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The Arctic: Anthropogenic Noise, Shipping, Impact on Marine Mammals, & Future Management

Bibliography

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Table of Contents

Background & Scope

As sea ice diminishes due to global climate change, the Arctic has seen an increase in shipping. This trend is expected to continue, opening once-unpassable areas to new routes, increasing vessel traffic, and expanding the shipping window with longer ice-free periods. The Arctic provides shipping operators a more direct route, which can provide a reduction in shipping time as well as fuel cost savings. Along with added shipping emissions, potential oil discharge and spills, introduction of invasive species, and the disruption of migratory patterns, anthropogenic noise produced by shipping has been identified by the Arctic Council as a major concern. This bibliography focuses on the Arctic and anthropogenic noise due to marine shipping. It is organized into four sections including: Arctic Soundscapes, Vessel Noise Measurement, Impact on Marine Life, and the Reduction and Management of Noise Levels.

Section I – Arctic Soundscapes

Section one is intended to provide an overview of research relating to the recordings of Arctic soundscapes. The research in this area is a compilation of recordings in a number of Arctic and Subarctic regions including: the High Arctic, Fram Strait and Fram Strait Marginal Ice Zone, North Sea, Chukchi Sea, Sachs Harbor, Beaufort Sea, Canadian Arctic and Subarctic, Glacier Bay, Eastern Arctic, Anadyr Strait, and Bering Sea.

Section II – Vessel Noise Measurement

Section two is intended to provide an overview of research relating to the measurement of noise from vessels in the Arctic and Subarctic regions. Research in this area contains targeted recordings of individual vessels in order to establish baseline measurements, recordings of modified vessels, analysis of hydrophone recordings paired with AIS ship-traffic data, measurements in atmospheric towing tanks, and recordings of underwater radiated noise in various ports. In order to provide a fuller picture of research on this topic some non-Arctic related sources are included.

Section III – Impact on Marine Life

Section three is focused on providing research related to the impact of vessel noise on Arctic marine life. Research in this area includes Minke whales, Grey seals, Harbor seals, Fin whales, Bowhead whales, Belugas, Narwhals, Humpback whales, Right whales, and other marine life. Again this section includes research outside of the Arctic in certain cases to provide a fuller picture of research on this topic.

Section IV – Reduction and Management of Noise Levels

Finally, section four contains research on management related research that proposes ways to reduce, maintain, or manage noise levels in Arctic waters. Work in this area ranges from scientific research on masking sound, to mapping noise from shipping, and long term analysis and planning. Areas such as Glacier Bay, which are not technically considered Arctic waters, have been included since much of the work in this area has been on reducing or managing noise in more highly trafficked areas.

Sources Reviewed

Along with a web search for relevant reports from non-profits and other relevant materials the following databases were used to identify sources: Clarivate's Web of Science: Science Citation Index Expanded, Elsevier's Science Direct, BioOne Complete, ProQuest's Science and Technology including ASFA, and the Acoustical Society of America's web platform. Only English language materials were included. There was no date range specification in order to cover any relevant research.

Section I: Arctic Soundscapes

Ahonen, H., Stafford, K. M., de Steur, L., Lydersen, C., Wiig, O., & Kovacs, K. M. (2017). The underwater soundscape in western Fram Strait: Breeding ground of Spitsbergen's endangered bowhead whales. *Marine Pollution Bulletin, 123*(1-2), 97-112. https://doi.org/10.1016/j.marpolbul.2017.09.019

In the Arctic, warming and concomitant reductions in sea ice will affect the underwater soundscape, with the greatest changes likely being linked to anthropogenic activities. In this study, an acoustic recorder deployed on an oceanographic mooring in western Fram Strait documented the soundscape of this area, which is important habitat for the Critically Endangered Spitsbergen bowhead whale population. The soundscape was quasi-pristine much of the year, with low numbers of ships traversing the area. However, during summer/autumn, signals from airgun surveys were detected> 12 h/day. Mean received peak-to-peak SPLs for loud airgun pulses reached 160.46 ± 0.48 dB 1 μPa when seismic-survey ships were close (at ~57 km). Bowhead whales were present almost daily October–April in all years, with singing occurring in almost every hour November–March. Currently, loud anthropogenic sound sources do not temporally overlap the peak period of bowhead singing. This study provides important baseline data for future monitoring.

Ainslie, M. A., De Jong, C. A. F., Dol, H. S., Blacquiere, G., & Marasini, C. (2009). *Assessment of natural and anthropogenic sound sources and acoustic propagation in the North Sea*. Retrieved from: https://publications.tno.nl/publication/34618532/Zby01E/TNO-DV2009C085.pdf

The research reported on in this document aims at making an inventory of the existing knowledge and revealing the gaps. The study was started by making an inventory of all relevant natural and anthropogenic sources of sound in the water column. For the anthropogenic sources, a further distinction was made between intentional sources, for which the production of sound is a key feature (e.g. sonar equipment), and unintentional sources, for which the production of sound is merely an undesirable byproduct (e.g. shipping). Sound sources in the air (e.g. aircraft) have been excluded from the study, as the acoustic propagation from air into water is very small. Separate chapters are dedicated to discussion of the sound sources: Chapter 2 treats the natural noise sources, Chapter 3 focuses on intentional anthropogenic noise sources, while unintentional anthropogenic noise sources are the subject of Chapter 4. Where available, source levels, frequency bands, and other characteristic information are collected in these chapters. Based on the information collected in Chapters 2-4, an acoustic energy budget comparison is made in Chapter 5, putting the different natural and anthropogenic noise sources into perspective. For a limited number of cases, noise maps are presented in Chapter 6. Due to the uncertainties involved in the computation of these maps (measured source levels, modelling of environment), these maps are mainly indicative. Also, some attention will be given to the subject of mitigation in Chapter 7, giving possible measures to reduce the risk of harmful effects of the noise sources on sea life. Finally, in Chapter 8, some recommendations for future study are made.

Baumgartner, M. F., Stafford, K. M., Winsor, P., Statscewich, H., & Fratantoni, D. M. (2014). Glider-Based Passive Acoustic Monitoring in the Arctic. *Marine Technology Society Journal, 48*(5). https://doi.org/10.4031/MTSJ.48.5.2

Persistently poor weather in the Arctic makes traditional marine mammal research from aircraft and ships difficult, yet collecting information on marine mammal distribution and habitat utilization is vital for understanding the impact of climate change on Arctic ecosystems. Moreover, as industrial use of the

Arctic increases with the expansion of the open-water summer season, there is an urgent need to monitor the effects of noise from oil and gas exploration and commercial shipping on marine mammals. During September 2013, we deployed a single Slocum glider equipped with a digital acoustic monitoring (DMON) instrument to record and process in situ low-frequency (<5 kHz) audio to characterize marine mammal occurrence and habitat as well as ambient noise in the Chukchi Sea off the northwest coast of Alaska, USA.

Geyer, F., Sagen, H., Hope, G., Babiker, M., & Worcester, P. F. (2016). Identification and quantification of soundscape components in the Marginal Ice Zone. *The Journal of the Acoustical Society of America, 139*(4), 1873. https://doi.org/10.1121/1.4945989

Acoustic experiments using an integrated ice station were carried out during August 2012 and September 2013 in the Marginal Ice Zone (MIZ) of Fram Strait. The two experiments lasted four days each and collected under-ice acoustic recordings together with wave-in-ice and meteorological data. Synthetic aperture radar satellite data provided information on regional ice conditions. Four major components of the under-ice soundscape were identified: ship cavitation noise, seismic airgun noise, marine mammal vocalizations, and natural background noise. Ship cavitation noise was connected to heavy icebreaking. It dominated the soundscape at times, with noise levels (NLs) 100 km from the icebreaker increased by 10-28 dB. Seismic airgun noise that originated from seismic surveys more than 800 km away was present during 117 out of 188 observation hours. It increased NLs at 20-120 Hz by 2-6 dB. Marine mammal vocalizations were a minor influence on measured NLs, but their prevalence shows the biological importance of the MIZ. The 10th percentile of the noise distributions was used to identify the ambient background noise. Background NLs above 100 Hz differed by 12 dB between the two experiments, presumably due to variations in natural noise sources.

Haver, S. M., Klinck, H., Nieukirk, S. L., Matsumoto, H., Dziak, R. P., & Miksis-Olds, J. L. (2017). The not-so-silent world: Measuring Arctic, Equatorial, and Antarctic soundscapes in the Atlantic Ocean. *Deep Sea Research Part I: Oceanographic Research Papers, 122*, 95-104. https://doi.org/10.1016/j.dsr.2017.03.002

Anthropogenic noise in the ocean has been shown, under certain conditions, to influence the behavior and health of marine mammals. Noise from human activities may interfere with the low-frequency acoustic communication of many Mysticete species, including blue (Balaenoptera musculus) and fin whales (B. physalus). This study analyzed three soundscapes in the Atlantic Ocean, from the Arctic to the Antarctic, to document ambient sound. For 16 months beginning in August 2009, acoustic data (15–100 Hz) were collected in the Fram Strait (79°N, 5.5°E), near Ascension Island (8°S, 14.4°W) and in the Bransfield Strait (62°S, 55.5°W). Results indicate (1) the highest overall sound levels were measured in the equatorial Atlantic, in association with high levels of seismic oil and gas exploration, (2) compared to the tropics, ambient sound levels in polar regions are more seasonally variable, and (3) individual elements beget the seasonal and annual variability of ambient sound levels in high latitudes. Understanding how the variability of natural and manmade contributors to sound may elicit differences in ocean soundscapes is essential to developing strategies to manage and conserve marine ecosystems and animals.

Insley, S. J., Halliday, W. D., & de Jong, T. (2017). Seasonal Patterns in Ocean Ambient Noise near Sachs Harbour, Northwest Territories + Supplementary Appendix 1 (See Article Tools). *Arctic, 70*(3), 10. https://dx.doi.org/10.14430/arctic4662

Ocean ambient noise is a crucial habitat feature for marine animals because it represents the lower threshold of their acoustically active space. Ambient noise is affected by noise from both natural sources, like wind and ice, and anthropogenic sources, such as shipping and seismic surveys. During the ice-covered season, ambient conditions in the Arctic are quieter than those in other regions because sea ice has a dampening effect. Arctic warming induced by climate change can raise noise levels by reducing sea ice coverage and increasing human activity, and these changes may negatively affect several species of marine mammals and other acoustically sensitive marine fauna. We document ambient noise off the west coast of Banks Island near Sachs Harbour, Northwest Territories, to provide baseline noise levels for the eastern Beaufort Sea. Noise levels were comparable to those found in other studies of the Canadian Arctic and Alaska and were typically much lower than levels reported farther south. Stronger wind increased noise, whereas greater ice concentration decreased it, dampening the effect of wind speed. Future work should expand monitoring to other locations in the Arctic, model the impact of increased human activities on ambient noise levels, and predict the impact of these changing levels on marine animals.

Kinda, B. (2014). *Acoustic Remote Sensing of Arctic Sea Ice from Long Term Soundscape Measurements.* (Doctorate), Universite de Grenoble, Retrieved from https://tel.archives-ouvertes.fr/tel-00940393

The Arctic sea ice melting, in the global warming context, has become a major scientific topic during the last 30 years. The Arctic Ocean plays a fundamental role in the global climate balance and requires a particular attention. The Arctic Regions are then monitored by satellite observations and in-situ measurements. The climatic impact of the total melting of the Arctic sea ice is not yet understood and researches are still needed for long term monitoring of Arctic Ocean, particularly the dynamics of the ice cover and its consequences on the ecosystems. The loss of Arctic sea ice will gradually accompanied by the installation of seasonal or perennial industrial activities. As consequences, it will result a modification in the underwater soundscapes in these regions devoid of anthropogenic sound sources. The present study, focused on the Canadian Arctic and subarctic seas natural soundscapes, falls within this context through two research axes. The first part of the present study concerns the direct consequences of the melting of sea ice on Polar Regions soundscapes. We then examined the background noise, its seasonal variations and its environmental drivers. A dedicated algorithm to estimate this ocean noise component has been developed for this purpose, in order to constitute time series from long term acoustic measurements. Through statistical analysis, we determined that the environmental variables responsible for generating the background noise depends upon the state of the ocean surface and that during the winter period, the background noise is controlled by the same environmental variables driving the large-scale Arctic Ocean circulation. The second part of our work is to evaluate the potential of passive acoustics as a complementary means of monitoring the spatial and temporal dynamics of Arctic sea ice. To do this, we identified acoustic events related to the physical phenomena under the ice cover to improve our understanding of their generating mechanisms. We were able to bind various acoustic transients to some deformation processes of the moving ice cover.

Kinda, G. B., Simard, Y., Gervaise, C., Mars, J. I., & Fortier, L. (2013). Under-ice ambient noise in Eastern Beaufort Sea, Canadian Arctic, and its relation to environmental forcing. *The Journal of the Acoustical Society of America, 134*(1), 77-87. https://doi.org/10.1121/1.4808330

This paper analyzes an 8-month time series (November 2005 to June 2006) of underwater noise recorded at the mouth of the Amundsen Gulf in the marginal ice zone of the western Canadian Arctic when the area was >90% ice covered. The time-series of the ambient noise component was computed using an algorithm that filtered out transient acoustic events from 7-min hourly recordings of total ocean noise over a [0–4.1] kHz frequency band. Under-ice ambient noise did not respond to thermal changes, but showed consistent correlations with large-scale regional ice drift, wind speed, and measured currents in upper water column. The correlation of ambient noise with ice drift peaked for locations at ranges of 300km off the mouth of the Amundsen Gulf. These locations are within the multi-year ice plume that extends westerly along the coast in the Eastern Beaufort Sea due to the large Beaufort Gyre circulation. These results reveal that ambient noise in Eastern Beaufort Sea in winter is mainly controlled by the same meteorological and oceanographic forcing processes that drive the ice drift and the large-scale circulation in this part of the Arctic Ocean.

Kinda, G. B., Simardb, Y., Gervaise, C., Mars, J. I., & Fortier, L. (2015). Arctic underwater noise transients from sea ice deformation: Characteristics, annual time series, and forcing in Beaufort Sea. *The Journal of the Acoustical Society of America, 138*(4), 2034-2045. https://doi.org/10.1121/1.4929491

A 13-month time series of Arctic Ocean noise from the marginal ice zone of the Eastern Beaufort Sea is analyzed to detect under-ice acoustic transients isolated from ambient noise with a dedicated algorithm. Noise transients due to ice cracking, fracturing, shearing, and ridging are sorted out into three categories: broadband impulses, frequency modulated (FM) tones, and high-frequency broadband noise. Their temporal and acoustic characteristics over the 8-month ice covered period, from November 2005 to mid-June 2006, are presented and their generation mechanisms are discussed. Correlations analyses showed that the occurrence of these ice transients responded to large-scale ice motion and deformation rates forced by meteorological events, often leading to opening of large-scale leads at main discontinuities in the ice cover. Such a sequence, resulting in the opening of a large lead, hundreds by tens of kilometers in size, along the margin of land fast ice and multiyear ice plume in the Beaufort Chukchi seas is detailed. These ice transients largely contribute to the soundscape properties of the Arctic Ocean, for both its ambient and total noise components. Some FM tonal transients can be confounded with marine mammal songs, especially when they are repeated, with periods similar to wind generated waves.

