Primer on Ocean Noise and its Impacts

Government of Canada Gouvernement du Canada

Canada

Notes to readers

Although the physics of sound in the ocean is well understood by the scientific community, the manner in which sound functions in the marine environment and the associated effects of noise on marine animals can be a very complicated issue to describe. In fact, many aspects related to impacts are not fully known. Readers may wish to consult the list of references in this document for more information on ocean noise.

While this document was primarily informed by western scientific findings associated with ocean sound, noise and its impacts, the Government of Canada acknowledges the need for and importance of Indigenous Knowledge systems in understanding and managing ocean noise. Readers may wish to consult Canada's Ocean Noise Strategy for more information on the Government of Canada's efforts to better understand and manage ocean noise.

Terms in **bold** are defined in the **Glossary** section of the document.

Published by:
Fisheries and Oceans Canada, Ottawa, Ontario K1A 0E6
Également disponible en français.

Title: Primer on Ocean Noise and its Impacts.
Issue number: 23-2345 Cat. No. Fs23-741/2024E-PDF ISBN 978-0-660-71709-8

Cover, top: Scientist listening for real-time sounds of marine mammals and other marine fauna; Arctic Ocean, Canada Basin. Credit: Jeremy Potter NOAA/OAR/OER.
Cover, bottom: Humpback whale (*Megaptera novaeangliae*). Credit: Elianne Dipp.

Three cargo vessels in the distance. Credit: Vancouver Fraser Port Authority and John Sinal Photography.

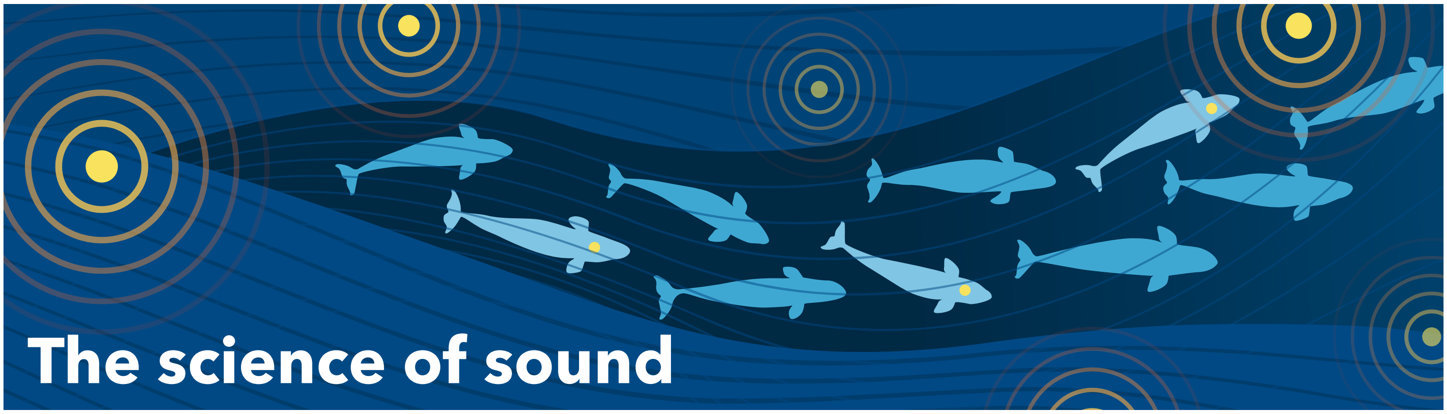
Table of Contents

Importance of sound in the ocean

Sound is crucial to life under water. Although acoustic communication is important for many terrestrial animals, it is even more important for marine animals because sound travels very efficiently underwater.[1] The ocean has a rich natural soundscape that is made up of natural **biotic** and **abiotic** sounds. Natural biotic sounds include whale calls, dolphin whistles, fish grunts, and other sounds that are produced by marine wildlife for communication, foraging, mating, and avoiding predators.[2] Abiotic sounds include those from non-living sources, such as waves, cracking ice, and undersea volcanos. This combination of sounds makes the ocean an extremely dynamic environment where the ability for marine animals to send and receive sound signals is vital for their survival.[3,4,5]

Northern Gannets (*Morus bassanus*) hunting fish underwater.
Credit: Sallye photography.

Seabirds flying over waves hitting an iceberg. Credit: SOI Foundation.



The science of sound

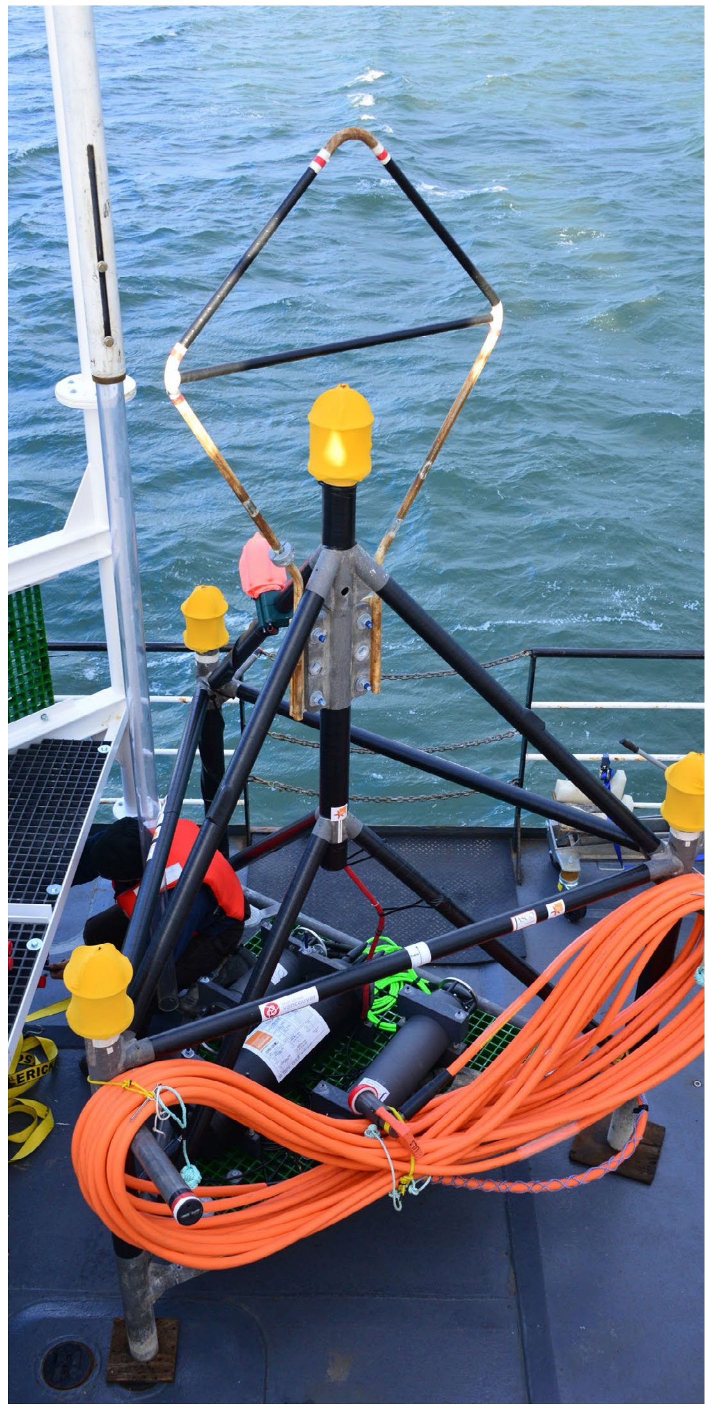
Sound is a type of energy created by the vibration of molecules. As energy is transferred between molecules, the movement generates sound-pressure waves that can travel through a medium, such as air or water. In short, sound is the term used to describe what is heard when these pressure waves are received and interpreted by recipients.

Sound is often described by its **amplitude** (or loudness) and **frequency** (or pitch). To the human ear, higher frequencies are perceived as higher-pitched sounds; larger amplitudes are perceived as louder sounds. As sound travels through a medium, it loses energy which limits its travel distance.[6] Loud sounds have more **acoustic energy** than quieter sounds. Low-frequency sounds lose less energy while they travel, allowing them to travel further than higher-frequency sounds.[7] That is why loud and low-frequency devices such as foghorns are commonly used to communicate over long distances. Similarly, a blue whale call, which is also very loud and low frequency, can be detected hundreds of kilometres away.[8]

Did you know?

Sound levels (how loud sound is) are measured in **decibels** (dB), which is a relative unit on the **logarithmic scale**.

A sound measured at 70 dB has 100 times more acoustic energy than a sound measured at 50 dB.



Hydrophone listening station. Credit: Ocean Networks Canada.

Understanding sound in the marine environment

Sound behaves differently in water as compared to air due to the difference in physical properties of these two media. Sound can travel approximately 4.5 times faster in seawater than in air (1450 to 1550 metres/second in saltwater compared to 343 metres/second in air).[7] Sound speed also increases with the **salinity** of the water making the ocean an extremely efficient transmitter of sound. This characteristic makes sound a highly effective and reliable means of communication in water, especially when compared to sight (vision is often limited to tens of metres at best underwater)[9,10] or smell (odours are often intermingled because of the turbulence of ocean waters).[11]

Other factors such as water temperature and pressure (which varies with depth), salinity, seafloor compositions and structure, and other **oceanographic conditions**, including the amount of ice cover and **sea state**, can also influence how fast and how far sounds travel. Studying these relationships allows scientists to better understand the characteristics of sound in the marine environment.

Did you know?

The decibel scale is measured differently in air than in water using different reference pressure. This means that comparing the exact decibel between air and water can be misleading, because a “quiet” decibel level in air can be a relatively “loud” decibel in water.

Polar low crossing the coast. Credit: Therato.

Temperature, salinity, and pressure

Temperature, salinity, and pressure impact the speed that sound travels underwater. Sound speed increases with increases in temperature, and pressure, and these vary greatly depending on depth (**Figure 1**). The interacting effects of temperature and pressure mean that sound travels the slowest at approximately 500-1000 m in depth where temperature and pressure are relatively low. This horizontal zone of minimum speed is called the SOFAR (SOund Fixing And Ranging) channel. Similarly, sound travels faster in water with increased salinity. In areas where freshwater inputs (such as estuaries or from the melting of glaciers) are present, sound in water would travel slower than the other marine areas if all other factors are the same.

Did You Know?

Sound waves can travel great distances with minimal energy loss in the SOFAR channel.

This channel is especially important for baleen whale communications and the study of ocean sounds.

Sea lion (*Otariinae*) diving in water. Credit: Samuel Crimshaw.

