of the noise sources. The higher the frequency, the louder the sounds commonly, and in the nearly vertical direction, the deeper the noise sources, the better the sounds propagate. It appears the same pattern in terms of noise sources distribution range as the pattern of depth distribution. As for the seawater depth, when it comes deeper, the noise level is weakened by the seawater, but the noise is more focused in the vertical direction. The last one is the seabed, including the seabed sediment and seafloor substrate. A downward slope can strengthen the weak sound. An upward-wedged seafloor will concentrate sound energy, while a downward-wedged seafloor will disperse sound energy, resulting in significant differences in sound intensity at the receiving point with direction [5]. Besides, as for the noise level, in the deep sea, the noise spectral level in the low-frequency band is higher than that on the continental slope because the sound loss in all direction is relatively small in the deep sea, while the noise spectral level in the high-frequency band on the continental slope is higher, because not only can the shallow water receive the noise from the noise sources directly, but also it will receive the reflect of high-frequency from the seabed [6].

3. The role of acoustics in the life history of marine mammals

3.1. Cetacean

Cetaceans, a mammalian population that is completely living underwater, belong to the order Artiodactyla of the class Mammalia. Normally, the larger ones are called "whales", whilst the smaller ones are called "dolphins" or "porpoises". Cetaceans are entirely carnivorous, except for the order Sirenia [7]. They use echolocation for prey capture.

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Due to the limitations of technology, nearly all ranges of research on hearing in cetaceans is based on small samples, especially the Atlantic bottlenose dolphin. Many people have successively measured different cetaceans, and the outcome shows that cetaceans have high-frequency hearing capabilities. The sound type can be generally divided into two parts based on the purpose: communication signal and echolocation. The communication signal usually happens when they express their feelings or communicate with others. This is also called a burst pulse, which plays an important role in combating each other. Cetaceans reproduce by internal fertilization. Their breeding is seasonal, which reflects that they normally calve one cub every two years. After a female is fertilized, she carries the fetus for about a year, some species even up to 18 months. There are some guesses that this kind of sound plays a role in cetaceans' breeding. Due to the uncertainty of the targets' location, this kind of sound is often featured with a wide spread range, and the frequency is relatively lower to spread farther.

The echolocation signals are characterized by frequency concentration in the ultrasonic range and energy concentration. There has already been some evidence that cetaceans' echolocation system evolution is likely related to a gene called Clan14. Besides, there is a protein called Prestin, which is used to transmit ultrasonic signals. Cetaceans can produce the ultrasonic signals whose peak is higher than 20kHz, some could even be higher than 100kHz. They have extremely high auditory sensitivity, which is because of their special outer hair cells. The cells will amplify vibration when they receive the sound, which makes cetaceans more sensitive to sounds.

3.2. Seal

Seals belong to the suborder Pinnipedia of the class Mammalia. They are totally carnivorous, mainly eating fish and cephalopoda. Thus, they use echolocation to follow the prey.

According to research conducted by Xiamen University, the sound production frequency is about 139~2323Hz. In terms of their breeding, seal has a seasonal breeding feature [1]. They come to the shores once a year for breeding. One male seal can mate with several female seals, which depends on the status of the male seal. After being fertilized, female seals will carry the fetuses for about 11 months until the pups are calved. The cubs were born on open ice or in the lair. The sexual maturity is reached at approximately 2 to 4 years old. The echolocation system is the key for them to survive as well. During the pup-rearing period, mother seals will emit waning calls to fend off threats, protecting their pups. Correspondingly, the pups emit distress calls when they meet danger. Besides, mother seals will emit begging calls to their partner as well. All of these sounds are generally concentrated between 200 to 1200Hz, which is distinguished based on whether adults or pops [8]. Pops show relatively higher frequency ranges than adults. Except for the breeding period, seals use sound to navigate, locate prey, and evade predators.

4. The harm that ocean noise causes to marine mammals

4.1. The reason

The marine mammals' auditory ranges are roughly estimated about 5Hz to 200kHz, while their vocalization frequencies are mainly concentrated between 30Hz to 30kHz [9]. Different species have different auditory abilities. For example, according to The global energy sector from a subsurface perspective, the Mysticetes can react to the low-frequency range from 20Hz to 50Hz, and they can also produce low-frequency sounds, while Odontocetes are capable of hearing 100Hz to 180kHz and the most sensitive frequency band is the high-frequency range about 10kHz to 65kHz.