Kipple, B., & Gabriele, C. M. (2003). *Glacier Bay Underwater Noise - August 2000 through August 2002*. Retrieved from https://www.nps.gov/glba/learn/nature/upload/GBUWNoise2003Rpt.pdf

Both manmade and naturally occurring underwater noise in lower Glacier Bay was studied using almost 10,000 hourly noise samples obtained during 20 months between August 2000 and August 2002. The primary contributor of natural noise was wind generated surface noise, which averaged 84 dB re 1 microPa at 1 kHz and ranged from 67 to a maximum of 102 dB. Average monthly wind noise levels were not widely variable by season. Noise from rainfall was present in an average of 2.1 out of 24 samples per day and was not especially prevalent in winter versus other seasons. Rain noise levels at 16 kHz averaged 91 dB and ranged as high as 110 dB. Humpback whales were the most common source of biologic noise. These sounds included various grunts, whoops, and squeaks as well as songs. They were most common from August through November. Sixty-percent of all humpback songs were logged in October 2000. Marine vessel noise was the only identifiable source of Man made noise that was observed. On average it was present in 7.7 out of 24 samples per day, but it ranged from a low of 1.7 samples per day in December 2000 to a high of 16.5 per day in August 2000. Not surprisingly, vessel noise was most common in summer. Peak vessel noise levels averaged 94 dB, 10 dB greater than the average wind noise level. The highest vessel level recorded was 129 dB, but only about 5% of the peak vessel noise levels exceeded 110 dB at the hydrophone. Medium sized vessels were the most prevalent vessel type at all times of year. They constituted 68% of all vessel types observed. At most, large ships were observed in 4 samples per day. Noise from small craft was most common from May to August. The average large vessel noise level was 2 dB higher than the average small vessel level and 7 dB higher than the average medium craft level. Vessel noise levels were lower during periods when a 10-knot speed limit was in effect, especially for large and small vessels. On average, a heavy rolling transient noise was observed in 75% of the samples acquired per day in June and July. The source of this noise was not identified, but its presence was strongly dependent on season.

Kipple, B. (2002). *Glacier Bay Underwater Noise Interim Report* (NSWCCD-71-TR-2002/579). Retrieved from https://www.nps.gov/glba/learn/nature/loader.cfm?csModule=security/getfile&PageID=846009

Both manmade and naturally occurring underwater noise in lower Glacier Bay was studied using over 5200 hourly noise samples obtained during 14 months between August 2000 and June 2002. The primary contributor of natural noise was wind generated surface noise, which averaged 83 dB re 1 microPa at 1 kHz and ranged from 67 to a maximum of 100 dB. Average monthly wind noise levels were not widely variable by season. Noise from rainfall was present in an average of 2.1 out of 24 samples per day and was not especially prevalent in winter versus other seasons. Rain noise levels at 16 kHz averaged 89 dB and ranged as high as 110 dB.

Matsumoto, H., Bohnenstiehl, D. R., Tournadre, J., Dziak, R. P., Haxel, J. H., Lau, T. K. A., . . . Salo, S. A. (2014). Antarctic icebergs: A significant natural ocean sound source in the Southern Hemisphere. *Geochemistry, Geophysics, Geosystems, 15*(8), 3448-3458. https://dx.doi.org/10.1002/2014GC005454

In late 2007, two massive icebergs, C19a and B15a, drifted into open water and slowly disintegrated in the southernmost Pacific Ocean. Archived acoustic records show that the high-intensity underwater sounds accompanying this breakup increased ocean noise levels at mid-to-equatorial latitudes over a period of 1.5 years. More typically, seasonal variations in ocean noise, which are characterized by austral summer-highs and winter-lows, appear to be modulated by the annual cycle of Antarctic iceberg drift and subsequent disintegration. This seasonal pattern is observed in all three Oceans of the Southern Hemisphere. The life cycle of Antarctic icebergs affects not only marine ecosystem but also the sound environment in far-reaching areas and must be accounted for in any effort to isolate anthropogenic or climate induced noise contributions to the ocean soundscape.

Moore, S. E., Stafford, K. M., Melling, H., Berchok, C., Wiig, Ø., Kovacs, K. M., . . . Richter-Menge, J. (2012). Comparing marine mammal acoustic habitats in Atlantic and Pacific sectors of the High Arctic: year-long records from Fram Strait and the Chukchi Plateau. *Polar Biology, 35*(3), 475-480. https://doi.org/10.1007/s00300-011-1086-y

During the International Polar Year (IPY), acoustic recorders were deployed on oceanographic moorings in Fram Strait and on the Chukchi Plateau, representing the first coordinated year-round sampling of underwater acoustic habitats at two sites in the High Arctic. Examination of species-specific marine mammal calls recorded from autumn 2008–2009 revealed distinctly different acoustic habitats at each site. Overall, the Fram Strait site was acoustically complex compared with the Chukchi Plateau site. In Fram Strait, calls from bowhead whales (Balaena mysticetus) and a variety of toothed whales (odontocetes) were recorded year-round, as were airgun pulses from seismic surveys. In addition, calls from blue whales (Balaenoptera musculus) and fin whales (B. physalus) were recorded from June to October and August to March, respectively. Conversely, at the Chukchi Plateau site, beluga

(Delphinapterus leucas) and bowhead whale calls were recorded primarily from May to August, with airgun signals detected only in September–October. Ribbon seal (Phoca fasciata) calls were detected in October–November, with no marine mammals calls at all recorded from December to February. Of note, ice-adapted bearded seals (Erignathus barbatus) were recorded at both sites, primarily in spring and summer, corresponding with the mating season for that species. Differences in acoustic habitats between the two sites were related to contrasts in sea ice cover, temperature, patterns of ocean circulation and contributions from anthropogenic noise sources. These data provide a provisional baseline for the comparison of underwater acoustic habitats between Pacific and Atlantic sectors of the High Arctic.

Ozanich, E., Gerstoft, P., Worcester, P. F., Dzieciuch, M. A., & Thode, A. (2017). Eastern Arctic ambient noise on a drifting vertical array. *The Journal of the Acoustical Society of America, 142*(4), 1997. https://doi.org/10.1121/1.5006053

Ambient noise in the eastern Arctic was studied from April to September 2013 using a 22 element vertical hydrophone array as it drifted from near the North Pole (89 degrees 23'N, 62 degrees 35'W) to north of Fram Strait (83 degrees 45'N, 4 degrees 28'W). The hydrophones recorded for 108 min/day on six days per week with a sampling rate of 1953.125 Hz. After removal of data corrupted by non-acoustic transients, 19 days throughout the transit period were analyzed. Noise contributors identified include broadband and tonal ice noises, bowhead whale calling, seismic airgun surveys, and earthquake T phases. The bowhead whale or whales detected are believed to belong to the endangered Spitsbergen population, and were recorded when the array was as far north as 86 degrees 24'N. Median power spectral estimates and empirical probability density functions along the array transit show a change in the ambient noise levels corresponding to seismic survey airgun occurrence and received level at low frequencies and transient ice noises at high frequencies. Median power for the same periods across the array shows that this change is consistent in depth. The median ambient noise for May 2013 was among the lowest of the sparse reported observations in the eastern Arctic but comparable to the more numerous observations of western Arctic noise levels.

Roth, E. H., Hildebrand, J. A., Wiggins, S. M., & Ross, D. (2012). Underwater ambient noise on the Chukchi Sea continental slope from 2006-2009. *The Journal of the Acoustical Society of America, 131*(1), 104-110. https://doi.org/10.1121/1.3664096

From September 2006 to June 2009, an autonomous acoustic recorder measured ambient noise north of Barrow, Alaska on the continental slope at 235 m depth, between the Chukchi and Beaufort Seas. Mean monthly spectrum levels, selected to exclude impulsive events, show that months with open-water had the highest noise levels (80-83 dB re: 1 muPa(2)/Hz at 20-50 Hz), months with ice coverage had lower spectral levels (70 dB at 50 Hz), and months with both ice cover and low wind speeds had the lowest noise levels (65 dB at 50 Hz). During ice covered periods in winter-spring there was significant transient energy between 10 and 100 Hz from ice fracture events. During ice covered periods in late spring there were significantly fewer transient events. Ambient noise increased with wind speed by ~ 1 dB/m/s for relatively open-water (0%-25% ice cover) and by ~ 0.5 dB/m/s for nearly complete ice cover (> 75%). In September and early October for all years, mean noise levels were elevated by 2-8 dB due to the presence of seismic surveys in the Chukchi and Beaufort Seas.

Sagen, H., Tollefsen, D., & Tengesdal, H. C. (2014). The Soundscape of the Fram Strait Marginal Ice Zone. https://doi.org/10.13140/2.1.1923.3928

A series of acoustic experiments were conducted in the Marginal Ice Zone (MIZ) of the Fram Strait in the years 2010-12 under the Waves-in-ice Forecasting for Arctic Operators (WIFAR) project led by NERSC. The focus of this paper is results from noise measurements with fields of sonobuoy deployed in the MIZ from the open ocean to compact ice under varying environmental conditions. Noise spectra (10 Hz – 1 kHz) are presented and categorized by environmental parameters that include sea state, wind force and direction, ice concentration, and ocean swell. Scatter plot representations of noise data are explored as a tool to infer local ice conditions. The noise fields also included components due to marine mammals and distant seismic exploration.

Sertlek, H. Ö., Aarts, G., Brasseur, S., Slabbekoorn, H., ten Cate, C., von Benda-Beckmann, A. M., & Ainslie, M. A. (2016). Mapping Underwater Sound in the Dutch Part of the North Sea. In A. N. Popper & A. Hawkins (Eds.), *The Effects of Noise on Aquatic Life II* (pp. 1001-1006). New York, NY: Springer New York.

The European Union requires member states to achieve or maintain good environmental status for their marine territorial waters and explicitly mentions potentially adverse effects of underwater sound. In this study, we focused on producing maps of underwater sound from various natural and anthropogenic origins in the Dutch North Sea. The source properties and sound propagation are simulated by mathematical methods. These maps could be used to assess and predict large-scale effects on behavior and distribution of underwater marine life and therefore become a valuable tool in assessing and managing the impact of underwater sound on marine life.

Stafford, K. M., Castellote, M., Guerra, M., & Berchok, C. L. (2017). Seasonal acoustic environments of beluga and bowhead whale core-use regions in the Pacific Arctic. *Deep Sea Research Part II: Topical Studies in Oceanography*. https://doi.org/10.1016/j.dsr2.2017.08.003

The acoustic environment of two focal Arctic species, bowhead (Balaena mysticetus) and beluga (Delphinapterus leucas) whales, varied among the three core-use regions of the Pacific Arctic examined during the months in which both species occur: (1) January-March in the St. Lawrence Island/Anadyr Strait region, (2) November-January in the Bering Strait region, and (3) August-October in the Barrow Canyon region. Biological noise (consisting of the signals of bowhead whales, walrus and bearded seals) dominated the acoustic environment for the focal species in the St. Lawrence Island/Anadyr Strait region, which was covered with ice throughout the months studied. In the Bering Strait region whales were exposed primarily to environmental noise (in the form of wind noise) during November, before the region was ice-covered in December, and biological noise (from bowhead and walrus) again was prevalent. Anthropogenic noise dominated the Barrow Canyon region for the focal species in late summer and fall (August through October); this was also the only region in which the two species did not overlap with sea ice. Under open water conditions both near Barrow Canyon and in Bering Strait, noise levels were tightly correlated with wind. However, with climate-change driven increases in open water leading to rising noise levels across multiple fronts (atmospheric, biological, anthropogenic), the relatively pristine acoustic environment of Arctic cetaceans is changing rapidly. Characterizing the acoustic habitat of these regions before they are further altered should be considered a management and conservation priority in the Arctic.

Tollefsen, D., & Sagen, H. (2014). Seismic exploration noise reduction in the Marginal Ice Zone. *J Acoust Soc Am, 136*(1), EL47-52. https://doi.org/10.1121/1.4885547

A sonobuoy field was deployed in the Marginal Ice Zone of the Fram Strait in June 2011 to study the spatial variability of ambient noise. High noise levels observed at 10–200Hz are attributed to distant (1400 km range) seismic exploration. The noise levels decreased with range into the ice cover; the reduction is fitted by a spreading loss model with a frequency-dependent attenuation factor less than for under-ice interior Arctic propagation. Numerical modeling predicts transmission loss of the same order as the observed noise level reduction and indicates a significant loss contribution from under-ice interaction.

Section II: Vessel Noise Measurement

Aulanier, F., Simard, Y., Roy, N., Gervaise, C., & Bandet, M. (2017). Effects of shipping on marine acoustic habitats in Canadian Arctic estimated via probabilistic modeling and mapping. *Marine Pollution Bulletin, 125*(1-2), 115-131. https://doi.org/10.1016/j.marpolbul.2017.08.002

Canadian Arctic and Subarctic regions experience a rapid decrease of sea ice accompanied with increasing shipping traffic. The resulting time-space changes in shipping noise are studied for four key regions of this pristine environment, for 2013 traffic conditions and a hypothetical tenfold traffic increase. A probabilistic modeling and mapping framework, called Ramdam, which integrates the intrinsic variability and uncertainties of shipping noise and its effects on marine habitats, is developed and applied. A substantial transformation of soundscapes is observed in areas where shipping noise changes from present occasional-transient contributor to a dominant noise source. Examination of impacts on low-frequency mammals within ecologically and biologically significant areas reveals that shipping noise has the potential to trigger behavioral responses and masking in the future, although no risk of temporary or permanent hearing threshold shifts is noted. Such probabilistic modeling and mapping is strategic in marine spatial planning of this emerging noise issues.

Arveson, P. T., & Vendittis, D. J. (2000). Radiated noise characteristics of a modern cargo ship. *The Journal of the Acoustical Society of America, 107*(1), 118-129. https://doi.org/10.1121/1.428344

Extensive measurements were made of the radiated noise of M/V OVERSEASHARRIETTE, a bulk cargo ship (length 173 m, displacement 25 515 tons) powered by a direct-drive low-speed diesel engine—a design representative of many modern merchant ships. The radiated noise data show high-level tonal frequencies from the ship's service diesel generator, main engine firing rate, and blade rate harmonics due to propeller cavitation. Radiated noise directionality measurements indicate that the radiation is generally dipole in form at lower frequencies, as expected. There are some departures from this pattern that may indicate hull interactions. Blade rate source level (174 dB *re* 1 μPa/m at 9 Hz, 16 knots) agrees reasonably well with a model of fundamental blade rate radiation previously reported by Gray and Greeley, but agreement for blade rate harmonics is not as good. Noise from merchant ships elevates the natural ambient by 20–30 dB in many areas; the effects of this noise on the biological environment have not been widely investigated.

Bassett, C., Polagye, B., Holt, M., & Thomson, J. (2012). A vessel noise budget for Admiralty Inlet, Puget Sound, Washington (USA). *Journal of the Acoustical Society of America, 132*(6), 3706-3719. https://doi.org/10.1121/1.4763548

One calendar year of Automatic Identification System (AIS) ship-traffic data was paired with hydrophone recordings to assess ambient noise in northern Admiralty Inlet, Puget Sound, WA (USA) and to quantify the contribution of vessel traffic. The study region included inland waters of the Salish Sea within a 20 km radius of the hydrophone deployment site. Spectra and hourly, daily, and monthly ambient noise statistics for unweighted broadband (0.02–30 kHz) and marine mammal, or M-weighted, sound pressure levels showed variability driven largely by vessel traffic. Over the calendar year, 1363 unique AIS transmitting vessels were recorded, with at least one AIS transmitting vessel present in the study area 90% of the time. A vessel noise budget was calculated for all vessels equipped with AIS transponders. Cargo ships were the largest contributor to the vessel noise budget, followed by tugs and passenger vessels. A simple model to predict received levels at the site based on an incoherent summation of noise from different vessels resulted in a cumulative probability density function of broadband sound pressure levels that shows good agreement with 85% of the temporal data.

De Robertis, A., Wilson, C. D., Furnish, S. R., & Dahl, P. H. (2013). Underwater radiated noise measurements of a noise-reduced fisheries research vessel. *Ices Journal of Marine Science, 70*(2), 480-484. https://doi.org/10.1093/icesjms/fss172

Vessel-radiated noise is traditionally measured at naval acoustic ranges, but lower-cost options are desirable for routine monitoring of research vessels. Measurements of a noise-reduced research vessel made at a naval noise range are compared to those made using an experimental mooring equipped with commercially available instrumentation. The measurements from the mooring were precise and within 2.5 dB of those from the noise range at third-octave bands ,500 Hz. At higher frequencies, direct comparisons were precluded by an intermittent shaft-related noise present only during the mooring measurements, but previously observed at the navy range. The agreement between the two methods suggests that simplified, field-deployable hydrophone systems can be used to accurately characterize the noise signatures of research vessels.