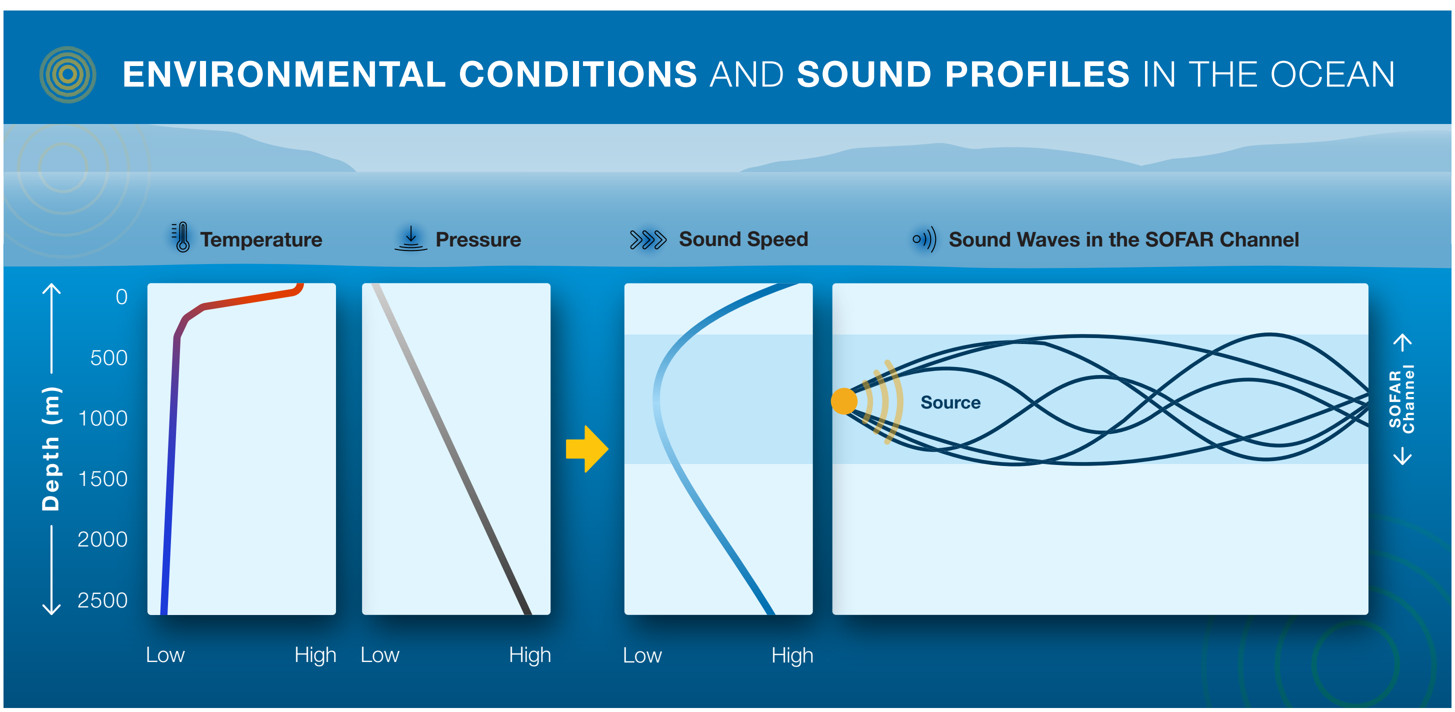


Figure 1. Temperature, pressure, and sound speed profile based on water depth and sound propagation in the SOFAR channel (adapted from Webb (2017))[12].

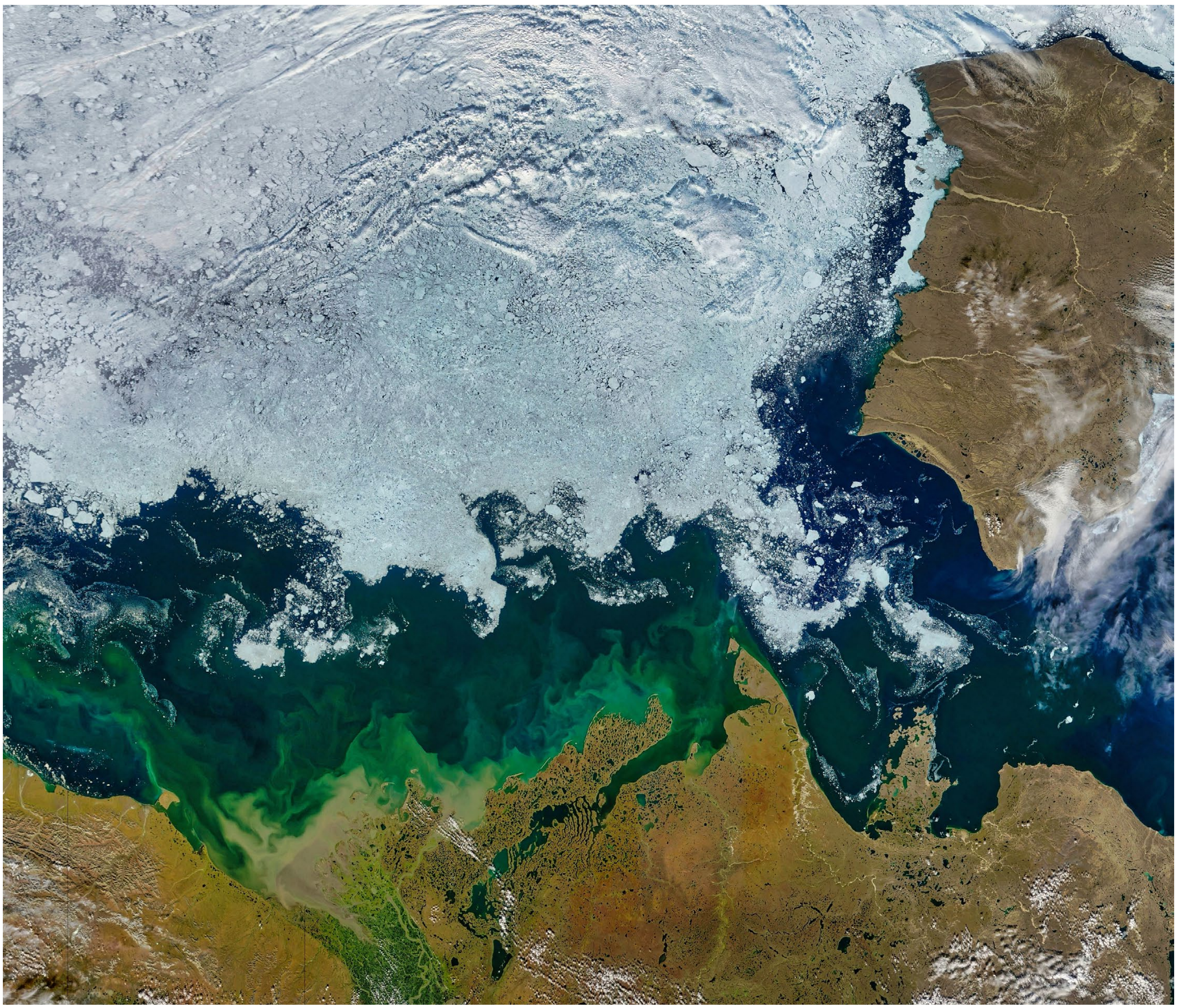
Water depth, seafloor composition, ice cover, and other oceanographic conditions

Sound travels differently depending on water depth. Every time the sound waves interact with either the ocean surface or seafloor, some or all of the acoustic energy gets reflected or absorbed.[13] In shallow waters, sound waves have an increased number of interactions with the surface and seafloor which results in increased loss of acoustic energy. The amount of absorption or reflection of sound depends on the bottom composition of the seafloor and the sea state.[13] In ice-covered conditions, sound is partially absorbed by sea ice and is reflected or scattered based on the smoothness of the underside of the ice. As a result, sound loses energy more rapidly and does not travel as far in polar regions when sea ice is present.[14,15]

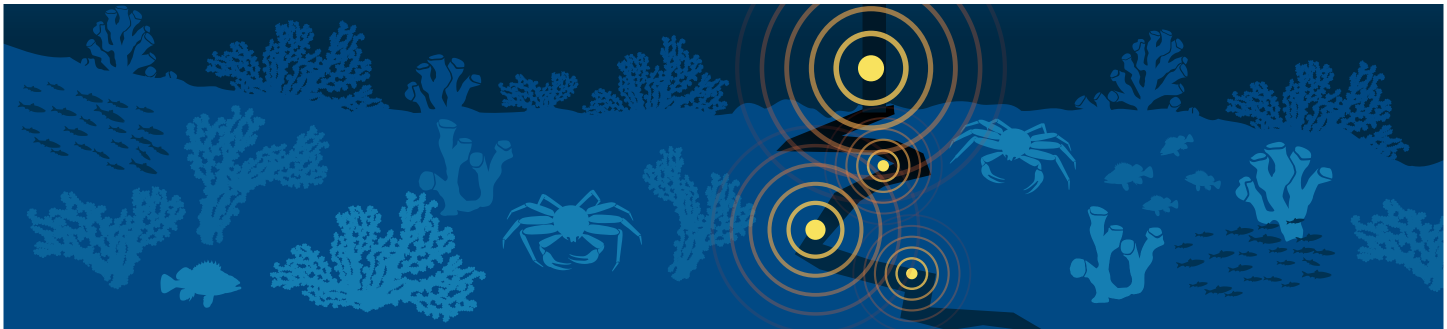
Did you know?

The acidity of the ocean also impacts sound absorption. As the ocean continues to become more acidic due to ocean acidification, it is predicted that there will be less sound absorption.

A study found that sound will be able to travel more efficiently underwater with increased acidity, and signals may have higher amplitudes by as much as 5 dB over long-ranges (~200 km).[16]



Mackenzie River and Mackenzie Bay, Yukon, Canada. Credit: BEST-BACKGROUNDS



Human activities and sources of ocean sound

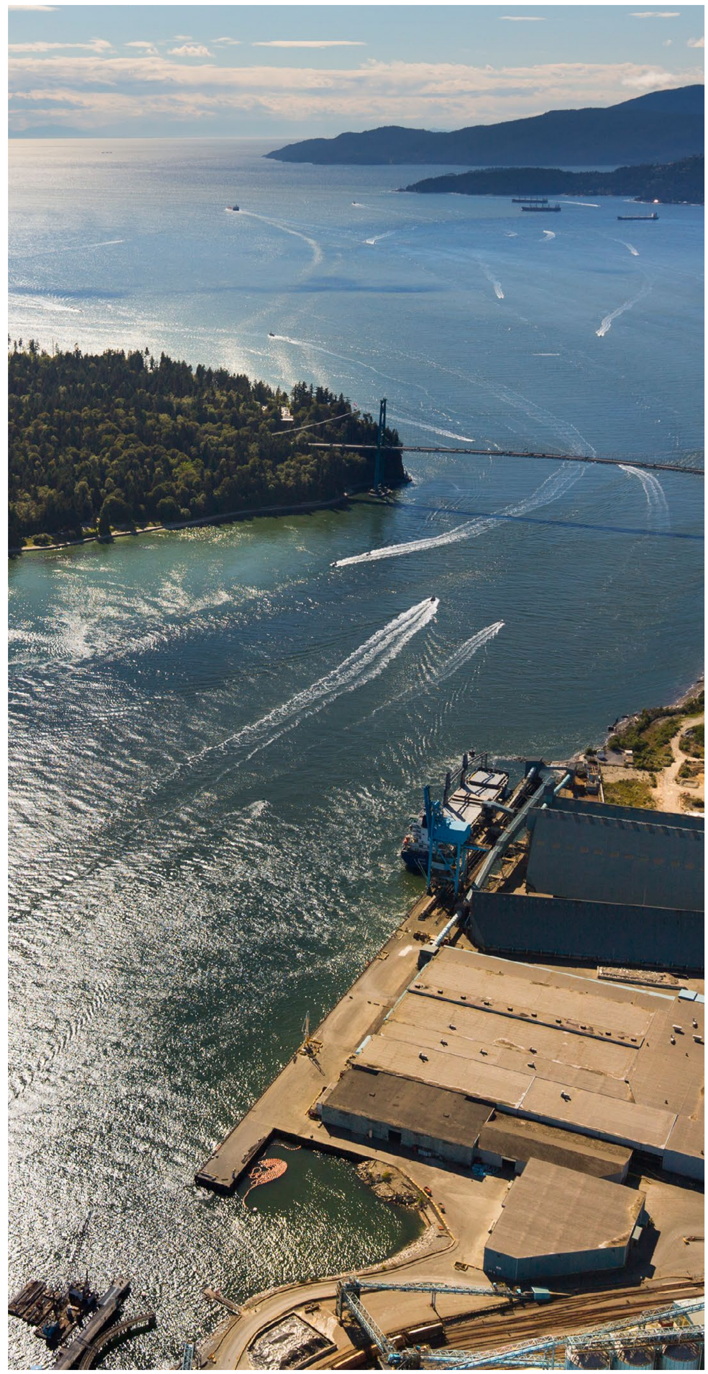
The development of the global marine economy over the last 200 years has increased the number of sources and overall loudness of human-generated (or **anthropogenic**) ocean sounds, completely changing the coastal and offshore underwater ocean soundscape (**Figure 2**).[17]