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Meanwhile, the most sensitive frequency bond of the spotted seal ranges from 0.1kHz to 100kHz, a group from Xiamen University [10], who learn that the spotted seal from the harbor seal, which has a close genetic relationship, and the acoustic research on harbor seals is relatively in-depth. These evidences indicate that marine mammals have a wide auditory range. It can be divided into three types [11]: infrasonic species(show a sensitive auditory ability between 20 Hz and 2 kHz), high-frequency sound species(maximum frequency between 100Hz and 100kHz) and ultrasonic species(sensitive to sounds between 200Hz to 200kHz).

A wide range of ocean noise, which will produce a series of severe noise problems, due to the noise level(dB), the sound frequency bands similar to those used or perceived by marine mammals, the misinterpretation of the behavior of marine mammals, etc. This article mainly focuses on the former two, which affect the marine mammals the most.

4.2. The impact

When the noise level is high enough, it will cause the hearing of marine mammals to suffer from severe damage. As for the noise, which is not really intense, but covers the sensitive auditory frequency bands of some marine mammals, although the noise level is not that high, it will still cause disturbance and hearing damage to them.

4.2.1. To cetacean

Large ships navigating will produce the low-frequency sounds, which are long-duration and intense. There has been some research on the impact of ocean noise affect to cetaceans. Popov, etc [12], found that when Yangtze finless porpoise suffer from long-time and high-intensity noise, they may experience temporary threshold shift (TTS), which means the hearing threshold temporarily elevates and the auditory ability is temporarily weakened. The diving time of Sousa chinensis will apparently increase when the ships come towards them [13]. Meanwhile, there are plenty of speculations and evidence that whale stranding is related to marine noise. The researchers from the Institute of Hydrobiology, Chinese Academy of Sciences, once tested the auditory ability of a stranded melon-headed whale and found that its hearing was severely damaged [14]. When their echolocation systems are damaged, they may hard to navigate, finally contribute to the stranding. Historically, a large-scale Hyperoodontidae's stranding has occurred in the Mediterranean Sea and the New Providence Channel in the Bahamas, which is affected by the sonar used at the moment [15]. Even though some noise intensity is lower than the cetaceans' target sounds within their most sensitive hearing frequency bands, they can still affect the echolocation due to the high-frequency sounds produced by cetaceans attenuating rapidly underwater [16].

4.2.2. To seal

The hearing threshold curve of seals is only 1-2dB higher than the ambient noise, so it can be considered that seals can detect almost any sound disturbance happening around. Most of the energy of ship noise is concentrated under 5kHz, which completely covers their sensitive hearing threshold range [1]. If the seal is exposed to the ship noise, the hearing threshold masking and perceptual dulling will occur in certain frequency bands, which leads to a weakening of their perceptual ability.

The vocalization frequency of seals is similar to their sensitive hearing threshold [10], which means the perceptual ability highly matches their behavior, such as communication and navigation. However, the frequency of subsea drilling sounds and ship noise covers the sensitive hearing

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threshold of seals, so it has an impact on their behavior. When the breeding season comes, the disturbance of a single seal by acoustic perturbation can affect the entire group, because the sounds do harm to their rest and nursing [16].

5. Progress and challenges in marine noise management

Up to now, there have already been lots of studies about ocean noise, including the sources, the categories, the frequency, etc. In order to protect the ecological environment and marine mammals, it is urgent to study further on ocean noise. Nowadays, there has been plenty of research on ocean noise, down to the specific type of noise. So far, China has adopted protective measures against marine piling noise and oil drilling equipment noise. Some have already given some suggestions on the electric engine and air conditioning system [17].

There have already been a number of efforts on governing ocean noise, including the technical dimension and the legal dimension. From a technical dimension, the bubble curtain [18], which is used for the subsea pilling. A bubble curtain can attenuate the noise level effectively within 1km. From a legal dimension, there is already some literature dedicated to protecting mammals from ocean noise. Agreement on the Conservation of Small Cetaceans of the Baltic, North-East Atlantic, Irish and North Seas(ASCOBANS), which was concluded in 1991 under the auspices of the Convention on the Conservation of Migratory Species of Wild Animals(CMS). However, most of the technical efforts are aimed at contributing to humans; there is still a gap in the protection of marine organisms. Meanwhile, although some organizations have noticed the impact that ocean noise brings to marine mammals, there are still no standardized and regulated agreements for this issue. Despite significant progress in marine noise research, effective governance still faces formidable technical challenges. First, bottlenecks exist in noise monitoring and source attribution technologies. The complex marine environment, where sound propagation is influenced by factors such as water temperature, salinity, and seabed topography, makes it difficult to conduct precise, real-time, and comprehensive monitoring and localization of noise. In particular, distinguishing the contribution of specific noise sources—such as multiple vessels navigating simultaneously—remains extremely challenging. Second, noise impact assessment models remain imperfect. Significant variations exist among marine mammal species in auditory sensitivity, behavioral response thresholds, and noise tolerance. Existing models struggle to accurately quantify noise-induced physiological damage, behavioral disruption, and long-term ecological consequences for specific populations, leaving management measures lacking a sufficient scientific basis. Furthermore, the development and application of noise reduction technologies face limitations. Although localized noise reduction technologies like “bubble curtains” exist, their cost, reliability, and applicability remain challenging in large-scale, deep-water, and complex sea conditions. Moreover, for vessels—the primary mobile noise source—innovations like low-noise propulsion systems and large-scale retrofitting are costly, leading to slow adoption.