Frisk, G. V. (2012). Noiseonomics: the relationship between ambient noise levels in the sea and global economic trends. *Scientific Reports, 2*, 437. https://doi.org/10.1038/srep00437

In recent years, the topic of noise in the sea and its effects on marine mammals has attracted considerable attention from both the scientific community and the general public. Since marine mammals rely heavily on acoustics as a primary means of communicating, navigating, and foraging in the ocean, any change in their acoustic environment may have an impact on their behavior. Specifically, a growing body of literature suggests that low-frequency, ambient noise levels in the open ocean increased approximately 3.3 dB per decade during the period 1950-2007. Here we show that this increase can be attributed primarily to commercial shipping activity, which in turn, can be linked to global economic growth. As a corollary, we conclude that ambient noise levels can be directly related to global economic conditions. We provide experimental evidence supporting this theory and discuss its implications for predicting future noise levels based on global economic trends.

Garrett, J. K., Blondel, P., Godley, B. J., Pikesley, S. K., Witt, M. J., & Johanning, L. (2016). Long-term underwater sound measurements in the shipping noise indicator bands 63Hz and 125Hz from the port of Falmouth Bay, UK. *Marine Pollution Bulletin, 110*(1), 438-448. https://doi.org/10.1016/j.marpolbul.2016.06.021

Chronic low-frequency anthropogenic sound, such as shipping noise, may be negatively affecting marine life. The EU's Marine Strategy Framework Directive (MSFD) includes a specific indicator focused on this noise. This indicator is the yearly average sound level in third-octave bands with centre frequencies at 63Hz and 125Hz. These levels are described for Falmouth Bay, UK, an active port at the entrance to the English Channel. Underwater sound was recorded for 30 min h(-1) over the period June 2012 to November 2013 for a total of 435 days. Mean third-octave levels were louder in the 125-Hz band (annual mean level of 96.0dB re 1muPa) than in the 63-Hz band (92.6dB re 1 muPa). These levels and variations are assessed as a function of seasons, shipping activity and wave height, providing comparison points for future monitoring activities, including the MSFD and emerging international regulation.

Gassmann, M., Wiggins, S. M., & Hildebrand, J. A. (2017). Deep-water measurements of container ship radiated noise signatures and directionality. *The Journal of the Acoustical Society of America, 142*(3), 1563. https://doi.org/10.1121/1.5001063

Underwater radiated noise from merchant ships was measured opportunistically from multiple spatial aspects to estimate signature source levels and directionality. Transiting ships were tracked via the Automatic Identification System in a shipping lane while acoustic pressure was measured at the ships' keel and beam aspects. Port and starboard beam aspects were 15 degrees , 30 degrees , and 45 degrees in compliance with ship noise measurements standards [ANSI/ASA S12.64 (2009) and ISO 17208-1 (2016)]. Additional recordings were made at a 10 degrees starboard aspect. Source levels were derived with a spherical propagation (surface-affected) or a modified Lloyd's mirror model to account for interference from surface reflections (surface-corrected). Ship source depths were estimated from spectral differences between measurements at different beam aspects. Results were exemplified with a 4870 and a 10 036 twenty-foot equivalent unit container ship at 40%-56% and 87% of service speeds, respectively. For the larger ship, opportunistic ANSI/ISO broadband levels were 195 (surface-affected) and 209 (surface-corrected) dB re 1 muPa2 1 m. Directionality at a propeller blade rate of 8 Hz exhibited asymmetries in stern-bow (<6 dB) and port-starboard (<9 dB) direction. Previously reported broadband levels at 10 degrees aspect from McKenna, Ross, Wiggins, and Hildebrand [(2012b). J. Acoust. Soc. Am. 131, 92-103] may be approximately 12 dB lower than respective surface-affected ANSI/ISO standard derived levels.

Hatch, L., Clark, C., Merrick, R., Van Parijs, S., Ponirakis, D., Schwehr, K., . . . Wiley, D. (2008). Characterizing the relative contributions of large vessels to total ocean noise fields: a case study using the Gerry E. Studds Stellwagen Bank National Marine Sanctuary. *Environ Manage, 42*(5), 735-752. https://doi.org/10.1007/s00267-008-9169-4

In 2006, we used the U.S. Coast Guard’s Automatic Identification System (AIS) to describe patterns of large commercial ship traffic within a U.S. National Marine Sanctuary located off the coast of Massachusetts. We found that 541 large commercial vessels transited the greater sanctuary 3413 times during the year. Cargo ships, tankers, and tug/tows constituted 78% of the vessels and 82% of the total transits. Cargo ships, tankers, and cruise ships predominantly used the designated Boston Traffic Separation Scheme, while tug/tow traffic was concentrated in the western and northern portions of the sanctuary. We combined AIS data with low-frequency acoustic data from an array of nine autonomous recording units analyzed for 2 months in 2006. Analysis of received sound levels (10–1000 Hz, rootmean-square pressure re 1 lPa ± SE) averaged 119.5 ± 0.3 dB at high-traffic locations. Hightraffic locations experienced double the acoustic power of less trafficked locations for the majority of the time period analyzed. Average source level estimates (71–141 Hz, rootmean-square pressure re 1 lPa ± SE) for individual vessels ranged from 158 ± 2 dB (research vessel) to 186 ± 2dB (oil tanker). Tankers were estimated to contribute 2 times more acoustic power to the region than cargo ships, and more than 100 times more than research vessels. Our results indicate that noise produced by large commercial vessels was at levels and within frequencies that warrant concern among managers regarding the ability of endangered whales to maintain acoustic contact within greater sanctuary waters.

Haimov, H., Gallego, V., Molinelli, E., & Trujillo, B. (2016). Propeller acoustic measurements in atmospheric towing tank. *Ocean Engineering, 120*, 190-201. https://doi.org/10.1016/j.oceaneng.2015.06.047

The study describes the implementation of experimental procedure for measuring the hydrodynamic noise generated by model scale marine propellers in atmospheric towing tank. The study is limited to non-cavitating conditions of the propeller as the experimental tank is at atmospheric pressure. The towing carriage and conditions have not been altered admitting the existence of considerable background noise. The feasibility analysis included experimental and theoretical study of the background noise at the operating conditions. Some considerations about the uncertainty of the results are also presented. The experimental equipment, set up and procedure for measuring the acoustic pressure around model ship propeller and/or hull is also described. Simultaneous measurements with various differently positioned hydrophones at multiple hydrodynamic conditions permitted to evaluate the background and propeller/hull generated acoustic field at a range of frequencies. An appropriate treatment of the recorded time series characterized the background disturbances and permitted to obtain net results with sufficient signal to noise ratio, mostly from narrowband spectral analysis. Results for the impact of the hull presence on propeller acoustic field are presented and discussed. The extrapolated results are compared informatively with full scale measurements

Hermannsen, L., Beedholm, K., Tougaard, J., & Madsen, P. T. (2014). High frequency components of ship noise in shallow water with a discussion of implications for harbor porpoises (Phocoena phocoena). *The Journal of the Acoustical Society of America, 136*(4), 1640-1653. https://doi.org/10.1121/1.4893908

Growing ship traffic worldwide has led to increased vessel noise with possible negative impacts on marine life. Most research has focused on low frequency components of ship noise, but for high-frequency specialists, such as the harbor porpoise (Phocoena phocoena), medium-to-high frequency noise components are likely more of a concern. To test for biologically relevant levels of medium-to-high frequency vessel noise, different types of Automatic Identification System located vessels were recorded using a broadband recording system in four heavily ship-trafficked marine habitats in Denmark. Vessel noise from a range of different ship types substantially elevated ambient noise levels across the entire recording band from 0.025 to 160 kHz at ranges between 60 and 1000 m. These ship noise levels are estimated to cause hearing range reduction of >20dB (at 1 and 10 kHz) from ships passing at distances of 1190m and >30dB reduction (at 125 kHz) from ships at distances of 490m or less. It is concluded that a diverse range of vessels produce substantial noise at high frequencies, where toothed whale hearing is most sensitive, and that vessel noise should be considered over a broad frequency range, when assessing noise effects on porpoises and other small toothed whales.

Huang, W., Wang, D. L., Garcia, H., Godo, O. R., & Ratilal, P. (2017). Continental Shelf-Scale Passive Acoustic Detection and Characterization of Diesel-Electric Ships Using a Coherent Hydrophone Array. *Remote Sensing, 9*(8). https://doi.org/10.3390/rs9080772

The passive ocean acoustic waveguide remote sensing (POAWRS) technique is employed to detect and characterize the underwater sound radiated from three scientific research and fishing vessels received at long ranges on a large-aperture densely-sampled horizontal coherent hydrophone array. The sounds radiated from the research vessel (RV) Delaware II in the Gulf of Maine, and the RV Johan Hjort and the fishing vessel (FV) Artus in the Norwegian Sea are found to be dominated by distinct narrowband tonals and cyclostationary signals in the 150 Hz to 2000 Hz frequency range. The source levels of these signals are estimated by correcting the received pressure levels for transmission losses modeled using a calibrated parabolic equation-based acoustic propagation model for random range-dependent ocean waveguides. The probability of the detection region for the most prominent signal radiated by each ship is estimated and shown to extend over areas spanning roughly 200 km in diameter when employing a coherent hydrophone array. The current standard procedure for quantifying ship-radiated sound source levels via one-third octave bandwidth intensity averaging smooths over the prominent tonals radiated by a ship that can stand 10 to 30 dB above the local broadband level, which may lead to inaccurate or incorrect assessments of the impact of ship-radiated sound.

Humphrey, V., & Brooker, A. (2017). *Measurement of the Underwater Noise Footprint of a Vessel*. Paper presented at the 24th International Congress on Sound and Vibration, London, England. Retrieved from https://www.iiav.org/archives_icsv_last/2017_icsv24/content/papers/papers/full_paper_890_20170602184629716.pdf

The impacts of man-made underwater noise on the marine environment have received increased attention over recent years, primarily resulting from recognition of the increased pressures placed on the oceans by human activities. A main source of such anthropogenic noise is shipping. In order to understand the underwater soundscape considerable effort is being placed on generating underwater noise maps, based on using AIS data to provide details of vessel locations and operational characteristics. A key input for noise mapping models is an adequate knowledge of the source strength and characteristics for each vessel. Currently the sources are usually assumed omnidirectional, given the limited data on the true vessel radiation pattern. This paper presents the result of a trial undertaken on a small survey vessel, operating under realistic conditions at sea in shallow water, as part of the SONIC project. This trial used an autonomous recorder to measure the sound pressure as a function of range and azimuth. The vessel made a repeated runs past the autonomous recorder for a variety of different ranges. This has enabled the vessel noise footprint to be measured as a function of frequency and speed for the vessel, showing how the azimuthal characteristics change with frequency.

Ianniello, S., Muscari, R., & Di Mascio, A. (2014). Ship underwater noise assessment by the Acoustic Analogy part II: hydroacoustic analysis of a ship scaled model. *Journal of Marine Science and Technology, 19*(1), 52-74. https://doi.org/10.1007/s00773-013-0236-z

In this paper the Acoustic Analogy is used to predict the underwater noise from a complete scaled ship model in a steady course. The numerical investigation is performed by coupling an incompressible RANS code, equipped with a level-set approach to account for the fundamental time evolution of the free surface, to a FWH-based hydroacoustic solver, here suitably designed to manage the huge set of data coming from a full-unsteady hydrodynamic simulation. The results reveal the overall limited contribution from the propeller thickness and loading noise components and the fundamental one from the nonlinear quadrupole sources. The comparison between the hydrodynamic and hydroacoustic solutions point out the noticeable scattering effects due to the hull surface, the possible influence of sound refractions at the free surface and, above all, the leading role played by the turbulent fluctuating component of the velocity field. Finally, by computing the pressure time histories at a prescribed set of virtual hydrophones and turning them into the frequency domain, the ship noise footprint in dB is traced out, thus showing how the Acoustic Analogy can be effectively used to analyze the ship hydroacoustic behavior, both in terms of amplitude and directivity.

Kinda, G. B., Le Courtois, F., & Stephan, Y. (2017). Ambient noise dynamics in a heavy shipping area. *Marine Pollution Bulletin, 124*(1), 535-546. https://doi.org/10.1016/j.marpolbul.2017.07.031

The management of underwater noise within the European Union's waters is a significant component (Descriptor 11) of the Marine Strategy Framework Directive (MSFD). The indicator related to continuous noise, is the noise levels in two one-third octave bands centered at 63Hz and 125Hz. This paper presents an analysis of underwater noise in the Celtic Sea, a heavy shipping area which also hosts the seasonal Ushant thermal front. In addition to the MSFD recommended frequency bands, the analysis was extended to lower and upper frequency bands. Temporal and spatial variations as well as the influence of the properties of the water column on the noise levels were assessed. The noise levels in the area had a high dynamic range and generally exceeded 100dB re 1muPa. Finally, the results highlighted that oceanic mooring must be designed to minimize the pseudo-noise and consider the water column physical properties.

Kipple, B. (2002). *Southeast Alaska Cruise Ship Underwater Acoustic Noise* Glacier Bay National Park and Preserve (NSWCCD-71-TR-2002/574) Retrieved from https://www.nps.gov/glba/learn/nature/upload/CruiseShipSoundSignaturesSEAFAC.pdf

Between September 2000 and June 2001, the underwater radiated noise levels for six Southeast Alaska cruise ships were measured at the U.S. Navy's Southeast Alaska Acoustic Measurement Facility near Ketchikan, Alaska. The primary objective of this project was to quantify noise levels typical of large cruise ships common to Southeast Alaska. This group of ships included diesel-electric, direct-diesel, and steam turbine propulsion plant ships ranging in size from 23 to 77 thousand gross tons and from 617 to 856 feet in length. Ten-knot overall sound levels ranged from 175 to 185 dB relative to 1 micro Pascal at 1 yard with the highest one-third octave band level at 182 dB. The 10-knot sound level for the steam turbine ship was the lowest among the ships tested, but no ship was clearly the loudest or quietest at all frequencies.

Kipple, B., & Gabriele, C. (2003). *Glacier Bay Watercraft Noise*. Glacier Bay National Park and Preserve (NSWCCD-71-TR-2003/522). Retrieved from https://www.nps.gov/glba/learn/nature/upload/GBWatercraftNoiseRpt.pdf

Underwater noise levels of 14 vessels operated by Glacier Bay National Park and Preserve were measured in 2000 and 2002. The vessels tested were from 14 to 65 feet in length and engine power ratings ranged from 25 to 420 horsepower. Most boats were evaluated at speeds of 10, 14, and 20 knots. These watercraft generated peak one-third octave noise levels ranging from 150 to 177 dB re 1 microPa at 1 yard and sound levels from 157 to 181 dB re 1 microPa at 1 yard. Noise levels depended on vessel type. All vessels but one, the 65 foot Nunatak, were classified as small craft with high-speed engines. As a group, skiffs under 20 feet in length and 100 horsepower produced the lowest sound levels, followed closely by the jet powered craft, which were the largest and highest powered small craft that were evaluated. Propeller powered small craft with engine power ratings over 100 horsepower produced the highest noise levels. Nunatak's noise levels were lower than those produced by many of the over 100 horsepower propeller driven group. Noise levels also depended on vessel speed. On the average, vessel sound levels were about 4 dB greater at 20 knots compared to 10 knots. However, increases of up to 6 dB were observed for some vessels over this speed range. In comparison with noise levels from large cruise ships, the small craft one-third octave noise levels were generally lower at lower frequencies. However, in some bands at frequencies above 1 kHz, the small craft noise levels were comparable to, or in some cases greater than, cruise ship noise levels.

Kipple, B., & Gabriele, C. (2004). *Glacier Bay Watercraft Noise - Noise Characterization for Tour, Charter, Private, and Government Vessels*. Glacier Bay National Park and Preserve (NSWCCD-71-TR-2004/545). Retrieved from https://www.nps.gov/glba/learn/nature/upload/Kipple_Gabriele2004GBWatercraftNoiseRpt.pdf

Underwater sound levels of 16 vessels were measured under controlled conditions in Glacier Bay National Park and Preserve during July and August of 2003. Vessels ranged from 17 to 257 feet in length and included two small craft, a sailboat under power, one workboat, one tugboat, one fishing vessel, one research vessel, one yacht, and eight tour vessels. Sound levels associated with these vessels ranged from 153 to 180 dB re 1 microPa at 1 yard. On the average, overall sound levels were higher for the larger vessel categories. Increased vessel speeds also resulted in higher sound levels.