While there are many human activities in the marine environment that produce sound over a wide range of frequencies, there are six main categories of activities that produce the majority of underwater ocean sound, which are described below. When examining the sounds created by these activities, it is important to consider four aspects of the noise source:

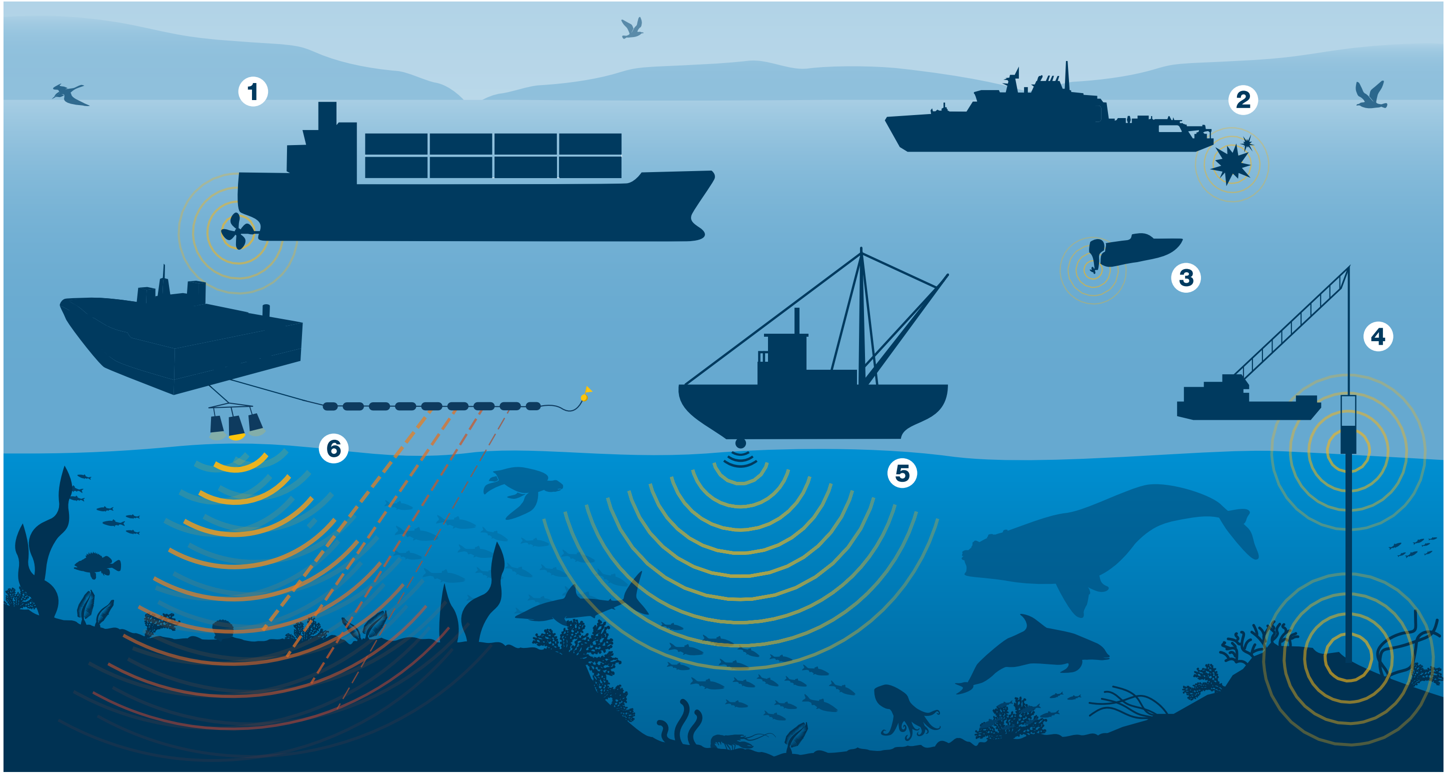
1. the amplitude (or loudness) of the source;
2. the frequency range of the source;
3. whether the source is producing **continuous** or **impulsive** noise; and
4. the extent of source, including how common the activity is in an area at which it can impact marine life.

What is "ocean noise?"

In the context of this document and *Canada's Ocean Noise Strategy*, ocean noise is defined as human-generated sounds that are transmitted beneath the surface of the water and has a wide range of impacts on marine animals, including limiting acoustic communication, causing behavioural and physiological changes, physical injury, and even death.



Vessels crossing First Narrows/Lions Gate Bridge, Vancouver, BC. Credit: Vancouver Fraser Port Authority and William Jans Photograph.



ANTHROPOGENIC SOURCES OF **OCEAN NOISE**

1 Large vessels **2** Military activities **3** Small vessels **4** Industrial activities and construction **5** Echosounders and sonars **6** Seismic surveying

Figure 2: Main categories of human activities that produce the majority of underwater ocean sound.

Large vessels

Large ocean-going vessels, such as container ships, bulk carriers, coastal freighters, ferries, and cruise ships are, collectively, the largest human source of low-frequency underwater sound.[17] While these vessels produce a variety of sounds, the most significant sound source is the low-frequency continuous sound from the ship's propeller.[18,19] This low-frequency range is critical for many marine species as they use it to communicate with and locate each other, sometimes over great distances.[17] These sounds contribute to the background of anthropogenic sound over large geographical areas.[20,21]

Small vessels

Smaller vessels, such as, fishing vessels, pleasure craft, and tourism vessels (excluding cruise ships), are another significant source of continuous sound that span a broad range of frequencies. These vessels are plentiful and often found close to shore in waters of less than 200 metres where there is significant absorption and reflection of sound. Some small vessels, such as tugs, produce comparable levels of sound to large vessels; whereas other small vessels, such as tourism vessels and pleasure craft, produce less sound individually than large crafts, but the high number of these vessels and their presence in shallower waters can contribute to significant increases in anthropogenic sound in coastal areas.[22,23,24,25,26,27]

Did you know?

As the ocean continues to warm due to climate change, it is anticipated that the reduced sea ice will also result in significant increases in ocean noise in the Arctic.

While much of this increase will come from more vessel traffic, increases in abiotic sounds (such as ice break-ups, **iceberg calvings**, etc.) are also expected.

Seismic surveying

Marine **seismic surveys** are often used for geological research and oil and gas exploration. These surveys use airguns that rapidly release compressed air. The collapsing air bubbles create a very loud and intense impulsive sound directed towards the seafloor; the reflected sound waves are used to identify **subsurface geological features**.[28] Seismic surveys can vary in **intensity** and frequency range depending on the purpose of the surveys.[29,30]

Industrial activities and construction

Pile driving, dredging, drilling, tunnel boring, marine renewable energy, and canal-lock operations are all examples of industrial and construction activities that contribute to underwater sound in the ocean and along shorelines. This diverse group of activities can release both high-intensity and impulsive sound (e.g., impact pile driving) as well as low-intensity and continuous sound (e.g. dredging, vibratory pile driving) into the marine environment.[9,31]

Military activities

Military operations, such as ship-shock trials (where explosives are purposely detonated near a vessel to simulate a near miss during battle), live-fire exercises, and operations using military sonar, all result in very high sound levels. Operations involving explosions are impulsive sounds, whereas naval sonar is a short continuous sound that is often repeated frequently. These activities contribute some of the loudest and most intense anthropogenic sound in the marine environment.[21,32]

Echosounders and sonars

The use of echosounders and sonars for scientific, industrial, and recreational purposes is steadily increasing. These systems typically create an impulsive acoustic signal to seek information about objects (such as fish) within the water column, at seafloor, or within the sediment. Unlike seismic airguns, these signals use a **transducer** to create a sound wave rather than using compressed air. Moreover, echosounders and sonars typically transmit signals in much higher frequency bands than seismic airguns **(Figure 3)**. The use of these systems in the marine environment is pervasive and they can operate in a wide range of frequencies.[33]

Shipping vessel travelling between offshore wind turbines. Credit: TwiXteR.

Categories of impacts on marine wildlife

At any given time and place, the combination of natural and anthropogenic sounds can create a highly variable soundscape. While marine animals have adapted to changes in natural marine sounds, loud and intense anthropogenic ocean noise is relatively new.[17,21,34] While sound is any vibration that travels through a medium, noise is specifically unwanted or harmful sound.[35] Ocean noise can interfere with essential biological and ecological functions and can cause a wide range of impacts on marine wildlife.[36,37] It is important to note that the behavioural impact of noise on marine animals is likely context-driven.[38] For example, age, sex, location, activity, and prior noise exposure of the individual animal can all influence how that animal responds to anthropogenic noise.[39,40,41]

A raft of steller sea lion (*Eumetopias jubatus*) underwater Vancouver Island, BC. Credit: William Drumm.

There are four general categories of ocean noise impacts on marine life:

Masking

Sounds from different sources at similar frequencies can interfere with one another making accurate interpretation of sound signals difficult. **Masking** occurs when noise interferes with a sound or signal of interest and decreases the animal's ability to detect, recognize, or understand that sound. Anthropogenic ocean noise may mask sounds such as those from prey, predators, and mates that are vital to marine animals. Researchers have found that animals have trouble using sound for communication when anthropogenic noise is loud and occurs in similar frequencies, time, and space as the animal's own acoustic signals (**Figure 3**).[42,43] Given the widespread nature of human activities, masking may be one of the most extensive and significant impacts on the acoustic communication of marine organisms.[44]

Imagine being at a music festival where two bands are playing close together:

How well can you differentiate the songs?

Can you verbally communicate well with the person standing next to you?