6. Inspiration

Technologically, marine noise mitigation relies on the development and systematic integration of forward-looking technologies, centered on noise reduction at the source, propagation path isolation, and real-time monitoring and early warning of noise impacts. First, advancing comprehensive low-noise design for vessels is key to reducing mobile noise sources. This goes far beyond engine improvements, encompassing a comprehensive approach: adopting quieter electric propulsion systems to replace traditional mechanical transmissions; optimizing propeller design and

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manufacturing processes to minimize broadband noise from cavitation effects; and installing high-performance damping materials and acoustic enclosures in critical hull areas (such as engine rooms and machinery spaces) to create an "acoustic envelope." Ultimately, establishing and enforcing mandatory "vessel quietness rating" certification is essential to set clear noise limits for vessels operating in sensitive marine areas.

Second, for offshore engineering activities, the development and mandatory application of efficient active noise reduction and alternative technologies must be prioritized. For transient high-intensity noise sources like subsea pile driving and seismic surveys, single bubble curtain technology may sometimes prove insufficient. Composite barrier technologies such as "dual bubble curtain" systems and hydroacoustic barriers should be researched and deployed to create a more complete acoustic isolation wall around noise sources. Simultaneously, active encouragement and investment should be directed toward developing and applying alternative construction methods, such as vibratory pile drivers, which generate significantly lower noise impacts than traditional impact pile drivers.

Finally, establishing an intelligent marine soundscape monitoring and early warning system is crucial. By deploying integrated underwater acoustic monitoring stations in key habitats and shipping lanes, combined with shore-based radar and satellite AIS data, real-time capture of noise field changes and vessel tracking can be achieved. Leveraging this big data, artificial intelligence models can be trained to accurately predict noise propagation ranges under varying sea conditions and generate dynamic "acoustic footprint" maps. This system can automatically alert vessels or issue navigation advisories when endangered species approach or regional noise levels approach thresholds, triggering temporary speed restrictions or intelligent route adjustments. This elevates management from static exclusion zones to dynamic, adaptive soundscape conservation.

At the management level, technological innovation enables precise control. First, governments can leverage these monitoring technologies to establish "marine quiet zones" in critical habitats such as marine mammal breeding and foraging grounds. Within these zones, dynamic acoustic controls based on scientific data can be implemented—for example, limiting the speed and number of large vessels, setting navigation window times to avoid sensitive periods, and prohibiting high-noise engineering operations. However, as the high seas are considered a shared heritage of humankind, comprehensive implementation remains challenging in the short term without concerted international efforts. Therefore, nations can take the lead by demonstrating such measures within their territorial waters and exclusive economic zones, gradually advancing global collaborative governance through regional agreements.

7. Conclusion

This study systematically examines the impacts of marine noise pollution on marine mammals and proposes mitigation strategies. First, it dissects the primary sources and complex propagation mechanisms of marine noise, clarifying its physical characteristics as a significant anthropogenic environmental stressor. Subsequently, it emphasizes the critical role of sound in the life histories of cetaceans and pinnipeds, including their high-frequency auditory and echolocation capabilities for communication, reproduction, navigation, and foraging. Building on this foundation, the paper delves into the multifaceted harms caused by marine noise of varying spectra and intensities across marine mammal species. These range from physical damage to auditory systems and behavioral disruption to severe ecological cascading effects. Finally, the study reviews the progress and limitations of existing mitigation measures at both technical and legal levels.

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Looking ahead, effective marine noise governance urgently requires interdisciplinary collaboration and innovation. Research should focus on developing more precise real-time noise monitoring networks and risk assessment models for noise impacts at individual and population levels. Technologically, accelerated development and deployment of low-cost, high-efficiency source noise reduction and propagation pathway blocking technologies are essential. Management approaches should actively transition from static marine quiet zones to dynamic adaptive management paradigms based on real-time acoustic landscape data. Furthermore, strengthening the enforceability and implementation of international conventions is crucial for establishing a globally coordinated marine acoustic landscape governance framework.

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