McKenna, M. F., Wiggins, S. M., & Hildebrand, J. A. (2013). Relationship between container ship underwater noise levels and ship design, operational and oceanographic conditions. *Scientific Reports, 3*. https://doi.org/10.1038/srep01760

Low-frequency ocean ambient noise is dominated by noise from commercial ships, yet understanding how individual ships contribute deserves further investigation. This study develops and evaluates statistical models of container ship noise in relation to design characteristics, operational conditions, and oceanographic settings. Five-hundred ship passages and nineteen covariates were used to build generalized additive models. Opportunistic acoustic measurements of ships transiting offshore California were collected using seafloor acoustic recorders. A 5–10 dB range in broadband source level was found for ships depending on the transit conditions. For a ship recorded multiple times traveling at different speeds, cumulative noise was lowest at 8 knots, 65% reduction in operational speed. Models with highest predictive power, in order of selection, included ship speed, size, and time of year. Uncertainty in source depth and propagation affected model fit. These results provide insight on the conditions that produce higher levels of underwater noise from container ships.

McKenna, M. F., Ross, D., Wiggins, S. M., & Hildebrand, J. A. (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

Underwater radiated noise measurements for seven types of modern commercial ships during normal operating conditions are presented. Calibrated acoustic data (<1000 Hz) from an autonomous seafloor-mounted acoustic recorder were combined with ship passage information from the Automatic Identification System. This approach allowed for detailed measurements (i.e., source level, sound exposure level, and transmission range) on ships of opportunity. A key result was different acoustic levels and spectral shapes observed from different ship-types. A 54 kGT container ship had the highest broadband source level at 188 dB re 1 muPa@1m; a 26 kGT chemical tanker had the lowest at 177 dB re

1 muPa@1m. Bulk carriers had higher source levels near 100 Hz, while container ship and tanker noise was predominantly below 40 Hz. Simple models to predict source levels of modern merchant ships as a group from particular ship characteristics (e.g., length, gross tonnage, and speed) were not possible given individual ship-type differences. Furthermore, ship noise was observed to radiate asymmetrically. Stern aspect noise levels are 5 to 10 dB higher than bow aspect noise levels. Collectively, these results emphasize the importance of including modern ship-types in quantifying shipping noise for predictive models of global, regional, and local marine environments.

Merchant, N. D., Pirotta, E., Barton, T. R., & Thompson, P. M. (2014). Monitoring ship noise to assess the impact of coastal developments on marine mammals. *Marine Pollution Bulletin, 78*(1-2), 85-95. https://doi.org/10.1016/j.marpolbul.2013.10.058

The potential impacts of underwater noise on marine mammals are widely recognized, but uncertainty over variability in baseline noise levels often constrains efforts to manage these impacts. This paper characterizes natural and anthropogenic contributors to underwater noise at two sites in the Moray Firth Special Area of Conservation, an important marine mammal habitat that may be exposed to increased shipping activity from proposed offshore energy developments. We aimed to establish a pre-development baseline, and to develop ship noise monitoring methods using Automatic Identification System (AIS) and time-lapse video to record trends in noise levels and shipping activity. Our results detail the noise levels currently experienced by a locally protected bottlenose dolphin population, explore the relationship between broadband sound exposure levels and the indicators proposed in response to the EU Marine Strategy Framework Directive, and provide a ship noise assessment toolkit which can be applied in other coastal marine environments.

Merchant, N. D., Witt, M. J., Blondel, P., Godley, B. J., & Smith, G. H. (2012). Assessing sound exposure from shipping in coastal waters using a single hydrophone and Automatic Identification System (AIS) data. *Marine Pollution Bulletin, 64*(7), 1320-1329. https://doi.org/10.1016/j.marpolbul.2012.05.004

Underwater noise from shipping is a growing presence throughout the world's oceans, and may be subjecting marine fauna to chronic noise exposure with potentially severe long-term consequences. The coincidence of dense shipping activity and sensitive marine ecosystems in coastal environments is of particular concern, and noise assessment methodologies which describe the high temporal variability of sound exposure in these areas are needed. We present a method of characterizing sound exposure from shipping using continuous passive acoustic monitoring combined with Automatic Identification System (AIS) shipping data. The method is applied to data recorded in Falmouth Bay, UK. Absolute and relative levels of intermittent ship noise contributions to the 24-h sound exposure level are determined using an adaptive threshold, and the spatial distribution of potential ship sources is then analyzed using AIS data. This technique can be used to prioritize shipping noise mitigation strategies in coastal marine environments.

Roth, E. H., Schmidt, V., Hildebrand, J. A., & Wiggins, S. M. (2013). Underwater radiated noise levels of a research icebreaker in the central Arctic Ocean. *The Journal of the Acoustical Society of America, 133*(4), 1971-1980. https://doi.org/10.1121/1.4790356

U.S. Coast Guard Cutter Healy's underwater radiated noise signature was characterized in the central Arctic Ocean during different types of ice-breaking operations. Propulsion modes included transit in variable ice cover, breaking heavy ice with backing-and-ramming maneuvers, and dynamic positioning with the bow thruster in operation. Compared to open-water transit, Healy's noise signature increased approximately 10 dB between 20 Hz and 2 kHz when breaking ice. The highest noise levels resulted while the ship was engaged in backing-and-ramming maneuvers, owing to cavitation when operating the propellers astern or in opposing directions. In frequency bands centered near 10, 50, and 100 Hz, source levels reached 190-200 dB re: 1 muPa at 1 m (full octave band) during ice-breaking operations.

Rudd, A. B., Richlen, M. F., Stimpert, A. K., & Au, W. W. L. (2015). Underwater Sound Measurements of a High-Speed Jet-Propelled Marine Craft: Implications for Large Whales. *Pacific Science, 69*(2), 155-164. https://doi.org/10.2984/69.2.2

The radiated noise from a high-speed jet propelled watercraft (the M/V Alakai, 1646 tons, length of 117 m) was measured at hydrophone depths of 3, 6 and 10 m while the ship passed by at speeds of 12, 24 and 37 knots. Noise spectra were similar for all speeds and hydrophone depths. The spectra peaked below 100 Hz and dropped off continuously at higher frequencies. The calculated source level noise was 10 to 20 dB lower than noise from propeller driven ships, and much lower than for ships of similar speed. Although exposure to noise radiating from the M/V Alakai over short time periods is unlikely to cause hearing damage to whales, the combination of low radiated noise levels and high transit speeds leads to a shorter closing time (defined as the time between when the source level of the ship at a stationary receiver is greater than ambient noise and the time that a ship traveling directly toward the receiver arrives at its location) between the ship and the whale. Compared to other types of ships traveling at similar speeds, closing time for the Alakai ranges from 20 seconds shorter (at 12 knots) to 22 minutes shorter (at 37 knots). The shortest closing time for the Alakai is 89.1 seconds at a speed of 12 knots. Shortened closing time might reduce successful detection and avoidance of high-speed jet propelled ships by whales, and increased speed shortens the time during which whales have the opportunity to respond to this detection.

Santos-Domínguez, D., Torres-Guijarro, S., Cardenal-López, A., & Pena-Gimenez, A. (2016). ShipsEar: An underwater vessel noise database. *Applied Acoustics, 113*, 64-69. https://doi.org/10.1016/j.apacoust.2016.06.008

There is a manifest shortage of audio databases available to underwater acoustics researchers. With the aim of palliating this situation, ShipsEar, a database of underwater recordings of ship and boat sounds, has been made available to the research community at https://atlanttic.uvigo.es/underwaternoise/. The database is currently composed of 90 records representing sounds from 11 vessel types. It includes detailed information on technical aspects of the recordings and environmental and other conditions during acquisition. To demonstrate the usefulness of ShipsEar, a vessel classifier was developed, based on cepstral coefficients and Gaussian mixture models. It was tested on a subset of ShipsEar database in which the original 11 vessel types were merged into 4 vessel size classes. The system yielded an overall classification rate of 75.4%, and 100% accuracy in detecting vessel presence. ShipsEar is potentially useful for the development and testing of applications based on processing underwater vessel sound.

Spence, J. H., & Fischer, R. W. (2017). Requirements for Reducing Underwater Noise From Ships. *IEEE Journal of Oceanic Engineering, 42*(2), 388-398. https://doi.org/10.1109/joe.2016.2578198

Awareness of underwater noise from shipping has grown significantly within the marine community over the past decade. Concerns have been raised about the levels of anthropogenic noise in the world's oceans, as well as in harbors and areas with sensitive or protected marine life. Regulatory bodies are listening, and are considering what actions are available to reduce noise. Measurements of vessel noise in various situations have been performed to better quantify the problem, and efforts have been made by some to correlate noise levels with simplified vessel parameters. Such efforts provide insights into what levels of noise are possible and how they are related to ship operation. However, to reduce underwater noise, a deeper understanding of specific vessel design and factors that lead to noise are required. While generalities of primary noise sources can be applied to different classes of vessels, design details of specific vessels must be obtained and analyzed to implement noise reductions. Armed with knowledge of vessel details, noise control strategies can be optimized using various computer-aided tools. This must be done on a case-by-case basis for different vessel designs, and is most efficient and effective for new builds. Costs for such efforts must also be considered if vessel noise is to be made inherently quieter worldwide.

Trevorrow, M. V., Vasiliev, B., & Vagle, S. (2008). Directionality and maneuvering effects on a surface ship underwater acoustic signature. *The Journal of the Acoustical Society of America, 124*(2), 767-778. https://doi.org/10.1121/1.2939128

This work examines underwater source spectra of a small (560tons560tons, 40m40mlength), single-screw oceanographic vessel, focusing on directionality and effects of maneuvers. The measurements utilized a set of four, self-contained buoys with GPS positioning, each recording two calibrated hydrophones with effective acoustic bandwidth from 150Hzto5kHz150Hzto5kHz. In straight, constant-speed runs at speeds up to 6.2ms−16.2ms−1, the ship source spectra showed spectral levels in reasonable agreement with reference spectra. The broadband source level was observed to increase as approximately speed to the fourth power over the range of 2.6–6.1ms−12.6–6.1ms−1, partially biased at low speeds by nonpropulsion machinery signals. Source directionality patterns were extracted from variations in source spectra while the ship transited past the buoy field. The observed spectral source levels exhibited a broadside maximum, with bow and stern aspect reduced by approximately 12–9dB12–9dB, respectively, independent of frequency. An empirical model is proposed assuming that spectral source levels exhibit simultaneous variations in aspect angle, speed, and turn rate. After correction for source directionality and speed during turning maneuvers, an excess of up to 18dB18dB in one-third octave source levels was observed.

Veirs, S., Veirs, V., & Wood, J. D. (2016). Ship noise extends to frequencies used for echolocation by endangered killer whales. *PeerJ, 4*, e1657. https://doi.org/10.7717/peerj.1657

Combining calibrated hydrophone measurements with vessel location data from the Automatic Identification System, we estimate underwater sound pressure levels for 1,582 unique ships that transited the core critical habitat of the endangered Southern Resident killer whales during 28 months between March, 2011, and October, 2013. Median received spectrum levels of noise from 2,809 isolated transits are elevated relative to median background levels not only at low frequencies (20-30 dB re 1 microPa(2)/Hz from 100 to 1,000 Hz), but also at high frequencies (5-13 dB from 10,000 to 96,000 Hz). Thus, noise received from ships at ranges less than 3 km extends to frequencies used by odontocetes. Broadband received levels (11.5-40,000 Hz) near the shoreline in Haro Strait (WA, USA) for the entire ship population were 110 +/- 7 dB re 1 microPa on average. Assuming near-spherical spreading based on a transmission loss experiment we compute mean broadband source levels for the ship population of 173 +/- 7 dB re 1 microPa 1 m without accounting for frequency-dependent absorption. Mean ship speed was 7.3 +/- 2.0 m/s (14.1 +/- 3.9 knots). Most ship classes show a linear relationship between source level and speed with a slope near +2 dB per m/s (+1 dB/knot). Spectrum, 1/12-octave, and 1/3-octave source levels for the whole population have median values that are comparable to previous measurements and models at most frequencies, but for select studies may be relatively low below 200 Hz and high above 20,000 Hz. Median source spectrum levels peak near 50 Hz for all 12 ship classes, have a maximum of 159 dB re 1 microPa(2)/Hz @ 1 m for container ships, and vary between classes. Below 200 Hz, the class-specific median spectrum levels bifurcate with large commercial ships grouping as higher power noise sources. Within all ship classes spectrum levels vary more at low frequencies than at high frequencies and the degree of variability is almost halved for classes that have smaller speed standard deviations. This is the first study to present source spectra for populations of different ship classes operating in coastal habitats, including at higher frequencies used by killer whales for both communication and echolocation.

Wales, S. C., & Heitmeyer, R. M. (2002). An ensemble source spectra model for merchant ship-radiated noise. *The Journal of the Acoustical Society of America, 111*(3), 1211-1231. https://doi.org/10.1121/1.1427355

This paper presents an evaluation of the classical model for determining an ensemble of the broadband source spectra of the sound generated by individual ships and proposes an alternate model to overcome the deficiencies in the classical model. The classical model, proposed by Ross [Mechanics of Underwater Noise (Pergamon, New York, 1976)] postulates that the source spectrum for an individual ship is proportional to a baseline spectrum with the constant of proportionality determined by a power-law relationship on the ship speed and length. The model evaluation, conducted on an ensemble of 54 source spectra over a 30–1200-Hz to 1200-Hz frequency band, shows that this assumption yields large rms errors in the broadband source level for the individual ships and significantly overestimates the variability in the source level across the ensemble of source spectra. These deficiencies are a consequence of the negligible correlation between the source level and the ship speed and the source level and the ship length. The alternate model proposed here represents the individual ship spectra by a modified rational spectrum where the poles and zeros are restricted to the real axis and the exponents of the terms are not restricted to integer values. An evaluation of this model on the source spectra ensemble indicates that the rms errors are significantly less than those obtained with any model where the frequency dependence is represented by a single baseline spectrum. Furthermore, at high frequencies (400 to 1200 Hz), a single-term rational spectrum model is sufficient to describe the frequency dependence and, at the low frequencies (30 to 400 Hz), there is only a modest reduction in the rms error for a higher order model. Finally, a joint probability density on the two parameters of the single term model based on the measured histograms of these parameters is proposed. This probability density provides a mechanism for generating an ensemble of ship spectra.

Wittekind, D. K. (2014). A Simple Model for the Underwater Noise Source Level of Ships. *Journal of Ship Production and Design, 30*(1), 7-14. https://doi.org/10.5957/JSPD.30.1.120052

Underwater noise becomes a field of growing concern because of the possible interaction with sound vocalization of marine mammals. Modeling the effect of shipping noise being a predominant contribution worldwide requires more than statistics of measured ships in the field. This article is an attempt to characterize the underwater radiated noise level of a ship by relating spectral components of noise to naval architectural features of the ship.

World Wildlife Fund. *Underwater Noise from Arctic Shipping Impacts, Regulations and Recommendations*. (2017). Retrieved from https://www.issuelab.org/resources/27416/27416.pdf

This source is brief review of underwater noise and its impact on marine mammals. The report summarizes information of anthropogenic underwater sound from different vessel types and reviews hearing and vocalizing ranges of marine mammals. It provides an overview of mitigation measures that can help reduce radiated noise, future challenges, and a list of recommendations.