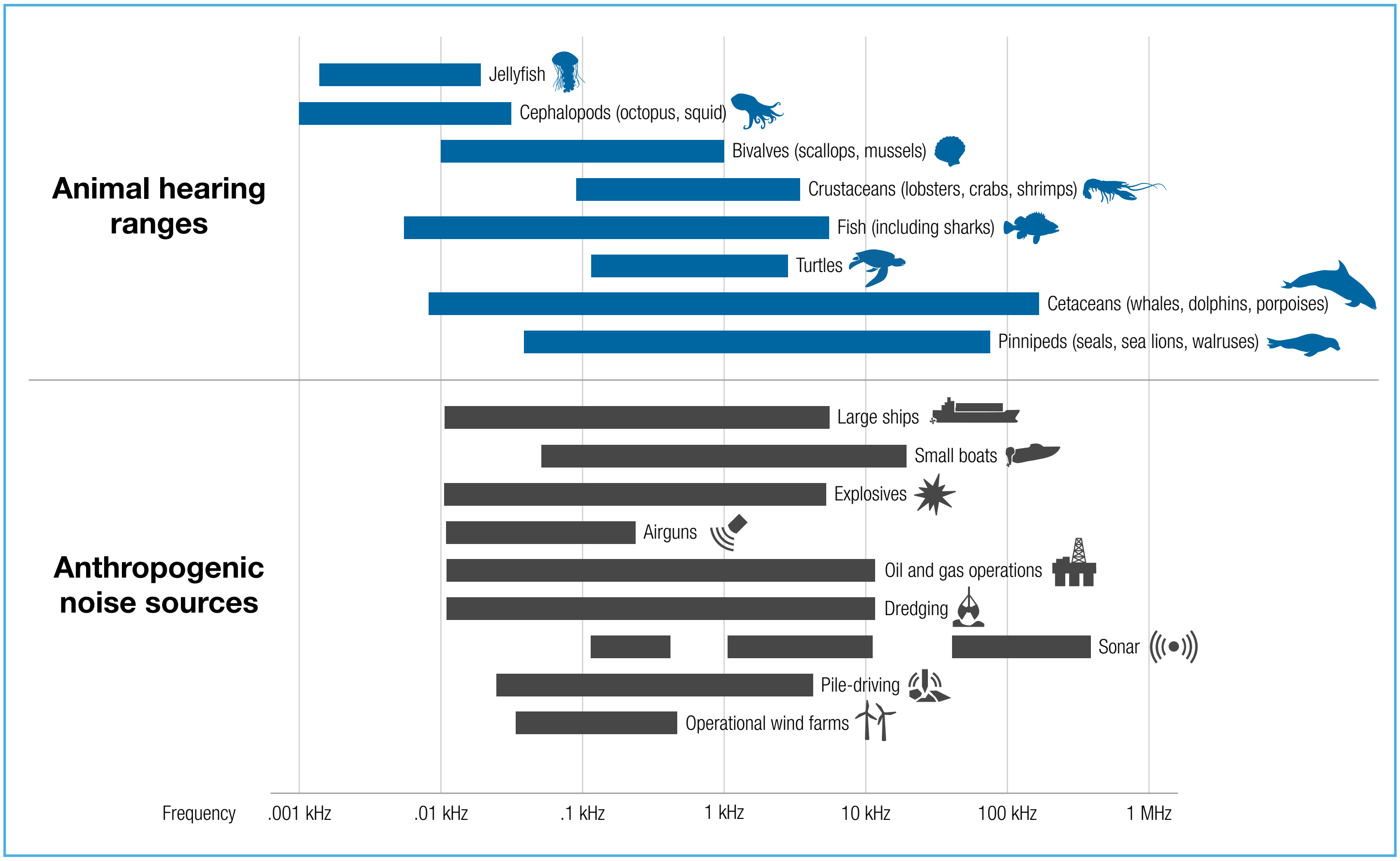


Figure 3: Frequencies of animal hearing ranges and anthropogenic noise sources (adapted from Duarte et al. (2021)[17] and Vergara et al. (2021)[45]).

Physical injury

Intense noise exposure may cause physical injury, including temporary or permanent hearing impairment, and potentially even death. While all animals have different **hearing ranges**, animals exposed to intense sound have been shown to be unable to detect signals in their entire hearing range for a period of time following exposure.[46,47] Although the magnitude of this impairment normally decreases over time, noise exposure can sometimes result in permanent hearing damage.[48] This permanent inability to detect signals at particular frequencies could impair vital life functions to the point where the animal's survival is jeopardized.

Physiological impacts

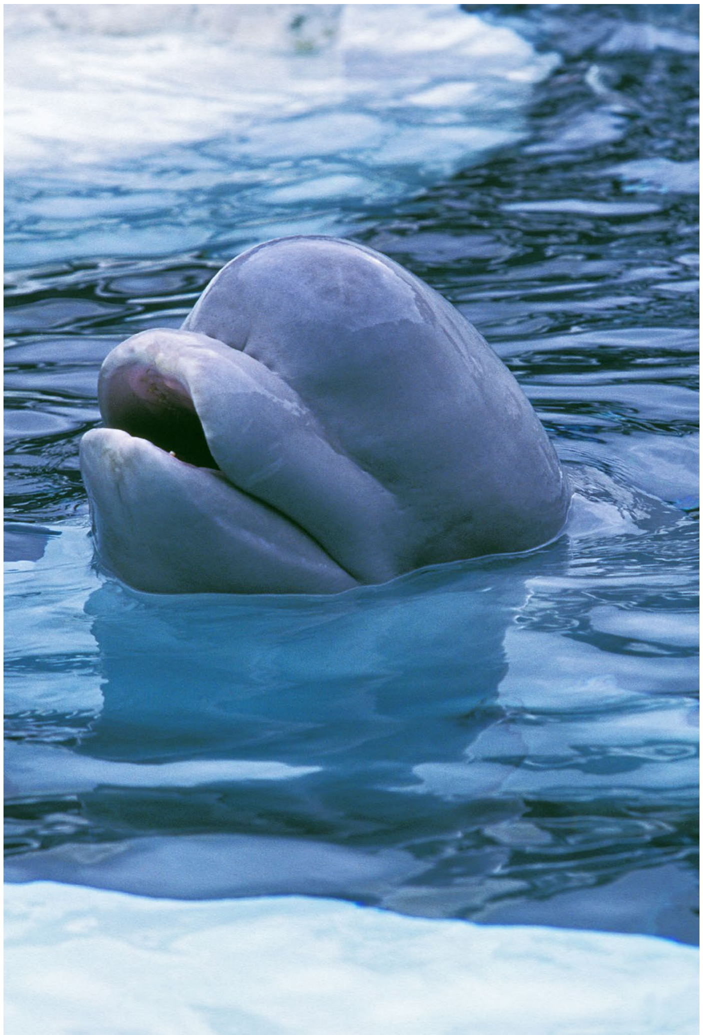
Noise may have various physiological impacts, including increased stress,[49,50,51] changed **metabolic rates**,[52] weakened immune system responses,[53] and reduced reproductive rates.[54] Extended exposures and repeated increases in stress could have long-term health impacts on marine animals.[55]

Behavioural changes

Noise exposure may cause behavioural changes and interruptions of normal activities,[56,57] including changes in acoustic communication (or vocalizations), withdrawal from feeding or social interactions, changes in movement or diving behaviour, and temporary or permanent habitat abandonment.[58,59,60] Over the long term, any permanent behavioural change could impact an animal's ability to find food and reproduce.[61] In severe cases, noise can also cause acute and severe reactions, such as panic, flight, stampeding, or stranding which can result in the animal's injury or death.[10]

How different marine species respond to ocean noise

A growing list of scientific studies confirms that noise generated by human activities in or near the ocean can cause a multitude of negative impacts on many different marine species. While most of the research to date has centred on **cetaceans**,[62] there are many other studies focused on understanding the impacts of ocean noise on other marine species. In fact, a recent review of 538 studies of the impacts of anthropogenic ocean noise confirmed that noise negatively affected many different species of marine animals[17] at the individual, population, and community levels by affecting interactions between individuals of the same and different species.[63,64,65]

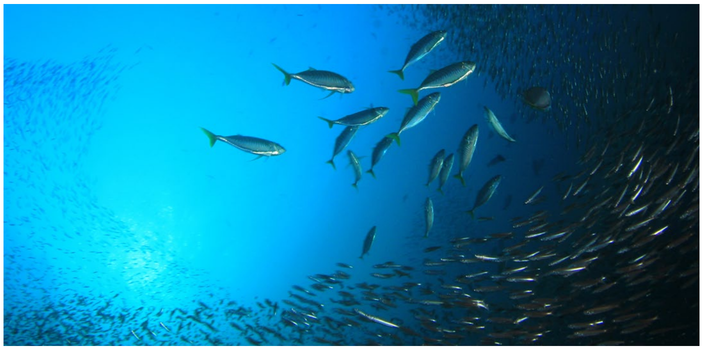


Beluga whale (*Delphinapterus leucas*) surfacing. Credit: slowmotiongli.

The following sections highlight some of the ways noise affects marine mammals, marine fishes, invertebrates, sea turtles, and seabirds.

Marine mammals

Field studies have found that marine mammals respond to ocean noise exposure in a variety of ways. In the past, primary research tended to focus more on evaluating physiological responses, physical injury, and mortality, but it has broadened in recent years to consider noise impacts on behavior and acoustic communication. Hearing impairment, masking, increased stress, and displacement from preferred feeding areas are just some of the impacts that have been documented in a large number of marine mammals.[66,67,68] The consequences of these impacts are not always well understood but could include reduced foraging success, decreased social bonding, and failure to avoid predators.[69,70] All of these effects have the potential for cascading and **cumulative impacts** on survival and reproduction, both at the individual and population level.[17,71,72] For cetaceans in general, while **Figure 3** illustrated that they communicate over a large frequency range, most individual cetacean species only communicate over a narrower frequency range and they are often categorized into three groups: low frequency (baleen whales) cetaceans, high frequency (toothed whales and most dolphins) cetaceans, and very high frequency cetaceans (porpoises and a few dolphins).[48] These differences are also important when considering the impact of noise on cetaceans as they are sensitive to different types of noise based on their hearing range.



Marine fishes

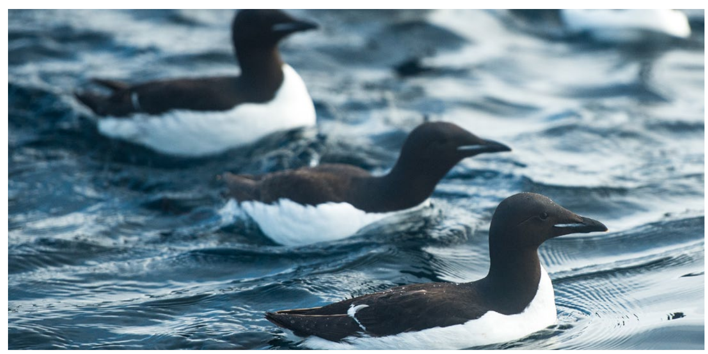
Research has shown that in response to noise marine fish can change their behaviour, experience elevated stress levels, impaired abilities to detect predators, reduced foraging capacities, and temporary hearing loss.[47,56,73,74,75] The number of different fish species and the variety of habitats that these fish occupy suggest that research on noise impacts should also consider individual physiologies and life cycles.[76,77] For example, noise may have developmental impact on stationary nesting fish eggs compared to live birth fish.[78] Moreover, the presence of a **swim bladder** in marine fishes can also impact their sensitivity to noise. Fish with swim bladders have higher hearing sensitivity and tend to use sound more for communication, and they may be more impacted by ocean noise than those without swim bladders.[79]

Marine invertebrates

The term **marine invertebrates** encompasses a large number of animals that live in various ocean habitats including the water column and the seafloor.[83] These species (which include corals, sponges, sea urchins, and molluscs such as squid and mussels) are sensitive to sound transmitted through both the water column and the seabed.[84,85,86,87] Several studies suggest that ocean noise may cause a variety of different impacts on these species: animals may be distracted from finding food or shelter, have an increase in stress-related chemicals, have malformed embryos, or suffer damage to hearing cells.[88,89,90] High amplitude ocean noise, such as that from seismic surveys, can also cause a decrease in abundance of marine invertebrates such as zooplankton.[91]

Sea turtles

Compared to marine mammals and fishes, sea turtles have received very little research attention.[80] While recent research shows that freshwater turtles can experience temporary hearing impairment from an excess of ocean noise,[81] the highly migratory nature of sea turtles makes it difficult to study the potential impacts of ocean noise on this group of animals.[82]



Seabirds

There are very few studies on the potential impacts of ocean noise on seabirds, but a recent study found that diving birds such as common murres may be exposed to and affected by ocean noise when feeding.[92] It is worth noting that while seabirds only spend limited amount of time underwater, research show that they are sensitive to both in-air and underwater sound.[93,94] Therefore, more complete evaluations of the potential ocean noise impacts on seabirds are needed.

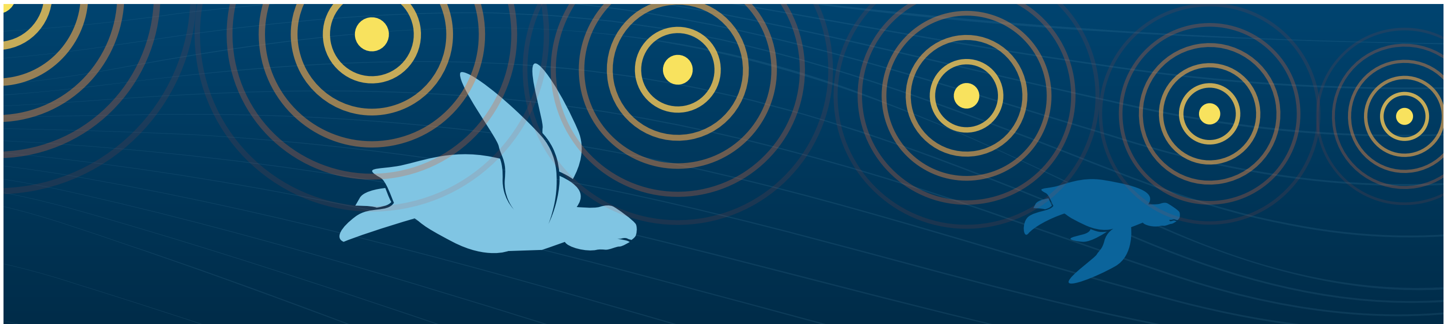
Photo, clockwise from top left: Fish hunting herring. Credit: Rich Carey. Giant Pacific octopus (*Enteroctopus dofleini*) on the ocean floor. Credit: Martin Voeller. A colony of Thick-billed Murre (*Uria lomvia*) on water. Credit: Mike Sudoma. Green sea turtle (*Chelonia mydas*) swimming underwater. Credit: Baptiste RIFFARD.

Impacts of ocean noise on human cultural and societal practices

Anthropogenic ocean noise does not only have great impacts on wildlife, it also has an impact on many cultural and societal practices of coastal and Indigenous communities.[95,96] For example, coastal communities and Indigenous subsistence hunting and fishing rely heavily on certain important marine species being available in specific habitats and at specific times. The presence of ocean noise can drive these species away, disrupt traditional practices, and impact the pursuit of constitutionally protected Indigenous rights.[97]

Whale watching boat near surfacing marine mammal. Credit: Ruth Troughton.

First Nations community working with Fisheries and Oceans Canada to collect sockeye salmon (*Oncorhynchus nerka*) broodstock for hatchery production. Credit: Fisheries and Oceans Canada.



Reducing complex ocean noise impacts

In addition to understanding how human activity creates noise and the characteristics of those individual sounds, it is also critically important to understand the impacts on marine wildlife when more than one human activity occurs in the same place at the same time. Simultaneous noise from multiple human activities can add to and interact with other **marine stressors** to increase the cumulative impacts on marine life.

While there is ongoing research on individual noise impacts on species, it remains extremely difficult to quantify the cumulative impact and interacting effects of so many different noise sources on any particular animal. The physical properties of noise, the biology and behaviour of the animals exposed to it, and the circumstances around their exposure, are all important considerations that can interact with and influence the cumulative impacts of ocean noise on marine life.

Several examples in the scientific literature illustrate that the conditions and the health of impacted wildlife can improve quickly once noise levels decrease.[98] A 2012 study noted that a 6-decibel decrease in ocean noise in the Bay of Fundy (the result of reduced ship traffic following the events of September 11, 2001) reduced stress in right whales.[51] Several other studies found evidence that the reduction in noise from commercial shipping during the COVID-19 pandemic [99,100,101,102] was linked to an expansion of movements of marine mammals into busy harbours and coastal areas where they are not normally observed.[103,104]

These particular research findings indicate that an improved understanding of noise impacts can support targeted efforts to address the causes of ocean noise. While more research is needed, the circumstantial evidence collected during these periods of severely reduced ocean noise does suggest that marine species respond positively to reductions in anthropogenic ocean noise.

This document has provided a brief and general overview of the characteristics of sound, ocean noise, and its impact. Readers are encouraged to further explore this topic and participate in any of the current and future Government of Canada collaborative initiatives to address this stressor. Given the complexity of ocean noise, it is crucial to continue research to better understand this topic. This will support the joint efforts of governments, organizations and communities in effectively managing anthropogenic noise sources to significantly mitigate their impacts on marine wildlife.

Southern resident killer whale (*Orcinus orca*). Credit: Fisheries and Oceans Canada.

Glossary

Abiotic: refers to something that is physical rather than biological, devoid of life.[105] In the context of an ecosystem, abiotic factors could include sunlight, temperature, wind patterns, and precipitation.

Acoustic energy: the energy that travels through a substance in the form of sound waves is referred to as acoustic energy.[106] When sound passes through any medium, it creates waves of vibrations, which vary in their energy in proportion to the amplitude of the sound waves.

Amplitude: refers to the height of the sound pressure wave or the "loudness" of a sound.[107] It is often measured using the decibel (dB) scale. Small variations in amplitude ("short" pressure waves) produce weak or quiet sounds, while large variations ("tall" pressure waves) produce strong or loud sounds. For example, imagine a wave on the surface of a pond. The amplitude would be the maximum height of the water above or below its calm level.

Anthropogenic: caused and/or generated by humans.

Biotic: refers to anything that is related to or resulting from living things, especially in their ecological relations.[108] It is the opposite of abiotic, which refers to non-living things in an ecosystem.

Continuous sound: a type of sound that is long-lasting and does not have impulsive characteristics.[109]

Cetaceans: whales, dolphins, and porpoises.

Cumulative impacts: the total changes to the individual animal, environment, health, social and economic conditions due to various human activities and natural processes happening over time and in different places. They include the additive effects of a project or development when combined with other past, present, and foreseeable future activities.[110]

Decibel: a unit used to measure the intensity of a sound or the power level of an electrical signal. It is a relative unit, not an absolute one. Decibel is used to describe sounds in terms of their loudness.[111] For underwater ocean sounds, a reference pressure of 1 microPascal (μPa) is used to describe sounds in terms of decibel.

Frequency: sound moves through a medium like water as a wave, thus the term sound wave. Frequency, also known as pitch, indicates how often a sound wave repeats within a single second. Measured in Hertz (Hz), also known as cycles per second, higher numbers signify higher-pitched sounds and lower numbers mean lower-pitched sounds.[10]

Hearing range: particular range of sound frequencies that certain species are most receptive to.

Ice(berg) calving: the process or event that occurs when large slabs of ice detach from a glacier into the water.[112] The sound waves generated by calving can be detected by microphones, seismometers, and hydrophones, providing information about the frequency of calving events as well as the icebergs' size.[112] Iceberg calving is one of the main sources of natural ocean noise in polar regions and can be extremely loud capable of being perceived thousands of kilometres away.[113]

Impulsive sound: is an acoustic signal with an instantaneous start and stop. Underwater impulsive sounds are generated by certain human activities such as geophysical surveys, impact pile driving, acoustic deterrent devices, multi-beam echosounders, and detonation of explosives.[114]

Intensity: the amount of energy contained in a sound wave, measured in a given area at a given time; this also translates to the subjective perception of sound pressure and loudness.

Logarithmic scale: a way of measuring data that grows exponentially. It is a relative unit, not an absolute one. The numbers on the axis are logarithms or powers of a base number, resulting in an exponential rise in value between units.[115] For instance, on a logarithmic scale with base 10, the distance from 1 to 10 is the same as the distance from 10 to 100 or from 100 to 1000.

Marine invertebrates: marine animals lacking a vertebral column (or spine) and include animals such as shellfish (e.g., lobsters, crabs, clams, mollusks, etc.), sea cucumbers, sea urchins, corals, and many others.

Marine stressors: factors that affect the health and functioning of marine ecosystems.[116] They can be natural, such as earthquakes or storms, or caused by humans, such as fishing, pollution or climate change. The cumulative impact of various pressures in the ocean can result in a reduction in the ability of marine ecosystems to withstand and recover from these challenges. This can ultimately lead to a decline in biodiversity in marine environments.[117]

Mask (or masking): a phenomenon where one or more sounds, typically a louder sound, influences how another sound is perceived. This interference makes it difficult for the listener to accurately grasp and identify the sound of interest, causing it to become less distinct and harder to understand.[42] Masking can occur underwater when background noise, such as waves, wind, rain, or human activities, interferes with the detection or communication of sounds produced by marine animals or devices.[64]

Metabolic rate: the amount of energy that an organism expends over a specific period of time.[118] It refers to how quickly fuels such as sugars are broken down to keep the organism's cells running. The metabolic rate varies among species and depends on the environmental conditions and activity level of an individual organism.

Oceanographic conditions: physical and chemical features of the ocean that vary in space and time. They include factors such as temperature, salinity, currents, waves, tides, ice concentration and thickness, and surface winds.[119]

Salinity: the amount of salt dissolved in a body of water. The speed of sound traveling through water tends to increase as salinity increases.[120]

Sea state: the general condition of the surface of the ocean related to waves and swells at a certain location and time. It is influenced by many factors such as winds, current, and sea ice.[121] Sea state affects ambient sound levels, such that levels are lower under calm seas and higher under high sea states. It can also affect speed of sound in water, which in turn affects how far sound can travel before it becomes too weak to detect.[9]

Seismic survey: a geophysical operation that uses a seismic air source to generate acoustic waves that propagate through the water and sediment, are reflected from or refracted along subsurface layers of the sediment, and are subsequently recorded by hydrophones at the surface.[122]

Subsurface geological feature: any geological structure or formation that is located below the surface of the earth. These features can include rock formations, mineral deposits, and other geological structures that are not visible from the surface.[123] Subsurface geological features can be studied using a variety of geophysical techniques, such as seismic surveys.

Swim bladder: an internal air filled organ used by some fishes to control their buoyancy. It is also linked to the inner ear and can be used to make different sounds and acts as a detection mechanism for changes in sound pressure.[79]

Transducer: A device that converts electrical signals into sound waves or vice versa, for the purpose of generating or receiving ocean noise.[124,125]