Section III: Impact on Marine Life

Andersen, J. H., Berzaghi, F., Christensen, T., Geertz-Hansen, O., Mosbech, A., Stock, A., . . . Wisz, M. S. (2017). Potential for cumulative effects of human stressors on fish, sea birds and marine mammals in Arctic waters. *Estuarine, Coastal and Shelf Science, 184*, 202-206. https://doi.org/10.1016/j.ecss.2016.10.047

We estimate the potential for cumulative impacts from multiple anthropogenic stressors on fish, sea birds, and marine mammals in the western, southern and south-eastern parts of marine waters around Greenland. The analysis is based on a comprehensive data set representing five human activities including two proxies for climate change, as well as 25 key animal species including commercially important fish and top predators such as sea birds and marine mammals. Anthropogenic stressors are concentrated in two areas: the offshore waters south of Greenland, and especially the western coast from the Qeqertarsuaq (Disko Island) area to the southern tip of Greenland. The latter is also an area of high importance for many key species, thus the potential for cumulative impacts is high along Greenland's west coast. We conclude that this area should be under high scientific scrutiny and conservation attention. Our study is a first attempt and a stepping-stone towards more detailed and accurate estimates of the effects of multiple human stressors on Arctic marine ecosystems.

Anderwald, P., Brandecker, A., Coleman, M., Collins, C., Denniston, H., Haberlin, M. D., . . . Walshe, L. (2013). Displacement responses of a mysticete, an adontocete, and a phacid seal to construction-related vessel traffic. *Endangered Species Research, 21*(3), 231-240. https://doi.org/10.3354/esr00523

Marine construction works often lead to temporary increases in vessel traffic, which, in addition to the construction activity itself, contribute to underwater ambient noise in the affected area and increase the risk of vessel collision for marine mammals. Using a 3 yr data set of cliff-based observations, we investigated whether the presence/absence of minke whales, bottlenose dolphins and grey seals varied with the overall number and type of vessels present during the construction of an underwater gas pipeline through a bay on the northwest coast of Ireland. Results from binary generalized estimation equations showed a positive relationship between the presence of bottlenose dolphins and the overall number of boats, as well as the number of construction vessels. However, the presence of the 2 taxa with higher hearing sensitivity at low frequencies—minke whales and grey seals—was negatively correlated with the total number of boats and the number of utility vessels (as well as the number of fishing boats in the case of minke whales). While bottlenose dolphins may have been attracted to either the vessels per se or high prey concentrations coinciding with construction activities, both minke whales and grey seals appear to have been displaced by high levels of vessel traffic, most likely due to noise disturbance. Careful consideration of mitigation measures, especially for taxa with low-frequency hearing, is therefore essential in the planning phase of offshore construction activities, which should also take local circumstances into account.

Blundell, G. M., & Pendleton, G. W. (2015). Factors Affecting Haul-Out Behavior of Harbor Seals (Phoca vitulina) in Tidewater Glacier Inlets in Alaska: Can Tourism Vessels and Seals Coexist? *PLoS One, 10*(5), e0125486. https://doi.org/10.1371/journal.pone.0125486

Large numbers of harbor seals (Phoca vitulina) use habitat in tidewater glaciers in Alaska for pupping, breeding, and molting. Glacial fjords are also popular tourist destinations; however, visitation by numerous vessels can result in disturbance of seals during critical life-history phases. We explored factors affecting haul-out behavior of harbor seals at a glacial site frequented by tourism vessels. In 2008-10, we deployed VHF transmitters on 107 seals in Endicott Arm, Alaska. We remotely monitored presence and haul-out behavior of tagged seals and documented vessel presence with time-lapse cameras. We evaluated the influence of environmental and physical factors on the probability of being hauled out, duration of haul-out bouts, and as factors associated with the start and end of a haulout. Location, season, hour, and interactions of location by year, season, hour, and sex significantly influenced haul-out probability, as did ice, weather, and vessels. Seals were more likely to be hauled out with greater ice availability during the middle of the day, and less likely to be hauled out if vessels were present. Cruise ships had the strongest negative effect; however, most vessel types negatively affected haul-out probability. Haul-out duration was longest in association with starting on incoming tides, clear skies, no precipitation, occurring in the middle of the day, and ending in the late afternoon or evening. End of haulouts was associated with increasing cloud cover, low ice availability, and vessel presence; large-sized tourism vessels or all-vessel-types combined were significant predictors of ending a haul-out bout. Probability of being hauled out was highest in June, during pupping season. Potential disturbances of harbor seals could be reduced, enabling longer resting times for seals and fewer interruptions for nursing pups, if vessels focused the majority of visits to glacial habitat to before or after the hours of 08:00-17:00 or, less optimally, 09:00-16:00.

Castellote, M., Clark, C. W., & Lammers, M. O. (2012). Acoustic and behavioural changes by fin whales (Balaenoptera physalus) in response to shipping and airgun noise. *Biological Conservation, 147*(1), 115-122. https://doi.org/10.1016/j.biocon.2011.12.021

Non-lethal behavioral effects of underwater noise in marine mammals are difficult to measure. Here we report acoustic and behavioral changes by fin whales in response to two different types of anthropogenic noise: shipping and airgun noise. Acoustic features of fin whale 20-Hz song notes recorded in the Mediterranean Sea and Northeast Atlantic Ocean were compared for areas with different shipping noise levels, different traffic intensities in the Strait of Gibraltar and during a seismic airgun array survey. In high noise conditions 20-Hz note duration shortened, bandwidth decreased, center frequency decreased and peak frequency decreased. Similar results were obtained in 20-Hz song notes recorded during a 10-day seismic survey. During the first 72 h of the survey, a steady decrease in song received levels and bearings to singers indicated that whales moved away from the airgun array source and out of our detection area, and this displacement persisted for a time period well beyond the 10-day duration of seismic airgun activity. This study provides evidence that male fin whales from two different subpopulations modify song characteristics under increased background noise conditions, and that under seismic airgun activity conditions they leave an area for an extended period. We hypothesize that fin whale acoustic communication is modified to compensate for increased background noise and that a sensitization process may play a role in the observed temporary displacement. The observed acoustic and behavioral changes of this endangered species are discussed in the context of reproduction success and population survival.

Chen, F., Shapiro, G. I., Bennett, K. A., Ingram, S. N., Thompson, D., Vincent, C., . . . Embling, C. B. (2017). Shipping noise in a dynamic sea: a case study of grey seals in the Celtic Sea. *Marine Pollution Bulletin, 114*(1), 372-383. https://doi.org/10.1016/j.marpolbul.2016.09.054

Shipping noise is a threat to marine wildlife. Grey seals are benthic foragers, and thus experience acoustic noise throughout the water column, which makes them a good model species for a case study of the potential impacts of shipping noise. We used ship track data from the Celtic Sea, seal track data and a coupled ocean-acoustic modelling system to assess the noise exposure of grey seals along their tracks. It was found that the animals experience step changes in sound levels up to ~20dB at a frequency of 125Hz, and ~10dB on average over 10-1000Hz when they dive through the thermocline, particularly during summer. Our results showed large seasonal differences in the noise level experienced by the seals. These results reveal the actual noise exposure by the animals and could help in marine spatial planning.

Clark, C. W., Berchok, C. L., Blackwell, S. B., Hannay, D. E., Jones, J., Ponirakis, D., & Stafford, K. M. (2015). A year in the acoustic world of bowhead whales in the Bering, Chukchi and Beaufort seas. *Progress in Oceanography, 136*, 223-240. https://doi.org/10.1016/j.pocean.2015.05.007

Bowhead whales, Balaena mysticetus, in the Bering–Chukchi–Beaufort (BCB) population, experience a variable acoustic environment among the regions they inhabit throughout the year. A total of 41,698 h of acoustic data were recorded from 1 August 2009 through 4 October 2010 at 20 sites spread along a 2300 km transect from the Bering Sea to the southeast Beaufort Sea. These data represent the combined output from six research teams using four recorder types. Recorders sampled areas in which bowheads occur and in which there are natural and anthropogenic sources producing varying amounts of underwater noise. We describe and quantify the occurrence of bowheads throughout their range in the Bering, Chukchi, and Beaufort seas over a 14-month period by aggregating our acoustic detections of bowhead whale sounds. We also describe the spatial–temporal variability in the bowhead acoustic environment using sound level measurements within a frequency band in which their sounds occur, by dividing a year into three, 4-month seasons (Summer–Fall 2009, August–November 2009: Winter 2009–2010, December 2009–March 2010: and Spring–Summer 2010, April–July 2010) and their home range into five zones. Statistical analyses revealed no significant relationship between acoustic occurrence, distance offshore, and water depth during Summer–Fall 2009, but there was a significant relationship during Spring– Summer 2010. A continuous period with elevated broadband sound levels lasting ca. 38 days occurred in the Bering Sea during the Winter 2009–2010 season as a result of singing bowheads, while a second period of elevated levels lasting at least 30 days occurred during the early spring–summer season as a result of singing bearded seals. The lowest noise levels occurred in the Chukchi Sea from the latter part of November into May. In late summer 2009 very faint sounds from a seismic airgun survey approximately 700 km away in the eastern Beaufort Sea were detected on Chukchi recorders. Throughout the year, but most obviously during the November into May period, clusters of intermittent, nearly synchronized, high-level events were evident on multiple recorders hundreds of miles apart. In some cases, these clusters occurred over 2–5 day periods and appear to be associated with high wind conditions.

Committee on Characterizing Biologically Significant Marine Mammal Behavior, National Research Council (2005). *Marine Mammal Populations and Ocean Noise: Determining When Noise Causes Biologically Significant Effects*. Washington, DC: The National Academies Press. Retrieved from https://www.nap.edu/catalog/11147.html

Attention has been drawn to the subject of how ocean noise affects marine mammals by a series of marine mammal strandings, lawsuits, and legislative hearings, and most recently, the report from the U.S. Commission on Ocean Policy. One way to assess the impact of ocean noise is to consider whether it causes changes in animal behavior that are "biologically significant," that is, those that affect an animal's ability to grow, survive, and reproduce. This report offers a conceptual model designed to clarify which marine mammal behaviors are biologically significant for conservation purposes. The report is intended to help scientists and policymakers interpret provisions of the federal Marine Mammal Protection Act.

Cosens, S., & Dueck, L. (1993). Icebreaker Noise in Lancaster Sound, N.W.T., Canada: Implications for Marine Mammal Behavior. *Marine Mammal Science, 9*(3), 285-300. https://doi.org/10.1111/j.1748-7692.1993.tb00456.x

In 1986, we recorded the MV Arctic, CCGS des Grosseilliers and MV Lady Franklin during routine icebreaking operations and travel to and from the mine at Nanisivik, Baffin Island, Northwest Terrirories, Canada. We found that the Arctic generated more high frequency noise than did the other vessels we recorded. Monitoring of vessel noise levels indicated that belugas and, probably, narwhals should be able to detect the high frequency components of Arctic noise at least as far as 25 to 30 km from the source. The ability of whales to detect the MV Arctic at long distances may explain why belugas and narwhals in Lancasrer Sound seem to react to ships at longer distances than do other stocks of arctic whales.

Culloch, R. M., Anderwald, P., Brandecker, A., Haberlin, D., McGovern, B., Pinfield, R., . . . Cronin, M. (2016). Effect of construction-related activities and vessel traffic on marine mammals. *Marine Ecology Progress Series, 549*, 231-242. https://doi.org/10.3354/meps11686

During the construction of a gas pipeline from an offshore gas field in northwest Ireland, a year-round shore-based marine mammal monitoring programme was undertaken. Using 6 yr of data, generalised estimating equations-generalised additive models (GEE-GAMs) were used to investigate if construction-related activity and vessel traffic influenced the occurrence of common dolphin, minke whale, harbour porpoise and grey seal within the area where the pipeline made landfall. Construction-related activity reduced harbour porpoise and minke whale presence, whilst an increase in vessel numbers (independent of construction-related activity) reduced common dolphin presence. All species showed some degree of annual and seasonal variation in occurrence. For common dolphins and harbour porpoises, we found similar seasonal patterns to those reported in broader Irish waters, which tentatively suggests that seasonal patterns persisted irrespective of construction-related activity or vessel traffic, indicating that any impact might have been only short-term. Multiple construction-related activities occurred simultaneously in different areas, and the inter-annual variation may, in part, be an indication of variation in species' response to particular activities, their intensity and their location. However, the precise location of the activities was not regularly recorded, limiting our ability to investigate the fine-scale spatio−temporal impact of the diverse range of construction-related activities. Improved communication and coordination between developers, regulators and scientists will help ensure that monitoring programmes are effective and efficient, to better inform our understanding of potential impacts and to mitigate effectively against them for future developments.

Ellison, W. T., Racca, R., Clark, C. W., Streever, B., Frankel, A. S., Fleishman, E., . . . 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*, 95-108. https://doi.org/10.3354/esr00727

Potential responses of marine mammals to anthropogenic underwater sound are usually assessed by researchers and regulators on the basis of exposure to a single, relatively loud sound source. However, marine mammals typically receive sounds from multiple, dynamic sources. We developed a method to aggregate modeled sounds from multiple sources and estimate the sound levels received by individuals. To illustrate the method, we modeled the sound fields of 9 sources associated with oil development and estimated the sound received over 47 d by a population of 10000 simulated bowhead whales *Balaena mysticetus* on their annual migration through the Alaskan Beaufort Sea. Empirical data were sufficient to parameterize simulations of the distribution of individual whales over time and their range of movement patterns. We ran 2 simulations to estimate the sound exposure history and distances traveled by bowhead whales: one in which they could change their movement paths (avert) in response to set levels of sound and one in which they could not avert. When animals could not avert, about 2% of the simulated population was exposed to root mean square (rms) sound pressure levels (SPL) ≥180 dB re 1 μPa, a level that regulators in the U.S. often associate with injury. When animals could avert from sound levels that regulators often associate with behavioral disturbance (rms SPL >160 dB re 1 μPa), <1% of the simulated population was exposed to levels associated with injury. Nevertheless, many simulated bowhead whales received sound levels considerably above ambient throughout their migration. Our method enables estimates of the aggregated level of sound to which populations are exposed over extensive areas and time periods.

Erbe, C. (2003). *Assessment of Bioacoustic Impact of Ships on Humpback Whales in Glacier Bay, Alaska*. Retrieved from https://www.nps.gov/glba/learn/nature/loader.cfm?csModule=security/getfile&PageID=846005

The objective of this study was to assess whether ships travelling in Glacier Bay, Alaska, had any acoustic impact on humpback whales. The type of bioacoustic impact and impact ranges were determined. This study made use of a software package that had originally been developed by the author for the Department of Fisheries and Oceans Canada, for the purpose of assessing anthropogenic (human-caused), bioacoustic impact on the marine environment. However, due to limitations in knowledge about the hearing thresholds of humpback whales, the model is based on a transfer of data from odontocetes, pinnipeds and terrestrial mammals to humpback whales. The feasibility and accuracy of such an interspecies transfer is highly debatable. Therefore, the results of this modeling exercise should not be used for environmental decision-making.

Erbe, C., & Farmer, D. M. (2000). Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea. *The Journal of the Acoustical Society of America, 108*(3 Pt 1), 1332-1340. https://doi.org/10.1121/1.1288938

A software model estimating zones of impact on marine mammals around man-made noise [C. Erbe and D. M. Farmer, J. Acoust. Soc. Am. 108, 1327-1331 (2000)] is applied to the case of icebreakers affecting beluga whales in the Beaufort Sea. Two types of noise emitted by the Canadian Coast Guard icebreaker Henry Larsen are analyzed: bubbler system noise and propeller cavitation noise. Effects on beluga whales are modeled both in a deep-water environment and a near-shore environment. The model estimates that the Henry Larsen is audible to beluga whales over ranges of 35-78 km, depending on location. The zone of behavioral disturbance is only slightly smaller. Masking of beluga communication signals is predicted within 14-71-km range. Temporary hearing damage can occur if a beluga stays within 1-4 km of the Henry Larsen for at least 20 min. Bubbler noise impacts over the short ranges quoted; propeller cavitation noise accounts for all the long-range effects. Serious problems can arise in heavily industrialized areas where animals are exposed to ongoing noise and where anthropogenic noise from a variety of sources adds up.