References

1. Weir, C. R., & Dolman, S. J. (2007). Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic survey, and guidance towards a worldwide standard. *Journal of International Wildlife Law and Policy*, *10*(1), 1–27. https://www.tandfonline.com/doi/full/10.1080/13880290701229838
2. Looby, A., Riera, A., Cox, K., & Vela, S. (2022). *Grunts, boops, chatters and squeals — fish are noisy creatures*. https://theconversation.com/grunts-boops-chatters-and-squeals-fish-are-noisy-creatures-178460
3. Holt, M. M., Noren, D. P., Dunkin, R. C., & Williams, T. M. (2015). Vocal performance affects metabolic rate in dolphins: implications for animals communicating in noisy environments. *Journal of Experimental Biology*, *218*(11), 1647–1654. https://doi.org/10.1242/jeb.122424
4. Moore, S. E., Reeves, R. R., Southall, B. L., Ragen, T. J., Suydam, R. S., & Clark, C. W. (2012). A new framework for assessing the effects of anthropogenic sound on marine mammals in a rapidly changing arctic. *BioScience*, *62*(3), 289–295. https://doi.org/10.1525/bio.2012.62.3.10
5. Thomsen, F., Mendes, S., Bertucci, F., Breitzke, M., Ciappi, E., Cresci, A., Debusschere, E., Ducatel, C., Folegot, F., Juretzek, C., Lam, F.-P., O'Brien, J., & dos Santos, M. E. (2021). Addressing underwater noise in Europe: Current state of knowledge and future priorities. In *Future Science Brief 7 of the European Marine Board* (Issue October). https://doi.org/10.5281/zenodo.5534224
6. Brabandere, S. De. (2019). *What Do You Hear Underwater?* Scientific American. https://www.scientificamerican.com/article/what-do-you-hear-underwater/
7. URI Graduate School of Oceanography. (2021). *DOSITS: Discovery of Sound in the Sea*. Discovery of Sound in the Sea. https://dosits.org/
8. Samaran, F., Adam, O., & Guinet, C. (2010). Detection range modeling of blue whale calls in Southwestern Indian Ocean. *Applied Acoustics*, *71*(11), 1099–1106. https://doi.org/10.1016/j.apacoust.2010.05.014
9. Hildebrand, J. (2004). *Sources of Anthropogenic Sound in the Marine Environment*. https://www.mmc.gov/wp-content/uploads/hildebrand.pdf
10. Nolet, V. (2017). Understanding Anthropogenic Underwater Noise. *Transport Canada Green Marine Alliance*, *3*, 1–6. https://tc.canada.ca/en/initiatives/oceans-protection-plan/understanding-anthropogenic-underwater-noise
11. Erbe, C., & Farmer, D. M. (2000). A software model to estimate zones of impact on marine mammals around anthropogenic noise. *The Journal of the Acoustical Society of America*, *108*(3), 1327. https://doi.org/10.1121/1.1288939
12. Webb, P. (2017). *Introduction to Oceanography*. https://rwu.pressbooks.pub/webboceanography/chapter/6-4-sound/
13. Vagle, S., Burnham, R. E., O'Neill, C., & Yurk, H. (2021). Variability in Anthropogenic Underwater Noise Due to Bathymetry and Sound Speed Characteristics. *Journal of Marine Science and Engineering*, *9*(10), 1047. https://doi.org/10.3390/jmse9101047
14. Halliday, W. D., Barclay, D., Barkley, A. N., Cook, E., Dawson, J., Hilliard, R. C., Hussey, N. E., Jones, J. M., Juanes, F., Marcoux, M., Niemi, A., Nudds, S., Pine, M. K., Richards, C., Scharffenberg, K., Westdal, K., & Insley, S. J. (2021). Underwater sound levels in the Canadian Arctic, 2014–2019. *Marine Pollution Bulletin*, *168*, 112437. https://doi.org/10.1016/j.marpolbul.2021.112437
15. Hebbar, A. A., Schröder-Hinrichs, J.-U., Mejia, M. Q., Deggim, H., & Pristrom, S. (2020). *Governance of Arctic Shipping* (A. Chircop, F. Goerlandt, C. Aporta, & R. Pelot (Eds.)). Springer International Publishing. https://doi.org/10.1007/978-3-030-44975-9
16. Duda, T. F. (2017). Acoustic signal and noise changes in the Beaufort Sea Pacific Water duct under anticipated future acidification of Arctic Ocean waters. *The Journal of the Acoustical Society of America*, *142*(4), 1926–1933. https://doi.org/10.1121/1.5006184
17. Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., Erbe, C., Gordon, T. A. C., Halpern, B. S., Harding, H. R., Havlik, M. N., Meekan, M., Merchant, N. D., Miksis-Olds, J. L., Parsons, M., Predragovic, M., Radford, A. N., Radford, C. A., Simpson, S. D., … Juanes, F. (2021). The soundscape of the Anthropocene ocean. *Science*, *371*(6529), eaba4658. https://doi.org/10.1126/science.aba4658
18. Marine Environment Protection Committee. (2014). *Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts of Marine Life*. *MEPC.1/Cir*, 6. https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics
19. McKenna, M., Ross, D., Wiggins, S., & Hildebrand, J. (2012). Underwater radiated noise from modern commercial ships. *The Journal of the Acoustical Society of America*, *131*(1), 92–103. https://doi.org/10.1121/1.3664100
20. Cato, D. H. (2014). Shipping noise impacts on marine life. *INTERNOISE 2014 - 43rd International Congress on Noise Control Engineering: Improving the World Through Noise Control*, 1–6.
21. Hildebrand, J. A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology-Progress Series*, *395*, 5–20. https://doi.org/10.3354/Meps08353
22. Burnham, R. E., Vagle, S., O'Neill, C., & Trounce, K. (2021). The Efficacy of Management Measures to Reduce Vessel Noise in Critical Habitat of Southern Resident Killer Whales in the Salish Sea. *Frontiers in Marine Science*, *8*(July), 1–18. https://doi.org/10.3389/fmars.2021.664691
23. Halliday, W. D., Pine, M. K., Mouy, X., Kortsalo, P., Hilliard, R. C., & Insley, S. J. (2020). The coastal Arctic marine soundscape near Ulukhaktok, Northwest Territories, Canada. *Polar Biology*, *43*(6), 623–636. https://doi.org/10.1007/s00300-020-02665-8
24. Hermannsen, L., Mikkelsen, L., Tougaard, J., Beedholm, K., Johnson, M., & Madsen, P. T. (2019). Recreational vessels without Automatic Identification System (AIS) dominate anthropogenic noise contributions to a shallow water soundscape. *Scientific Reports*, *9*(1), 15477. https://doi.org/10.1038/s41598-019-51222-9
25. Lesage, V., Barrette, C., Kingsley, M. C. S., & Sjare, B. (1999). The effect of vessel noise on the vocal behaviour of belugas in the St. Lawrence River Estuary, Canada. *Marine Mammal Science*, *15*(1), 65–84. https://doi.org/10.1111/j.1748-7692.1999.tb00782.x
26. Parsons, M. J. G., Erbe, C., Meekan, M. G., & Parsons, S. K. (2021). A Review and Meta-Analysis of Underwater Noise Radiated by Small (<25 m Length) Vessels. *Journal of Marine Science and Engineering*, *9*(8), 827. https://doi.org/10.3390/jmse9080827
27. Wilson, L., Pine, M. K., & Radford, C. A. (2022). Small recreational boats: a ubiquitous source of sound pollution in shallow coastal habitats. *Marine Pollution Bulletin*, *174*, 113295. https://doi.org/10.1016/j.marpolbul.2021.113295
28. Popper, A. N., Smith, M. E., Cott, P. A., Hanna, B. W., MacGillivray, A. O., Austin, M. E., & Mann, D. A. (2005). Effects of exposure to seismic airgun use on hearing of three fish species. *The Journal of the Acoustical Society of America*, *117*(6), 3958–3971. https://doi.org/10.1121/1.1904386
29. Kyhn, L. A., Wisniewska, D. M., Beedholm, K., Tougaard, J., Simon, M., Mosbech, A., & Madsen, P. T. (2019). Basin-wide contributions to the underwater soundscape by multiple seismic surveys with implications for marine mammals in Baffin Bay, Greenland. *Marine Pollution Bulletin*, *138*(January 2018), 474–490. https://doi.org/10.1016/j.marpolbul.2018.11.038

30. Nieukirk, S. L., Mellinger, D. K., Moore, S. E., Klinck, K., Dziak, R. P., & Goslin, J. (2012). Sounds from airguns and fin whales recorded in the mid-Atlantic Ocean, 1999–2009. *The Journal of the Acoustical Society of America*, *131*(2), 1102–1112. https://doi.org/10.1121/1.3672648
31. Madsen, P. T., Johnson, M., Miller, P. J. O., Aguilar Soto, N., Lynch, J., & Tyack, P. (2006). Quantitative measures of air-gun pulses recorded on sperm whales (Physeter macrocephalus) using acoustic tags during controlled exposure experiments. *The Journal of the Acoustical Society of America*, *120*(4), 2366–2379. https://doi.org/10.1121/1.2229287
32. Dolman, S. J., Weir, C. R., & Jasny, M. (2009). Comparative review of marine mammal guidance implemented during naval exercises. *Marine Pollution Bulletin*, *58*(4), 465–477. https://doi.org/10.1016/j.marpolbul.2008.11.013
33. Cholewiak, D., DeAngelis, A. I., Palka, D., Corkeron, P. J., & Van Parijs, S. M. (2017). Beaked whales demonstrate a marked acoustic response to the use of shipboard echosounders. *Royal Society Open Science*, *4*(12). http://rsos.royalsocietypublishing.org/content/4/12/170940.abstract
34. Hildebrand, J. (2005). Impacts of Anthropogenic Sound. *Marine Mammal Research: Conservation beyond Crisis*, *124*, 101–124. https://escholarship.org/content/qt8997q8wj/qt8997q8wj.pdf?t=lnokwc
35. Fink, D. (2019). A new definition of noise: noise is unwanted and/or harmful sound. Noise is the new 'secondhand smoke'. *178th Meeting of the Acoustical Society of America*, *050002*(2019), 050002. https://doi.org/10.1121/2.0001186
36. Hatch, L. T., Wahle, C. M., Gedamke, J., Harrison, J., Laws, B., Moore, S. E., Stadler, J. H., & Van Parijs, S. M. (2016). Can you hear me here? Managing acoustic habitat in US waters. *Endangered Species Research*, *30*(1), 171–186. https://doi.org/10.3354/esr00722
37. Shannon, G., McKenna, M. F., Angeloni, L. M., Crooks, K. R., Fristrup, K. M., Brown, E., Warner, K. A., Nelson, M. D., White, C., Briggs, J., McFarland, S., & Wittemyer, G. (2016). A synthesis of two decades of research documenting the effects of noise on wildlife. *Biological Reviews*, *91*(4), 982–1005. https://doi.org/10.1111/brv.12207
38. Bruintjes, R., & Radford, A. N. (2013). Context-dependent impacts of anthropogenic noise on individual and social behaviour in a cooperatively breeding fish. *Animal Behaviour*, *85*(6), 1343–1349.
39. Ellison, W. T., Southall, B. L., Clark, C. W., & Frankel, A. S. (2012). A New Context-Based Approach to Assess Marine Mammal Behavioral Responses to Anthropogenic Sounds. *Conservation Biology*, *26*(1), 21–28. https://doi.org/10.1111/j.1523-1739.2011.01803.x
40. Gomez, C., Lawson, J. W., Wright, A. J., Buren, A. D., Tollit, D., & Lesage, V. (2016). A systematic review on the behavioural responses of wild marine mammals to noise: The disparity between science and policy. *Canadian Journal of Zoology*, *94*(12), 801–819. https://doi.org/10.1139/cjz-2016-0098
41. Harris, C. M., Thomas, L., Falcone, E. A., Hildebrand, J., Houser, D., Kvadsheim, P. H., Lam, F. P. A., Miller, P. J. O., Moretti, D. J., Read, A. J., Slabbekoorn, H., Southall, B. L., Tyack, P. L., Wartzok, D., & Janik, V. M. (2018). Marine mammals and sonar: Dose-response studies, the risk-disturbance hypothesis and the role of exposure context. *Journal of Applied Ecology*, *55*(1), 396–404. https://doi.org/10.1111/1365-2664.12955
42. Clark, C. W., Ellison, W. T., Southall, B. L., Hatch, L., Van Parijs, S. M., Frankel, A., & Ponirakis, D. (2009). Acoustic masking in marine ecosystems: Intuitions, analysis, and implication. *Marine Ecology Progress Series*, *395*, 201–222. https://doi.org/10.3354/meps08402
43. Erbe, C., Reichmuth, C., Cunningham, K., Lucke, K., & Dooling, R. (2016). Communication masking in marine mammals: A review and research strategy. *Marine Pollution Bulletin*, *103*(1–2), 15–38. https://doi.org/10.1016/j.marpolbul.2015.12.007
44. Hatch, L., Clark, C., Van Parijs, S., Frankel, A., & Ponirakis, D. (2012). Quantifying loss of acoustic communication space for right whales in and around a U.S. National Marine Sanctuary. *Conservation Biology*, *26*(6), 983–994. https://doi.org/10.1111/j.1523-1739.2012.01908.x
45. Vergara, V., Dearden, A., Chapman, J., & Miller, A. (2021). Understanding Underwater Noise Pollution from Marine Vessels and its Impact on Whales, Dolphins and Porpoises. In *Ocean Watch Spotlight* (Issue January). https://assets.ctfassets.net/
46. Lucke, K., Siebert, U., Lepper, P. A., & Blanchet, M.-A. (2009). Temporary shift in masked hearing thresholds in a harbor porpoise (Phocoena phocoena) after exposure to seismic airgun stimuli. *The Journal of the Acoustical Society of America*, *125*(6), 4060–4070. https://doi.org/10.1121/1.3117443
47. Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D. A., Bartol, S., Carlson, T. J., Coombs, S., Ellison, W. T., Gentry, R. L., Halvorsen, M. B., Løkkeborg, S., Rogers, P. H., Southall, B. L., Zeddies, D. G., & Tavolga, W. N. (2014). Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. In *Springer* (Issue July 2015). https://doi.org/10.1007/978-3-319-06659-2
48. Southall, E. B. L., Finneran, J. J., Reichmuth, C., Nachtigall, P. E., Ketten, D. R., Bowles, A. E., Ellison, W. T., Nowacek, D. P., & Tyack, P. L. (2019). Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. *Aquatic Mammals*, *45*(2), 125–232. https://doi.org/10.1578/AM.45.2.2019.125
49. Debusschere, E., Hostens, K., Adriaens, D., Ampe, B., Botteldooren, D., De Boeck, G., De Muynck, A., Sinha, A. K., Vandendriessche, S., Van Hoorebeke, L., Vincx, M., & Degraer, S. (2016). Acoustic stress responses in juvenile sea bass Dicentrarchus labrax induced by offshore pile driving. *Environmental Pollution*, *208*(2016), 747–757. https://doi.org/10.1016/j.envpol.2015.10.055
50. Nichols, T. A., Anderson, T. W., & Širović, A. (2015). Intermittent noise induces physiological stress in a coastal marine fish. *PLoS ONE*, *10*(9), 1–13. https://doi.org/10.1371/journal.pone.0139157
51. Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., Wasser, S. K., & Kraus, S. D. (2012). Evidence that ship noise increases stress in right whales. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1737), 2363–2368. https://doi.org/10.1098/RSPB.2011.2429
52. Simpson, S. D., Radford, A. N., Nedelec, S. L., Ferrari, M. C. O., Chivers, D. P., McCormick, M. I., & Meekan, M. G. (2016). Anthropogenic noise increases fish mortality by predation. *Nature Communications*, *7*, 10544. https://doi.org/10.1038/ncomms10544
53. Fitzgibbon, Q. P., Day, R. D., McCauley, R. D., Simon, C. J., & Semmens, J. M. (2017). The impact of seismic air gun exposure on the haemolymph physiology and nutritional condition of spiny lobster, Jasus edwardsii. *Marine Pollution Bulletin*, *125*(1–2), 146–156. https://doi.org/10.1016/j.marpolbul.2017.08.004
54. Johansson, K. (2011). *Impact of anthropogenic noise on fish behaviour and ecology* [Sveriges lantbruksuniversitet]. https://pub.epsilon.slu.se/8366/
55. Day, R. D., McCauley, R. D., Fitzgibbon, Q. P., Hartmann, K., & Semmens, J. M. (2017). Exposure to seismic air gun signals causes physiological harm and alters behavior in the scallop Pecten fumatus. *Proceedings of the National Academy of Sciences*, *114*(40), E8537. https://doi.org/10.1073/pnas.1700564114
56. Cox, K., Brennan, L. P., Gerwing, T. G., Dudas, S. E., & Juanes, F. (2018). Sound the alarm: A meta-analysis on the effect of aquatic noise on fish behavior and physiology. *Global Change Biology*, *24*(7), 3105–3116. https://doi.org/10.1111/gcb.14106
57. Hiley, H., Janik, V., & Götz, T. (2021). Behavioural reactions of harbour porpoises Phocoena phocoena to startle-eliciting stimuli: movement responses and practical applications. *Marine Ecology Progress Series*, *672*, 223–241. https://doi.org/10.3354/meps13757
58. Bejder, L., Samuels, A. M. Y., Whitehead, H. A. L., Gales, N., Mann, J., Connor, R., Heithaus, M., Watson-Capps, J., Flaherty, C., & Krützen, M. (2006). Decline in relative abundance of bottlenose dolphins exposed to long-term disturbance. *Conservation Biology*, *20*(6), 1791–1798. https://doi.org/10.1111/j.1523-1739.2006.00540.x

59. Falcone, E. A., Schorr, G. S., Watwood, S. L., DeRuiter, S. L., Zerbini, A. N., Andrews, R. D., Morrissey, R. P., & Moretti, D. J. (2017). Diving behaviour of cuvier's beaked whales exposed to two types of military sonar. *Royal Society Open Science*, *4*(8). https://doi.org/10.1098/rsos.170629
60. Tervo, O. M., Blackwell, S. B., Ditlevsen, S., Conrad, A. S., Samson, A. L., Garde, E., Hansen, R. G., & Mads Peter, H. J. (2021). Narwhals react to ship noise and airgun pulses embedded in background noise. *Biology Letters*, *17*(11). https://doi.org/10.1098/rsbl.2021.0220
61. Lusseau, D., & Bejder, L. (2007). The Long-term Consequences of Short-term Responses to Disturbance Experiences from Whalewatching Impact Assessment. *International Journal of Comparative Psychology*, *20*, 228–236.
62. Erbe, C., Marley, S. A., Schoeman, R. P., Smith, J. N., Trigg, L. E., & Embling, C. B. (2019). The Effects of Ship Noise on Marine Mammals—A Review. *Frontiers in Marine Science*, *6*, 606. https://doi.org/10.3389/fmars.2019.00606
63. Nabe-Nielsen, J., van Beest, F. M., Grimm, V., Sibly, R. M., Teilmann, J., & Thompson, P. M. (2018). Predicting the impacts of anthropogenic disturbances on marine populations. *Conservation Letters*, *11*(5), e12563. https://doi.org/10.1111/conl.12563
64. Peng, C., Zhao, X., & Liu, G. (2015). Noise in the Sea and Its Impacts on Marine Organisms. *International Journal of Environmental Research and Public Health*, *12*(10), 12304–12323. https://doi.org/10.3390/ijerph121012304
65. Slabbekoorn, H., Dalen, J., Haan, D., Winter, H. V., Radford, C., Ainslie, M. A., Heaney, K. D., Kooten, T., Thomas, L., & Harwood, J. (2019). Population-level consequences of seismic surveys on fishes: An interdisciplinary challenge. *Fish and Fisheries*, *20*(4), 653–685. https://doi.org/10.1111/faf.12367
66. Branstetter, B. K., Trickey, J. S., Bakhtiari, K., Black, A., Aihara, H., & Finneran, J. J. (2013). Auditory masking patterns in bottlenose dolphins (Tursiopstruncatus) with natural, anthropogenic, and synthesized noise. *The Journal of the Acoustical Society of America*, *133*(3), 1811–1818. https://doi.org/10.1121/1.4789939
67. Sivle, L. D., Kvadsheim, P. H., Fahlman, A., Lam, F. P. A., Tyack, P. L., & Miller, P. J. O. (2012). Changes in dive behavior during naval sonar exposure in killer whales, long-finned pilot whales, and sperm whales. *Frontiers in Physiology*, *3*(400), 1–11. https://doi.org/10.3389/fphys.2012.00400
68. Todd, S., Stevick, P., Lien, J., Marques, F., & Ketten, D. (1996). Behavioural effects of exposure to underwater explosions in humpback whales (Megaptera novaeangliae). *Canadian Journal of Zoology-Revue Canadienne De Zoologie*, *74*(9), 1661–1672.
69. Erbe, C. (2012). The effects of underwater noise on marine mammals. In A. N. Popper & A. D. Hawkins (Eds.), *The Effects of Noise on Aquatic Life. Advances in Experimental Medicine and Biology 730* (pp. 17–22). Springer Verlag. https://doi.org/10.1007/978-1-4419-7311-5_3
70. Weilgart, L. S. (2007). The impacts of anthropogenic ocean noise on cetaceans and implications for management. *Canadian Journal of Zoology*, *85*(11), 1091–1116. https://doi.org/10.1139/Z07-101
71. Ellison, W. T., Racca, R., Clark, C. W., Streever, B., Frankel, A. S., Fleishman, E., Angliss, R., Berger, J., Ketten, D., Guerra, M., Leu, M., McKenna, M., Sformo, T., Southall, B., Suydam, R., & Thomas, L. (2016). Modeling the aggregated exposure and responses of bowhead whales Balaena mysticetus to multiple sources of anthropogenic underwater sound. *Endangered Species Research*, *30*(1), 95–108. https://doi.org/10.3354/esr00727
72. Harwood, J., King, S., Booth, C., Donovan, C., Schick, R. S., Thomas, L., New, L., Popper, A. N., & Hawkins, A. (2016). Understanding the population consequences of acoustic disturbance for marine mammals. In A. N. Popper & A. Hawkins (Eds.), *The Effects of Noise on Aquatic Life II* (pp. 417–423). Springer Verlag. https://link.springer.com/chapter/10.1007/978-1-4939-2981-8_49
73. Brown, N. A. W., Halliday, W. D., Balshine, S., & Juanes, F. (2021). Low-amplitude noise elicits the Lombard effect in plainfin midshipman mating vocalizations in the wild. *Animal Behaviour*, *181*, 29–39. https://doi.org/10.1016/j.anbehav.2021.08.025
74. Ivanova, S. V., Kessel, S. T., Landry, J., O'Neill, C., McLean, M. F., Espinoza, M., Vagle, S., Hussey, N. E., & Fisk, A. T. (2018). Impact of vessel traffic on the home ranges and movement of shorthorn sculpin (Myoxocephalus scorpius) in the nearshore environment of the high Arctic. *Canadian Journal of Fisheries and Aquatic Sciences*, *75*(12), 2390–2400. https://doi.org/10.1139/cjfas-2017-0418
75. Ivanova, S. V., Kessel, S. T., Espinoza, M., McLean, M. F., O'Neill, C., Landry, J., Hussey, N. E., Williams, R., Vagle, S., & Fisk, A. T. (2019). Shipping alters the movement and behavior of Arctic cod (Boreogadus saida), a keystone fish in Arctic marine ecosystems. *Ecological Applications*, *30*(3), e02050. https://doi.org/10.1002/eap.2050
76. Kennedy, E., Bennett, L., Campana, S., Clark, K., Comeau, P., Fowler, M., Gjerdrum, C., Grégoire, F., Hannah, C., Harris, L., Harrison, G., James, M., Jonsen, I., Johnson, C., Law, B., Li, W. K. W., Melvin, G., Milligan, T., Paul, S.,   Worcester, T. (2011). The Marine Ecosystem of Georges Bank. *Canadian Science Advisory Secretariat Research Document*, *2011/059*, 246. https://publications.gc.ca/site/eng/9.577845/publication.html
77. Webster, F., Wise, B., Kemps, H., & Fletcher, W. (2018). Risk Assessment of the potential impacts of seismic air gun surveys on marine finfish and invertebrates in Western Australia. In *Fisheries research reports* (Issue 288). https://library.dpird.wa.gov.au/fr_rr/65
78. de Jong, K., Forland, T. N., Amorim, M. C. P., Rieucau, G., Slabbekoorn, H., & Sivle, L. D. (2020). Predicting the effects of anthropogenic noise on fish reproduction. *Reviews in Fish Biology and Fisheries*, *9*. https://doi.org/10.1007/s11160-020-09598-9
79. Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., ten Cate, C., & Popper, A. N. (2010). A noisy spring: the impact of globally rising underwater sound levels on fish. *Trends in Ecology & Evolution*, *25*(7), 419–427. https://doi.org/10.1016/j.tree.2010.04.005
80. Nelms, S. E., Piniak, W. E. D. D., Weir, C. R., & Godley, B. J. (2016). Seismic surveys and marine turtles: An underestimated global threat? *Biological Conservation*, *193*(November 2015), 49–65. https://doi.org/10.1016/j.biocon.2015.10.020
81. *Effects of noise on marine life: Study finds that turtles are among animals vulnerable to hearing loss -- ScienceDaily*. (n.d.-cc). Retrieved July 28, 2022, from https://www.sciencedaily.com/releases/2022/03/220302190004.htm
82. DeRuiter, S. L., & Larbi Doukara, K. (2012). Loggerhead turtles dive in response to airgun sound exposure. *Endangered Species Research*, *16*(1), 55–63. https://doi.org/10.3354/esr00396
83. Morley, E. L., Jones, G., & Radford, A. N. (2014). The importance of invertebrates when considering the impacts of anthropogenic noise. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1776), 20132683. https://doi.org/10.1098/rspb.2013.2683
84. Jeffrey, M. L., Brooke, M. C.-E., & Douglas, H. C. (2002). Sound detection in situ by the larvae of a coral-reef damselfish (Pomacentridae). *Marine Ecology Progress Series*, *232*, 259–268. https://www.int-res.com/abstracts/meps/v232/p259-268/
85. Moriyasu, M., Allain, R., Benhalima, K., & Claytor, R. (2004). Effects of seismic and marine noise on invertebrates: A literature Review. *CSAS Research Document*, *2004/126*, 50.
86. Roberts, L., Harding, H. R., Voellmy, I., Bruintjes, R., Simpson, S. D., Radford, A. N., Breithaupt, T., & Elliott, M. (2016). Exposure of benthic invertebrates to sediment vibration: From laboratory experiments to outdoor simulated pile-driving. *Proceedings of Meetings on Acoustics*, *27*(1). https://doi.org/10.1121/2.0000324
87. Solé, M., Kaifu, K., Mooney, T. A., Nedelec, S. L., Olivier, F., Radford, A. N., Vazzana, M., Wale, M. A., Semmens, J. M., Simpson, S. D., Buscaino, G., Hawkins, A., Aguilar de Soto, N., Akamatsu, T., Chauvaud, L., Day, R. D., Fitzgibbon, Q., McCauley, R. D., & André, M. (2023). Marine invertebrates and noise. *Frontiers in Marine Science*, *10*(March), 1–34. https://doi.org/10.3389/fmars.2023.1129057
88. Day, R. D., McCauley, R. D., Fitzgibbon, Q. P., Hartmann, K., & Semmens, J. M. (2019). Seismic air guns damage rock lobster mechanosensory organs and impair righting reflex. *Proceedings of the Royal Society B: Biological Sciences*, *286*(1907), 20191424. https://doi.org/10.1098/rspb.2019.1424