Finneran, J. J. (2015). Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. *The Journal of the Acoustical Society of America, 138*(3), 1702-1726. https://doi.org/10.1121/1.4927418

One of the most widely recognized effects of intense noise exposure is a noise-induced threshold shift-an elevation of hearing thresholds following cessation of the noise. Over the past twenty years, as concerns over the potential effects of human-generated noise on marine mammals have increased, a number of studies have been conducted to investigate noise-induced threshold shift phenomena in marine mammals. The experiments have focused on measuring temporary threshold shift (TTS)-a noise-induced threshold shift that fully recovers over time-in marine mammals exposed to intense tones, band-limited noise, and underwater impulses with various sound pressure levels, frequencies, durations, and temporal patterns. In this review, the methods employed by the groups conducting marine mammal TTS experiments are described and the relationships between the experimental conditions, the noise exposure parameters, and the observed TTS are summarized. An attempt has been made to synthesize the major findings across experiments to provide the current state of knowledge for the effects of noise on marine mammal hearing.

Frankel, A. S., & Gabriele, C. M. (2017). Predicting the acoustic exposure of humpback whales from cruise and tour vessel noise in Glacier Bay, Alaska, under different management strategies. *Endangered Species Research, 34*, 397-415. https://doi.org/10.3354/esr00857

Vessel traffic management regimes intended to protect baleen whales can have unexpected consequences on whale exposure to underwater noise. Using the Acoustic Integration Model, we simulated whale and vessel movements in Glacier Bay National Park (GBNP). We estimated vessel noise exposures to humpback whales Megaptera novaeangliae while varying the number, speed (13 vs. 20 knots [kn]), and timing of cruise ships, and keeping a constant number, speed, and timing of smaller tour vessels. Using calibrated noise signatures for each vessel and the known sound velocity profile and bathymetry of Glacier Bay, we estimated received sound levels for each simulated whale every 15 s in a 24 h period. Simulations with fast ships produced the highest maximal sound pressure level (MSPL) and cumulative sound exposure levels (CSEL). Ships travelling at 13 kn produced CSEL levels 3 times lower than those traveling at 20 kn. We demonstrated that even in cases where a ship is only a few dB quieter at a slower speed, CSEL is lower, but the ship's transit may take substantially longer. Synchronizing ship arrival times had little effect on CSEL or MSPL but appreciably decreased cumulative sound exposure time (CSET). Overall, our results suggest that the most effective way to reduce humpback whale acoustic exposure in GBNP is to reduce the numbers of cruise ships or their speed, although adjusting ship schedules may also be beneficial. Marine protected area managers may find these results illustrative or adapt these methods to better understand the acoustic effects of specific vessel management circumstances.

Götz, T., Hastie, G., Hatch, L. T., Raustein, O., Southall, B. L., Tasker, M., . . . Fredheim, B. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. In *OSPAR Biodiversity Series* (Vol. 441). Retrieved from https://www.ospar.org/documents?v=7147

Many marine organisms, including most marine mammals (whales, dolphins, porpoises and pinnipeds), many marine fish species, and even some invertebrates, use sound for a variety of purposes, for example in communication, to locate mates, to search for prey, to avoid predators and hazards, and for short- and long-range navigation (for reviews see for example Tyack & Clark 2000; Popper et al. 2001; Würsig & Richardson 2002; Popper et al. 2004). Depending on the intensity (sound pressure level) at the source, the pitch (frequency) and the distance between source and receiver, sound can potentially affect marine organisms in various ways. In this regard, it is also important to consider the cumulative effect when a sound source is long-lasting or repeated in time (Richardson et al. 1995). Concerns on the potential adverse effects of anthropogenic noise on marine life have been raised from within the scientific community since the 1970s, and research on the topic expanded in the 1980s (e.g. Payne & Webb 1971; Richardson et al. 1985). During the last decade the topic has been investigated extensively by a number of scientific institutions, governmental agencies and intergovernmental bodies, with major reviews dealing with the effects of sound on fish and marine mammals (e.g. Richardson et al. 1995; Würsig & Richardson 2002; Popper et al. 2004; Hastings & Popper 2005; Hildebrand 2005; ICES 2005; NRC 2003, 2005;

Wahlberg & Westerberg 2005; Thomsen et al. 2006; Madsen et al. 2006; Southall et al. 2007; Nowacek et al. 2007). These studies have documented both the presence and absence of physiological effects and behavioral responses of marine mammals, fish, and even invertebrates to various sound signals and have set the scene for discussions among scientists, stakeholders and policy makers on how to address potential impacts of underwater noise and how to develop meaningful mitigation measures within regulatory frameworks.

Halliday, W. D., Insley, S. J., Hilliard, R. C., de Jong, T., & Pine, M. K. (2017). Potential impacts of shipping noise on marine mammals in the western Canadian Arctic. *Marine Pollution Bulletin*. https://doi.org/10.1016/j.marpolbul.2017.09.027

As the Arctic warms and sea ice decreases, increased shipping will lead to higher ambient noise levels in the Arctic Ocean. Arctic marine mammals are vulnerable to increased noise because they use sound to survive and likely evolved in a relatively quiet soundscape. We model vessel noise propagation in the proposed western Canadian Arctic shipping corridor in order to examine impacts on marine mammals and marine protected areas (MPAs). Our model predicts that loud vessels are audible underwater when >100km away, could affect marine mammal behaviour when within 2km for icebreakers vessels, and as far as 52km for tankers. This vessel noise could have substantial impacts on marine mammals during migration and in MPAs. We suggest that locating the corridor farther north, use of marine mammal observers on vessels, and the reduction of vessel speed would help to reduce this impact.

Hatch, L. T., Clark, C. W., Van Parijs, S. M., Frankel, A. S., & Ponirakis, D. W. (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

The effects of chronic exposure to increasing levels of human-induced underwater noise on marine animal populations reliant on sound for communication are poorly understood. We sought to further develop methods of quantifying the effects of communication masking associated with human-induced sound on contact-calling North Atlantic right whales (Eubalaena glacialis) in an ecologically relevant area (~10,000 km(2)) and time period (peak feeding time). We used an array of temporary, bottom-mounted, autonomous acoustic recorders in the Stellwagen Bank National Marine Sanctuary to monitor ambient noise levels, measure levels of sound associated with vessels, and detect and locate calling whales. We related wind speed, as recorded by regional oceanographic buoys, to ambient noise levels. We used vessel-tracking data from the Automatic Identification System to quantify acoustic signatures of large commercial vessels. On the basis of these integrated sound fields, median signal excess (the difference between the signal-to-noise ratio and the assumed recognition differential) for contact-calling right whales was negative (-1 dB) under current ambient noise levels and was further reduced (-2 dB) by the addition of noise from ships. Compared with potential communication space available under historically lower noise conditions, calling right whales may have lost, on average, 63-67% of their communication space. One or more of the 89 calling whales in the study area was exposed to noise levels >/=120 dB re 1 muPa by ships for 20% of the month, and a maximum of 11 whales were exposed to noise at or above this level during a single 10-min period. These results highlight the limitations of exposure-threshold (i.e., dose-response) metrics for assessing chronic anthropogenic noise effects on communication opportunities. Our methods can be used to integrate chronic and wide-ranging noise effects in emerging ocean-planning forums that seek to improve management of cumulative effects of noise on marine species and their habitats.

Huntington, H. P. (2009). A preliminary assessment of threats to arctic marine mammals and their conservation in the coming decades. *Marine Policy, 33*(1), 77-82. https://doi.org/10.1016/j.marpol.2008.04.003

Over the next several decades, arctic marine mammals will face threats from six areas of human influence: climate change, environmental contaminants, offshore oil and gas activities, shipping, hunting, and commercial fisheries. This paper reviews these factors, the nature and magnitude of the threats they pose, current scientific understanding and management of those threats, and the potential for effective conservation action. Climate change, offshore oil and gas activities, and commercial fisheries likely pose the greatest threats. Addressing the combined effects of all six factors, however, will be particularly difficult but essential to prevent declines beyond those that have already occurred.

International Whaling Commission (2014) Report of the IWC Workshop on Impacts of Increased Marine Activities on Cetaceans in the Arctic. Anchorage, Alaska. Retrieved from https://www.nmfs.noaa.gov/ia/slider_stories/2014/09/workshop_report_iwc_arctic.pdf

The Workshop was held from 6-7 March 2014, in Anchorage, Alaska, USA. The workshop aimed to facilitate an open dialogue amongst stakeholders on inter alia what research has been/is being conducted; what management measures have been/are being implemented; what knowledge gaps and concerns exist; and what information the IWC can provide to assist managers in preparing for the expected impacts

Kunc, H. P., McLaughlin, K. E., & Schmidt, R. (2016). Aquatic noise pollution: implications for individuals, populations, and ecosystems. *Proceedings of the Royal Society B: Biological Sciences, 283*(1836). https://doi.org/10.1098/rspb.2016.0839

Anthropogenically driven environmental changes affect our planet at an unprecedented scale and are considered to be a key threat to biodiversity. According to the World Health Organization, anthropogenic noise is one of the most hazardous forms of anthropogenically driven environmental change and is recognized as a major global pollutant. However, crucial advances in the rapidly emerging research on noise pollution focus exclusively on single aspects of noise pollution, e.g. on behaviour, physiology, terrestrial ecosystems, or on certain taxa. Given that more than two-thirds of our planet is covered with water, there is a pressing need to get a holistic understanding of the effects of anthropogenic noise in aquatic ecosystems. We found experimental evidence for negative effects of anthropogenic noise on an individual's development, physiology, and/or behaviour in both invertebrates and vertebrates. We also found that species differ in their response to noise, and highlight the potential underlying mechanisms for these differences. Finally, we point out challenges in the study of aquatic noise pollution and provide directions for future research, which will enhance our understanding of this globally present pollutant.

Middel, H., & Verones, F. (2017). Making Marine Noise Pollution Impacts Heard: The Case of Cetaceans in the North Sea within Life Cycle Impact Assessment. *Sustainability, 9*(7). https://doi.org/10.3390/su9071138

Oceans represent more than 95% of the world’s biosphere and are among the richest sources of biodiversity on Earth. However, human activities such as shipping and construction of marine infrastructure pose a threat to the quality of marine ecosystems. Due to the dependence of most marine animals on sound for their communication, foraging, protection, and ultimately their survival, the effects of noise pollution from human activities are of growing concern. Life cycle assessment (LCA) can play a role in the understanding of how potential environmental impacts are related to industrial processes.

However, noise pollution impacts on marine ecosystems have not yet been taken into account. This paper presents a first approach for the integration of noise impacts on marine ecosystems into the LCA framework by developing characterization factors (CF) for the North Sea. Noise pollution triggers a large variety of impact pathways, but as a starting point and proof-of-concept we assessed impacts on the avoidance behaviour of cetaceans due to pile-driving during the construction of offshore windfarms in the North Sea. Our approach regards the impact of avoidance behaviour as a temporary loss of habitat, and assumes a temporary loss of all individuals within that habitat from the total regional population. This was verified with an existing model that assessed the population-level effect of noise pollution on harbour porpoises (Phocoena phocoena) in the North Sea. We expanded our CF to also include other cetacean species and tested it in a case study of the construction of an offshore windfarm (Prinses Amalia wind park). The total impact of noise pollution was in the same order of magnitude as impacts on other ecosystems from freshwater eutrophication, freshwater ecotoxicity, terrestrial acidification, and terrestrial ecotoxicity. Although there are still many improvements to be made to this approach, it provides a basis for the implementation of noise pollution impacts in an LCA framework, and has the potential to be expanded to other world regions and impact pathways.

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

The recent loss of Arctic sea ice provides humans unprecedented access to the region. Marine mammals rely on sound as a primary sensory modality, and the noise associated with increasing human activities offshore can interfere with vital life functions. Many coastal communities rely on marine mammals for food and cultural identity, and subsistence hunters have expressed strong concerns that underwater sound from human activities negatively affects both the animals and hunting success. Federal regulations require scientists and oil and gas operators to acquire incidental harassment authorizations for activities that may disturb marine mammals. Currently, authorization requests are focused on the impacts of sound from activities considered in isolation of one another, and this precludes any possibility of a meaningful analysis of the cumulative impacts from multiple sources. We propose a new assessment framework that is based on the acoustic habitats that constitute the aggregate sound field from multiple sources, compiled at spatial and temporal scales consistent with the ecology of Arctic marine mammals.

International Maritime Organization (IMO). (2010). *Noise from commercial shipping and its adverse impacts on marine life.* Marine Environment Protection Committee. Retrieved from https://www.ascobans.org/fr/document/imo-mepc-61-noise-commercial-shipping-and-its-adverse-impacts-marine-life-%E2%80%93-report

This document is the report of the Correspondence Group on the issue of "Noise from commercial shipping and its adverse impact on marine life". The Correspondence Group was established to identify and address ways to minimize the incidental introduction of noise from commercial shipping operations into the marine environment to reduce potential adverse impacts on marine life.

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

With the growing utilization and exploration of the ocean, anthropogenic noise increases significantly and gives rise to a new kind of pollution: noise pollution. In this review, the source and the characteristics of noise in the sea, the significance of sound to marine organisms, and the impacts of noise on marine organisms are summarized. In general, the studies about the impact of noise on marine organisms are mainly on adult fish and mammals, which account for more than 50% and 20% of all the cases reported. Studies showed that anthropogenic noise can cause auditory masking, leading to cochlear damage, changes in individual and social behavior, altered metabolisms, hampered population recruitment, and can subsequently affect the health and service functions of marine ecosystems. However, since different sampling methodologies and unstandardized measurements were used and the effects of noise on marine organisms are dependent on the characteristics of the species and noise investigated, it is difficult to compare the reported results. Moreover, the scarcity of studies carried out with other species and with larval or juvenile individuals severely constrains the present understanding of noise pollution. In addition, further studies are needed to reveal in detail the causes for the detected impacts.

Pine, M. K., Jeffs, A. G., Wang, D., & Radford, C. A. (2016). The potential for vessel noise to mask biologically important sounds within ecologically significant embayments. *Ocean & Coastal Management, 127*, 63-73. https://doi.org/10.1016/j.ocecoaman.2016.04.007

With underwater sound levels rising due to increasing vessel activity, there is a pressing need to better understand the potential distances for which masking impacts on acoustically sensitive marine life may occur, especially in embayments with shipping activity. Given the known detrimental noise impacts on the marine environment, managing underwater noise pollution has been identified as a pressing conservation issue. Therefore, baseline underwater noise measurements from a range of vessels in the Hauraki Gulf Marine Park, a large and ecologically significant embayment (1.2 M Ha) in New Zealand, were undertaken and used to estimate detection distances for which potential auditory masking in dolphins, fish and crustaceans is expected. Sound pressure measurements and octave analyses of recorded vessel noise revealed considerable energy below 5 kHz at source levels of approximately 30 dB above the highest threshold in dolphins and fish. Measureable increases to background sound levels below 5 kHz of at least 54 ± 5.8 dB (mean ± SD) at the source were estimated to have a masking effect inside a minimum 90 m within the busy inner Gulf and 1240 m within the quieter outer Gulf. Impact zones increased considerably for dolphins with assumed detection thresholds equal to ambient sound pressures. These findings show that the sound emanating from both recreational and commercial vessels within the Hauraki Gulf will be significantly raising background sound levels and is likely to have a wideranging masking impact on marine life. These findings have significance for embayments worldwide for which vessel activity is a common feature.

Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., . . . 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

Baleen whales (Mysticeti) communicate using low-frequency acoustic signals. These long-wavelength sounds can be detected over hundreds of kilometers, potentially allowing contact over large distances. Low-frequency noise from large ships (20-200 Hz) overlaps acoustic signals used by baleen whales, and increased levels of underwater noise have been documented in areas with high shipping traffic. Reported responses of whales to increased noise include: habitat displacement, behavioral changes and alterations in the intensity, frequency and intervals of calls. However, it has been unclear whether exposure to noise results in physiological responses that may lead to significant consequences for individuals or populations. Here, we show that reduced ship traffic in the Bay of Fundy, Canada, following the events of 11 September 2001, resulted in a 6 dB decrease in underwater noise with a significant reduction below 150 Hz. This noise reduction was associated with decreased baseline levels of stress-related faecal hormone metabolites (glucocorticoids) in North Atlantic right whales (Eubalaena glacialis). This is the first evidence that exposure to low-frequency ship noise may be associated with chronic stress in whales, and has implications for all baleen whales in heavy ship traffic areas, and for recovery of this endangered right whale population.

Small, R. J., Brost, B., Hooten, M., Castellote, M., & Mondragon, J. (2017). Potential for spatial displacement of Cook Inlet beluga whales by anthropogenic noise in critical habitat. *Endangered Species Research, 32*, 43-57. https://doi.org/10.3354/esr00786

The population of beluga whales in Cook Inlet, Alaska, USA, declined by nearly half in the mid-1990s, primarily from an unsustainable harvest, and was listed as endangered in 2008. In 2014, abundance was ~340 whales, and the population trend during 1999−2014 was −1.3% yr−1. Cook Inlet beluga whales are particularly vulnerable to anthropogenic impacts, and noise that has the potential to reduce communication and echolocation range considerably has been documented in critical habitat; thus, noise was ranked as a high potential threat in the Cook Inlet beluga Recovery Plan. The current recovery strategy includes research on effects of threats potentially limiting recovery, and thus we examined the potential impact of anthropogenic noise in critical habitat, specifically, spatial displacement. Using a subset of data on anthropogenic noise and beluga detections from a 5 yr acoustic study, we evaluated the influence of noise events on beluga occupancy probability. We used occupancy models, which account for factors that affect detection probability when estimating occupancy, the first application of these models to examine the potential impacts of anthropogenic noise on marine mammal behavior. Results were inconclusive, primarily because beluga detections were relatively infrequent. Even though noise metrics (sound pressure level and noise duration) appeared in high-ranking models as covariates for occupancy probability, the data were insufficient to indicate better predictive ability beyond those models that only included environmental covariates. Future studies that implement protocols designed specifically for beluga occupancy will be most effective for accurately estimating the effect of noise on beluga displacement.

Stafford, K. (2013). *Anthropogenic Sound and Marine Mammals in the Arctic: Increases in Man-Made Noises Pose New Challenges*. Pew Charitable Trusts. Retrieved from https://www.pewtrusts.org/en/projects/protecting-life-in-the-arctic/arctic-science/arctic-science-initiatives/anthropogenic-sound-and-marine-mammals-in-the-arctic

Marine mammals, including those found in the Arctic, depend more on their hearing than other senses because sound travels well underwater. Bowhead whales; walrus; ringed, ribbon, and bearded seals; and other marine mammals rely on the sounds they make and hear to navigate, contact one another, court potential mates, find food, and avoid predators. The Arctic soundscape has long been shaped by their clicks and calls, as well as by wind, waves, and sea ice. Today, the rapid loss of summer sea ice is opening this once largely inaccessible region to ship traffic, oil exploration, and other industrial activities. These changes mean the Arctic Ocean is becoming noisier—and that could have a profound impact on animals that rely on sound to survive. This science brief looks at how anthropogenic, or man-made, sounds from ship engines, seismic surveys, and drilling machinery overlap with and may interfere with sounds produced and received by marine mammals. Studies show that whales, for example, respond to anthropogenic noise by leaving the area, reducing respiration or surface time, and decreasing calls to other whales. A study of northern right whales suggests they may be chronically stressed from high levels of sounds from ships. Additionally, collisions between animals and ships may result if the former are unable to locate and avoid the vessels because of masking, or interference, created by the sounds of the ships.

Wartzok, D., Popper, A., Gordon, J., & Merrill, J. (2003). Factors Affecting the Responses of Marine Mammals to Acoustic Disturbance. *Marine Technology Society Journal, 37*, 6-15. https://doi.org/10.4031/002533203787537041

The issues surrounding marine mammals and noise cannot be managed effectively without an understanding of the effects of that noise on individual mammals and their populations. In the spring of 2003 the National Research Council released Ocean Noise and Marine Mammals, a report that reviewed sources of ocean noise (natural and anthropogenic), the effects of noise on marine mammals, patterns and long-term trends in ocean noise, and included recommendations intended to improve understanding of the sources and impacts of anthropogenic marine noise. This paper provides a brief summary of observed effects of ocean noise on marine mammals and the factors that can change the response of the animal to the noise exposure. It introduces the reader to short- and long-term behavior changes that have been observed in marine mammals in response to ocean noise, and discusses future directions for marine mammal research.

Williams, R., Ashe, E., Blight, L., Jasny, M., & Nowlan, L. (2014). Marine mammals and ocean noise: future directions and information needs with respect to science, policy and law in Canada. *Marine Pollution Bulletin, 86*(1-2), 29-38. https://doi.org/10.1016/j.marpolbul.2014.05.056

Marine mammals are ecologically and culturally important species, and various countries have specific legislation to protect the welfare of individual marine mammals and the conservation of their populations. Anthropogenic noise represents a particular challenge for conservation and management. There is a large and growing body of research to support the conclusion that anthropogenic noise can affect marine mammal behavior, energetics, and physiology. The legal, policy, and management issues surrounding marine mammals and noise are similarly complex. Our objective is twofold. First, we discuss how policy and legal frameworks in Canada have some important differences from other jurisdictions covered in previous reviews, and provide a useful general case study. Secondly, we highlight some priority research areas that will improve marine mammal conservation and management. Our examples focus on the research needed to meet stated conservation objectives for marine mammal species in waters under Canadian jurisdiction.

Williams, R., Erbe, C., Ashe, E., Beerman, A., & Smith, J. (2014). Severity of killer whale behavioral responses to ship noise: a dose-response study. *Marine Pollution Bulletin, 79*(1-2), 254-260. https://doi.org/10.1016/j.marpolbul.2013.12.004

Critical habitats of at-risk populations of northeast Pacific "resident" killer whales can be heavily trafficked by large ships, with transits occurring on average once every hour in busy shipping lanes. We modeled behavioral responses of killer whales to ship transits during 35 "natural experiments" as a dose-response function of estimated received noise levels in both broadband and audiogram-weighted terms. Interpreting effects is contingent on a subjective and seemingly arbitrary decision about severity threshold indicating a response. Subtle responses were observed around broadband received levels of 130 dB re 1 muPa (rms); more severe responses are hypothesized to occur at received levels beyond 150 dB re 1 muPa, where our study lacked data. Avoidance responses are expected to carry minor energetic costs in terms of increased energy expenditure, but future research must assess the potential for reduced prey acquisition, and potential population consequences, under these noise levels.

Williams, R., Wright, A. J., Ashe, E., Blight, L. K., Bruintjes, R., Canessa, R., . . . Wale, M. A. (2015). Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management. *Ocean & Coastal Management, 115*, 17-24. https://doi.org/10.1016/j.ocecoaman.2015.05.021

Anthropogenic underwater noise is now recognized as a world-wide problem, and recent studies have shown a broad range of negative effects in a variety of taxa. Underwater noise from shipping is increasingly recognized as a significant and pervasive pollutant with the potential to impact marine ecosystems on a global scale. We reviewed six regional case studies as examples of recent research and management activities relating to ocean noise in a variety of taxonomic groups, locations, and approaches. However, as no six projects could ever cover all taxa, sites and noise sources, a brief bibliometric analysis places these case studies into the broader historical and topical context of the peer-reviewed ocean noise literature as a whole. The case studies highlighted emerging knowledge of impacts, including the ways that non-injurious effects can still accumulate at the population level, and detailed approaches to guide ocean noise management. They build a compelling case that a number of anthropogenic noise types can affect a variety of marine taxa. Meanwhile, the bibliometric analyses revealed an increasing diversity of ocean noise topics covered and journal outlets since the 1940s. This could be seen in terms of both the expansion of the literature from more physical interests to ecological impacts of noise, management and policy, and consideration of a widening range of taxa. However, if our scientific knowledge base is ever to get ahead of the curve of rapid industrialization of the ocean, we are going to have to identify naïve populations and relatively pristine seas, and construct mechanistic models, so that we can predict impacts before they occur, and guide effective mitigation for the most vulnerable populations.

Wilson, S. C., Trukhanova, I., Dmitrieva, L., Dolgova, E., Crawford, I., Baimukanov, M., . . . Goodman, S. J. (2017). Assessment of impacts and potential mitigation for icebreaking vessels transiting pupping areas of an ice-breeding seal. *Biological Conservation, 214*, 213-222. https://doi.org/10.1016/j.biocon.2017.05.028

Icebreaker operations in the Arctic and other areas are increasing rapidly to support new industrial activities and shipping routes, but the impact on pinnipeds in these habitats is poorly explored. We present the first quantitative study of icebreakers transiting ice-breeding habitat of a phocid seal and recommendations for mitigation. Impacts were recorded from the vessel bridge during seven ice seasons 2006–2013, for Caspian seals (Pusa caspica) breeding on the winter ice-field of the Caspian Sea. Impacts included displacement and separation of mothers and pups, breakage of birth or nursery sites and vessel-seal collisions. The flight distance of mothers with pups ahead was< 100 m, but measurable disturbance occurred at distances exceeding 200 m. Separation distances of pups from mothers were greatest for seals< 10 m to the side of the vessel, and declined with increasing distance from the vessel. The relative risk of separation by ≥20 m was greatest for distances< 50 m from the vessel path. Seals on flat ice were more likely to be separated or displaced by ≥20 m than seals in an ice rubble field. The relative risk of vessel collisions with mothers or pups was significantly greater at night when breaking new channels (12.6 times), with vessel speeds ≥4 kn (7.8 times). A mitigation hierarchy is recommended for the Caspian Sea which could be applied to Arctic pinnipeds, including reducing icebreaker transits during critical periods, and using data from aerial surveys to plan routes to minimise encounters with seals. Where preemptive avoidance is not possible, recommendations include maintaining a safe separation from breeding seals at least 50 m beyond the distance at which measurable disturbance occurs, speed limits, use of thermal imaging at night, dedicated on-board Seal Observers, and training of vessel officers to take effective reactive measures.

Wright, A. J. (2008). *International Workshop on Shipping Noise and Marine Mammals*. Retrieved from https://sea-inc.net/assets/pdf/sn_HamburgReport_RevFinal.pdf

There are more than 90,000 ships larger than 100 gross tons in the world of very different types. Each is introducing noise into the marine environment. Although not directly lethal, noise from shipping is, in larger and larger portions of the world's oceans, the dominant source of underwater noise at frequencies that are central to the way that marine mammals, as well as many sea turtles, fish and invertebrate species, sense their surroundings and communicate. Research into much of the ultimate impacts of exposure to ship noise on the ability of animals to survive and reproduce, or the consequences for the long-term viability of populations (many of which are already heavily endangered or threatened), is in its infancy. However, enough is currently known to confirm that increased noise levels associated with shipping can interfere with communication, foraging, prey evasion and other important life history functions in marine mammals. It can also disrupt their behavior and may act synergistically with other human-induced stressors with detrimental effects, as has been studied for humans living near highways and airports or working in noisy environments. The U.S. National Oceanographic and Atmospheric Administration (NOAA) has held two symposia specifically on the issue of ship-introduced noise, its effects on marine fauna (especially marine mammals) and possible solutions to the problem. The wider issue of the effects of sound on marine mammals has also been discussed in various domestic and international arenas. However, to date several key parties have not been involved (e.g., IMO and ship builders/owners) and thus the format of some discussions has been limited. To address this limitation, Okeanos - Stiftung für das Meer (Foundation for the Sea), a non-profit organization created to protect the ocean and marine life, convened a workshop in April 2008 in Hamburg, Germany, focused on shipping noise and marine mammals.

Section IV: Reduction and Management of Noise Levels

Arctic Council Protection of the Arctic Marine Environment (PAME) working group (2009). *Arctic Marine Shipping Assessment 2009 Report*. Retrieved from https://www.pmel.noaa.gov/arctic-zone/detect/documents/AMSA_2009_Report_2nd_print.pdf

The AMSA 2009 Report is focused on current and future Arctic marine activity. The results of this comprehensive assessment are a range of key findings linked to the main topics identified. These findings are listed in full throughout The AMSA 2009 Report at the end of each section. Presented here is a synopsis, or review, of the AMSA findings for each section. The sections include: Arctic Marine Geography, Climate and Sea Ice, History of Arctic Marine Transport, Governance of Arctic Shipping, Current Marine Use and the AMSA Shipping Database, Scenarios - Futures and Regional Futures to 2020, Human Dimensions, Environmental Considerations and Impacts, and Arctic Marine Infrastructure.

Azzara, A., Wang, H., & Rutherford, D. (2015). *A 10-Year Projection of Maritime Activity in the U.S. Arctic Region*. The International Council on Clean Transportation. Retrieved from https://www.cmts.gov/downloads/CMTS_10-Year_Arctic_Vessel_Projection_Report_1.1.15.pdf

This report analyzes vessel traffic and climate modeling in the northern Bering Sea, Bering Strait, and Chukchi and Beaufort seas. It examines maritime traffic growth and puts forth arctic vessel traffic projection scenarios through 2025 based on several variables including trade, economic drivers, and geopolitical variables among others.

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

Acoustic masking from anthropogenic noise is increasingly being considered as a threat to marine mammals, particularly low-frequency specialists such as baleen whales. Low-frequency ocean noise has increased in recent decades, often in habitats with seasonally resident populations of marine mammals, raising concerns that noise chronically influences life histories of individuals and populations. In contrast to physical harm from intense anthropogenic sources, which can have acute impacts on individuals, masking from chronic noise sources has been difficult to quantify at individual or population levels, and resulting effects have been even more difficult to assess. This paper presents an analytical paradigm to quantify changes in an animal's acoustic communication space as a result of spatial, spectral, and temporal changes in background noise, providing a functional definition of communication masking for free-ranging animals and a metric to quantify the potential for communication masking. We use the sonar equation, a combination of modeling and analytical techniques, and measurements from empirical data to calculate time-varying spatial maps of potential communication space for singing fin (Balaenoptera physalus), singing humpback (M. novaeangliae), and calling right (Eubalaena glacialis) whales. These illustrate how the measured loss of communication space as a result of differing levels of noise is converted into a time-varying measure of communication masking. The proposed paradigm and mechanisms for measuring levels of communication masking can be applied to different species, contexts, acoustic habitats and ocean noise scenes to estimate the potential impacts of masking at the individual and population levels.

Erbe, C., MacGillivray, A., & Williams, R. (2012). Mapping cumulative noise from shipping to inform marine spatial planning. *The Journal of the Acoustical Society of America, 132*(5), EL423-EL428. https://doi.org/10.1121/1.4758779

Including ocean noise in marine spatial planning requires predictions of noise levels on large spatiotemporal scales. Based on a simple sound transmission model and ship track data (Automatic Identification System, AIS), cumulative underwater acoustic energy from shipping was mapped throughout 2008 in the west Canadian Exclusive Economic Zone, showing high noise levels in critical habitats for endangered resident killer whales, exceeding limits of "good conservation status" under the EU Marine Strategy Framework Directive. Error analysis proved that rough calculations of noise occurrence and propagation can form a basis for management processes, because spending resources on unnecessary detail is wasteful and delays remedial action.

Gabriele, C. M., Clark, C. W., Frankel, A. S., & Kipple, B. (2017). Glacier Bay's Underwater Sound Environment: The Effects of Cruise Ship Noise on Humpback Whale Habitat (U.S. National Park Service). Retrieved from https://www.nps.gov/articles/aps-9-2-3.htm

Glacier Bay National Park (GLBA) is mandated to manage the number and behavior of cruise ships and other vessels in such a way as to minimize their effects on park resources. While quotas for private, charter and tour vessels have been set at levels defined in the Code of Federal Regulations enacted in 2006 (36 CFR 13, subpart N), GLBA is faced with defining cruise ship quotas on an annual basis, based on a variety of scientific and other information sources.Here we describe three related avenues of inquiry that seek to quantify vessel-generated underwater sound and predict its effects on the acoustic habitat of humpback whales in GLBA.