89. Murchy, K. A., Davies, H., Shafer, H., Cox, K., Nikolich, K., & Juanes, F. (2020). Impacts of noise on the behavior and physiology of marine invertebrates: A meta-analysis. *178th Meeting of the Acoustical Society of America*, *39*(2019), 040002. https://doi.org/10.1121/2.0001217
90. Tidau, S., & Briffa, M. (2016). Review on behavioral impacts of aquatic noise on crustaceans. *Proceedings of Meetings on Acoustics*, *27*(1). https://doi.org/10.1121/2.0000302
91. McCauley, R. D., Day, R. D., Swadling, K. M., Fitzgibbon, Q. P., Watson, R. A., & Semmens, J. M. (2017). Widely used marine seismic survey air gun operations negatively impact zooplankton. *Nature Ecology & Evolution*, *1*(7), 0195. https://doi.org/10.1038/s41559-017-0195
92. Anderson Hansen, K., Hernandez, A., Mooney, T. A., Rasmussen, M. H., Sørensen, K., & Wahlberg, M. (2020). The common murre (Uria aalge), an auk seabird, reacts to underwater sound . *The Journal of the Acoustical Society of America*, *147*(6), 4069–4074. https://doi.org/10.1121/10.0001400
93. Larsen, O. N., Wahlberg, M., & Christensen-Dalsgaard, J. (2020). Amphibious hearing in a diving bird, the great cormorant (Phalacrocorax carbo sinensis). *Journal of Experimental Biology*, *223*(6). https://doi.org/10.1242/jeb.217265
94. Mooney, T. A., Smith, A., Larsen, O. N., Hansen, K. A., & Rasmussen, M. (2020). A field study of auditory sensitivity of the Atlantic puffin, Fratercula arctica. *Journal of Experimental Biology*, *223*(15), 1–9. https://doi.org/10.1242/jeb.228270
95. Fisheries and Oceans Canada. (2017). Action Plan for the Northern and Southern Resident Killer Whale (Orcinus orca) in Canada. In *Species at Risk Act Action Plan Series* (Issue March). https://publications.gc.ca/site/eng/9.828620/publication.html
96. Fisheries and Oceans Canada. (2020). Action plan to reduce the impact of noise on the beluga whale (Delphinapterus leucas) and other marine mammals at risk in the St. Lawrence estuary. *Species at Risk Act Action Plan Series*, iv + 31. https://publications.gc.ca/site/eng/9.884546/publication.html
97. Kochanowicz, Z., Dawson, J., Halliday, W. D., Sawada, M., Copland, L., Carter, N. A., Nicoll, A., Ferguson, S. H., Heide-Jørgensen, M. P., Marcoux, M., Watt, C., & Yurkowski, D. J. (2021). Using western science and Inuit knowledge to model ship-source noise exposure for cetaceans (marine mammals) in Tallurutiup Imanga (Lancaster Sound), Nunavut, Canada. *Marine Policy*, *130*, 104557. https://doi.org/10.1016/j.marpol.2021.104557
98. Williams, R., Erbe, C., Dewantama, I. M. I., & Hendrawan, I. G. (2018). Effect on ocean noise: Nyepi, a Balinese day of silence. *Oceanography*, *31*(2). https://doi.org/10.5670/oceanog.2018.207
99. Askitas, N., & Verheyden, B. (2020). Lockdown Strategies , Mobility Patterns and COVID-19 *. *Journal of Sustainable Tourism*, 1–20.
100. Millefiori, L. M., Braca, P., Zissis, D., Spiliopoulos, G., Marano, S., Willett, P. K., & Carniel, S. (2021). COVID-19 impact on global maritime mobility. *Scientific Reports*, *11*(18039), 1–16. https://doi.org/10.1038/s41598-021-97461-7
101. Ryan, K. L., Desfosses, C. J., Denham, A. M., Taylor, S. M., & Jackson, G. (2021). Initial insights on the impact of COVID-19 on boat-based recreational fishing in Western Australia. *Marine Policy*, *132*(April), 104646. https://doi.org/10.1016/j.marpol.2021.104646
102. Verschuur, J., Koks, E. E., & Hall, J. W. (2021). Observed impacts of the COVID-19 pandemic on global trade. *Nature Human Behaviour*, *5*(3), 305–307. https://doi.org/10.1038/s41562-021-01060-5
103. Gabriele, C. M., Ponirakis, D. W., Klinck, H., & Gabriele, C. M. (2021). *Underwater Sound Levels in Glacier Bay During Reduced Vessel Traffic Due to the COVID-19 Pandemic*. *8*(June), 1–14. https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2021.674787/full
104. Thomson, D. J. M., & Barclay, D. R. (2020). *Real-time observations of the impact of COVID-19 on underwater noise Real-time observations of the impact of COVID-19 on underwater noise a). 3390*. https://doi.org/10.1121/10.0001271
105. Cambridge University Press. (n.d.-da). *abiotic*. Cambridge Academic Content Dictionary. Retrieved November 27, 2023, from https://dictionary.cambridge.org/dictionary/english/abiotic
106. Rienstra, S. W., & Hirschberg, A. (2021). *An Introduction to Acoustics*. Eindhoven University of Technology.
107. Merriam-Webster. (n.d.-dc). *amplitude*. Retrieved October 4, 2023, from https://www.merriam-webster.com/dictionary/amplitude
108. Cambridge University Press. (n.d.-dd). *biotic*. Cambridge Academic Content Dictionary. Retrieved October 4, 2023, from https://dictionary.cambridge.org/dictionary/english/biotic
109. Rako-Gospić, N., & Picciulin, M. (2019). Underwater noise: Sources and effects on marine life. In *World Seas: An Environmental Evaluation Volume III: Ecological Issues and Environmental Impacts* (pp. 367–389). https://doi.org/10.1016/B978-0-12-805052-1.00023-1
110. Environment and Climate Change Canada. (2022). *Government of Canada interim message on cumulative effects*. https://www.canada.ca/en/services/environment/cumulative-effect/interim-messaging.html
111. The Editors of Encyclopædia Britannica. (2023). *decibel*. https://www.britannica.com/science/decibel
112. Overgaard, E. (2022). Underwater Sounds Help Reveal Extent of Glacial Calving. *Eos*, *103*. https://doi.org/10.1029/2022EO220559
113. Podolskiy, E. A. (2022). *What the sounds of iceberg calving can tell us*. The Arctic Ocean: Looking below the Surface. https://www.arcticwwf.org/the-circle/stories/what-the-sounds-of-iceberg-calving-can-tell-us/
114. Martin, S. B., Lucke, K., & Barclay, D. R. (2020). Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals. *The Journal of the Acoustical Society of America*, *147*(4), 2159–2176. https://doi.org/10.1121/10.0000971
115. Merriam-Webster. (2023). *logarithmic scale*. https://www.merriam-webster.com/dictionary/logarithmic scale
116. Intergovernmental Oceanographic Commission UNESCO. (2022). *Multiple Ocean Stressors: A Scientific Summary for Policy Makers* (P. W. Boyd, S. Dupont, & K. Isensee (Eds.); IOC Inform). UNESCO. https://doi.org/10.25607/OBP-1724
117. Reichelt-brushett, A. (2023). *Marine Pollution – Monitoring, Management and Mitigation* (A. Reichelt-Brushett (Ed.)). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-10127-4
118. Richards, J. G. (2010). Metabolic rate suppression as a mechanism for surviving environmental challenge in fish. *Progress in Molecular and Subcellular Biology*, *49*, 113–139. https://doi.org/10.1007/978-3-642-02421-4_6
119. Environment Canada. (2013). *National Marine Weather Guide*. Government of Canada. https://publications.gc.ca/site/eng/9.629465/publication.html
120. The Editors of Encyclopædia Britannica. (n.d.-dp). *salinity*. Retrieved October 5, 2023, from https://www.britannica.com/science/salinity
121. Ardhuin, F., Stopa, J. E., Chapron, B., Collard, F., Husson, R., Jensen, R. E., Johannessen, J., Mouche, A., Passaro, M., Quartly, G. D., Swail, V., & Young, I. (2019). Observing sea states. *Frontiers in Marine Science*, *6*(APR), 1–29. https://doi.org/10.3389/fmars.2019.00124
122. The Editors of Encyclopædia Britannica. (n.d.-dr). *Seismic Survey*. Encyclopædia Britannica. Retrieved September 1, 2023, from https://www.britannica.com/science/seismic-survey
123. Natural Resources Canada. (2015). *Structural Mapping & Terrain Analysis*. Educational Resources - Applications. https://natural-resources.canada.ca/maps-tools-and-publications/satellite-imagery-and-air-photos/tutorial-fundamentals-remote-sensing/educational-resources-applications/geology/structural-mapping-terrain-analysis/9345
124. Agarwal, A., & Lang, J. H. (2005). *Foundations of Analog and Digital Electronic Circuits*. Morgan Kaufmann Publishers.
125. Butler, J. L., & Sherman, C. H. (2016). *Transducers and Arrays for Underwater Sound*. Springer International Publishing. https://doi.org/10.1007/978-3-319-39044-4

Next page, top: Polar Prince on expedition. Credit: SOI Foundation. Bottom: Underwater photo of a kelp forest. Credit: Andrew b Stowe.


POLAR PRINCE
CANADA C3
COAST TO COAST TO COAST
TROIS CÔTES · UN VOYAGE