International Maritime Organization (IMO) (2014). *Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life*. Retrieved from https://www.ascobans.org/en/document/imo-mepc1circ833-guidelines-reduction-underwater-noise-commercial-shipping-address-adverse

The Marine Environment Protection Committee, at its sixty-sixth session (31 March to 4 April 2014), with a view to providing guidance on the reduction of underwater noise from commercial shipping, and following a recommendation made by the Sub-Committee on Ship Design and Equipment, at its fifty-seventh session, approved the annexed Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life.

Huntington, H. P., Daniel, R., Hartsig, A., Harun, K., Heiman, M., Meehan, R., . . . Stetson, G. (2015). Vessels, risks, and rules: Planning for safe shipping in Bering Strait. *Marine Policy, 51*, 119-127. https://doi.org/10.1016/j.marpol.2014.07.027

Commercial vessel traffic through the Bering Strait is increasing. This region has high biological and cultural significance, to which commercial shipping poses several risks. For this environment, these risks include ship strikes of whales, noise disturbance, chronic pollution, and oil spills. Indigenous Chukchi, Iñupiaq, St. Lawrence Island Yupik, Siberian Yupik, and Yup'ik peoples may be affected by proximity between small hunting boats and large commercial vessels leading to swamping or collisions, through displacement of animals or impacts to food security from contaminants, and through loss of cultural heritage if archeological sites and other important places are disturbed by wakes or an increase in people spending time on shore. Several measures are available to govern shipping through the region, including shipping lanes, Areas to Be Avoided (ATBAs), speed restrictions, communications measures, reporting systems, emissions controls, oil spill prevention and preparedness and salvage, rescue tug capability, voyage and contingency planning, and improved charting. These measures can be implemented in various ways, unilaterally by the U.S. or Russia, bilaterally, or internationally through the International Maritime Organization (IMO). Regulatory measures can be established as voluntary measures or as mandatory measures. No single measure will address all risks, but the framework presented herein may serve as a means of identifying what needs to be done and evaluating whether the goal of safe shipping has been achieved.

International Maritime Organization (IMO). (2014). Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life. Retrieved from https://cetsound.noaa.gov/Assets/cetsound/documents/MEPC.1-Circ%20883%20Noise%20Guidelines%20April%202014.pdf

The Marine Environment Protection Committee, at its sixty-sixth session (31 March to 4 April 2014), with a view to providing guidance on the reduction of underwater noise from commercial shipping, and following a recommendation made by the Sub-Committee on Ship Design and Equipment, at its fifty-seventh session, approved the annexed Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life.

Leaper, R. C., & Renilson, M. R. (2012). A review of practical methods for reducing underwater noise pollution from large commercial vessels. *International Journal of Maritime Engineering, 154*, A79-A88. https://doi.org/10.3940/rina.ijme.2012.a2.227

Underwater noise pollution from shipping is of considerable concern for marine life, particularly due to the potential for raised ambient noise levels in the 10-300Hz frequency range to mask biological sounds. There is widespread agreement that reducing shipping noise is both necessary and feasible, and the International Maritime Organization is actively working on the issue. The main source of noise is associated with propeller cavitation, and measures to improve propeller design and wake flow may also reduce noise. It is likely that the noisiest 10% of ships generate the majority of the noise impact, and it may be possible to quieten these vessels through measures that also improve efficiency. However, an extensive data set of full scale noise measurements of ships under operating conditions is required to fully understand how different factors relate to noise output and how noise reduction can be achieved alongside energy saving measures.

Leaper, R. C., Renilson, M. R., & Ryan, C. (2014). Reducing underwater noise from large commercial ships: current status and future directions. *The Journal of Ocean Technology, 9*(1), 50-69. Retrieved from https://www.thejot.net/?page_id=837&show_article_preview=530

Concerns about the effects of underwater noise pollution from shipping have led to a number of initiatives to develop quieting technologies for large commercial ships. These include the development of non-mandatory technical guidelines for reducing ship noise by the International Maritime Organization. For most merchant vessels the noise generated by cavitation will dominate all other sources of noise from that vessel. In addition, the noisiest vessels will contribute most of the shipping related hydroacoustic noise. The noisiest vessels are also likely to suffer excessive cavitation and may be operating inefficiently. Such vessels may be identified on the basis of efficiency indices or noise measurements and are most likely to benefit from remedial action to reduce noise which may also improve fuel efficiency. Slow steaming practices since 2007 resulted in an observed reduction in mean speeds from 15.6 (sd = 4.2) knots in 2007 to 13.8 (sd = 3.0) knots in 2013 for ships transiting the major shipping route in the eastern Mediterranean. Based on general observed relationships between speed and noise for vessels with fixed pitch propellers, we estimated that slow steaming in the last five years has likely reduced the overall broadband acoustic footprint from these ships by over 50%. There is still a lack of data on noise levels from individual ships and how these relate to different factors such as loading and trim and also a need for noise measurements from new propeller design concepts that offer improvement in fuel efficiency through reduced cavitation. Ongoing research on these issues should help develop further practical and economic quieting technologies in addition to measures already identified in the IMO guidelines.

McKenna, M. F., Gabriele, C., & Kipple, B. (2017). Effects of marine vessel management on the underwater acoustic environment of Glacier Bay National Park, AK. *Ocean & Coastal Management, 139*, 102-112. https://doi.org/10.1016/j.ocecoaman.2017.01.015

To protect the underwater acoustic environment and the marine mammals that depend upon it, Glacier Bay National Park implements marine vessel quotas, speed regulations, and routing restrictions in biologically important areas. Here, we characterize the underwater acoustic environment to quantify changes in conditions related to vessel management actions. Analysis of hourly 30-second acoustic samples obtained from a seafloor hydrophone included manual (aural and visual) identification of physical, biological, and human-made acoustic sources and measuring received sound pressure levels. A total of 10,659 30-second acoustic samples collected in 2000, 2001, 2007 and 2008 were analyzed. By quantifying the sources, occurrence, and characteristics of underwater sound we gained a new understanding of how the underwater acoustic environment relates to vessel management. For example, the occurrence of noise from large marine vessels (e.g. cruise ships) decreased despite an increase in the vessel quotas and use-days, likely due to changes in the timing of cruise ship entries. Our work documented the occurrence of biologically important humpback whale and harbor seal vocalizations; the frequency of occurrence of these vocalizations gives an indication of Glacier Bay's importance for these species and seasonality of calls documents the times of year at which a pristine acoustic environment would most benefit each species. These first descriptions of acoustic conditions in a protected coastal habitat indicate that both regulations and vessel behavior independent of regulations have discernible effects on the acoustic environment. Quantitatively describing these changes is a crucial first step toward protection of this important underwater habitat.

McKenna, M. F., Wiggins, S. M., & Hildebrand, J. A. (2013). Relationship between container ship underwater noise levels and ship design, operational and oceanographic conditions. *Scientific Reports, 3*. https://doi.org10.1038/srep01760

Low-frequency ocean ambient noise is dominated by noise from commercial ships, yet understanding how individual ships contribute deserves further investigation. This study develops and evaluates statistical models of container ship noise in relation to design characteristics, operational conditions, and oceanographic settings. Five-hundred ship passages and nineteen covariates were used to build generalized additive models. Opportunistic acoustic measurements of ships transiting offshore California were collected using seafloor acoustic recorders. A5–10 dB range in broadband source level was found for ships depending on the transit conditions. For a ship recorded multiple times traveling at different speeds, cumulative noise was lowest at 8 knots, 65% reduction in operational speed. Models with highest predictive power, in order of selection, included ship speed, size, and time of year. Uncertainty in source depth and propagation affected model fit. These results provide insight on the conditions that produce higher levels of underwater noise from container ships.

Mikhalevsky, P. N., Sagen, H., Worcester, P. F., Baggeroer, A. B., Orcutt, J., Moore, S. E., . . . Yuen, M. Y. (2015). Multipurpose Acoustic Networks in the Integrated Arctic Ocean Observing System. *Arctic, 68*(5). https://doi.org/10.14430/arctic4449

The dramatic reduction of sea ice in the Arctic Ocean will increase human activities in the coming years. This activity will be driven by increased demand for energy and the marine resources of an Arctic Ocean accessible to ships. Oil and gas exploration, fisheries, mineral extraction, marine transportation, research and development, tourism, and search and rescue will increase the pressure on the vulnerable Arctic environment. Technologies that allow synoptic in situ observations year-round are needed to monitor and forecast changes in the Arctic atmosphere-ice-ocean system at daily, seasonal, annual, and decadal scales. These data can inform and enable both sustainable development and enforcement of international Arctic agreements and treaties, while protecting this critical environment. In this paper, we discuss multipurpose acoustic networks, including subsea cable components, in the Arctic. These networks provide communication, power, underwater and under-ice navigation, passive monitoring of ambient sound (ice, seismic, biologic, and anthropogenic), and acoustic remote sensing (tomography and thermometry), supporting and complementing data collection from platforms, moorings, and vehicles. We support the development and implementation of regional to basin-wide acoustic networks as an integral component of a multidisciplinary in situ Arctic Ocean observatory.

Miksis-Olds, J. L., & Nichols, S. M. (2016). Is low frequency ocean sound increasing globally? *The Journal of the Acoustical Society of America, 139*(1), 501-511. https://doi.org/10.1121/1.4938237

Low frequency sound has increased in the Northeast Pacific Ocean over the past 60 years and in the Indian Ocean over the past decade. Recent observations in the Northeast Pacific show a level or slightly decreasing trend in low frequency noise. It remains unclear what the low frequency trends are in other regions of the world. In this work, data from the Comprehensive Nuclear-Test Ban Treaty Organization International Monitoring System was used to examine the rate and magnitude of change in low frequency sound (5-115 Hz) over the past decade in the South Atlantic and Equatorial Pacific Oceans. The dominant source observed in the South Atlantic was seismic air gun signals, while shipping and biologic sources contributed more to the acoustic environment at the Equatorial Pacific location. Sound levels over the past 5-6 yr in the Equatorial Pacific have decreased. Decreases were also observed in the ambient sound floor in the South Atlantic Ocean. Based on these observations, it does not appear that low frequency sound levels are increasing globally.

Ocean Conservancy. (2017). *Navigating the North: An Assessment of the Environmental Risks of Arctic Vessel Traffic*. Retrieved from https://oceanconservancy.org/wp-content/uploads/2017/06/Arctic-Vessel-Traffic-Report-WEB-2.pdf

This report synthesizes key information related to vessel traffic in Arctic waters, including the characteristics of Arctic vessel traffic, infrastructure, governance mechanisms, regulatory gaps and environmental risks. It also provides recommendations that chart a course for the next iteration of protections needed to address vessel-related threats including oil spills, air emissions, invasive species, disturbance to marine mammals and discharges of sewage and graywater.

Prins, H. J., Flikkema, M. B., Bosschers, J., Koldenhof, Y., de Jong, C. A. F., Pestelli, C., . . . Hyensjö, M. (2016). Suppression of Underwater Noise Induced by Cavitation: SONIC. *Transportation Research Procedia, 14*, 2668-2677. https://doi.org/10.1016/j.trpro.2016.05.439

In EU FP7 project SONIC, partners set out in October 2012 to study the underwater radiated noise of ships and shipping. The objectives of the project were (1) to study the numerical and experimental techniques to determine the underwater noise; (2) to develop methods for mapping the noise of ships and shipping; and (3) to determine mitigation measures to reduce the underwater radiated noise. Numerical methods focused on determination of the cavitation extent and dynamics on propellers which is the main source of noise of commercial shipping. Research also focused on methods to determine the underwater radiated noise from machinery. Experimental methods in model test facilities have been studied and validated against dedicated full scale measurements. The ship noise source levels obtained from these numerical and experimental methods provide input to shipping noise mapping tools to determine the overall underwater noise in a certain sea area. Based on the experience gained in the SONIC project, a set of guidelines for regulators concerned with underwater radiated noise of ships were developed together with the AQUO project. These guidelines discuss the definitions, numerical and experimental methods and mitigation solutions for underwater radiated noise. This paper gives an overview of the work done by all partners in the SONIC project.

Reeves, R. R., Ewins, P. J., Agbayani, S., Heide-Jørgensen, M. P., Kovacs, K. M., Lydersen, C., . . . Blijleven, R. (2014). Distribution of endemic cetaceans in relation to hydrocarbon development and commercial shipping in a warming Arctic. *Marine Policy, 44*, 375-389. https://doi.org/10.1016/j.marpol.2013.10.005

The Arctic is one of the fastest-changing parts of the planet. Global climate change is already having major impacts on Arctic ecosystems. Increasing temperatures and reductions in sea ice are particular conservation concerns for ice-associated species, including three endemic cetaceans that have evolved in or joined the Arctic sympagic community over the last 5 M years. Sea ice losses are also a major stimulant to increased industrial interest in the Arctic in previously ice-covered areas. The impacts of climate change are expected to continue and will likely intensify in coming decades. This paper summarizes information on the distribution and movement patterns of the three ice-associated cetacean species that reside year-round in the Arctic, the narwhal (Monodon monoceros), beluga (white whale, Delphinapterus leucas), and bowhead whale (Balaena mysticetus). It maps their current distribution and identifies areas of seasonal aggregation, particularly focusing on high-density occurrences during the summer. Sites of oil and gas exploration and development and routes used for commercial shipping in the Arctic are compared with the distribution patterns of the whales, with the aim of highlighting areas of special concern for conservation. Measures that should be considered to mitigate the impacts of human activities on these Arctic whales and the aboriginal people who depend on them for subsistence include: careful planning of ship traffic lanes (re-routing if necessary) and ship speed restrictions; temporal or spatial closures of specified areas (e.g. where critical processes for whales such as calving, calf rearing, resting, or intense feeding take place) to specific types of industrial activity; strict regulation of seismic surveys and other sources of loud underwater noise; and close and sustained monitoring of whale populations in order to track their responses to environmental disturbance.

Spence, J. H., & Fischer, R. W. (2017). Requirements for Reducing Underwater Noise From Ships. *IEEE Journal of Oceanic Engineering, 42*(2), 388-398. https://doi.org/10.1109/joe.2016.2578198

Awareness of underwater noise from shipping has grown significantly within the marine community over the past decade. Concerns have been raised about the levels of anthropogenic noise in the world's oceans, as well as in harbors and areas with sensitive or protected marine life. Regulatory bodies are listening, and are considering what actions are available to reduce noise. Measurements of vessel noise in various situations have been performed to better quantify the problem, and efforts have been made by some to correlate noise levels with simplified vessel parameters. Such efforts provide insights into what levels of noise are possible and how they are related to ship operation. However, to reduce underwater noise, a deeper understanding of specific vessel design and factors that lead to noise are required. While generalities of primary noise sources can be applied to different classes of vessels, design details of specific vessels must be obtained and analyzed to implement noise reductions. Armed with knowledge of vessel details, noise control strategies can be optimized using various computer-aided tools. This must be done on a case-by-case basis for different vessel designs, and is most efficient and effective for new builds. Costs for such efforts must also be considered if vessel noise is to be made inherently quieter worldwide.

World Wildlife Fund (2013). *Finding Management Solutions for Underwater Noise in Canada's Pacific*. Retrieved from Vancouver, B.C. Retrieved from https://awsassets.wwf.ca/downloads/ocean_noise_workshop_final_report_2013_2.pdf

WWF-Canada hosted its first workshop on Ocean Noise in Canada's Pacific on January 31-February 1, 2012. This report contain extended abstracts written by the presenters, followed by a synthesis of the breakout group discussions based on notes taken by WWF rapporteurs. The concluding recommendations are extracted from various presentations and discussions, and are organized by topic: translating science into policy; impact assessments; regulation; marine plans; acoustic monitoring; acoustic quieting and marine protected areas; voluntary and incentive programs; and education and communication.

Wright, A. J. (2014). *Reducing Impacts of Human Ocean Noise on Cetaceans: Knowledge Gap Analysis and Recommendations*. Retrieved from https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Report-Reducing-Impacts-of-Noise-from-Human-Activities-on-Cetaceans.pdf

Due to the physics of the underwater environment and factors such as turbidity, sound travels much further than light in the oceans. Consequently, many marine animals have evolved to use sound as their primary means for communication, foraging, navigating, and generally perceiving features in the environment around them. Sound from human activities represents unwanted noise to these species. This noise can disrupt their natural activities, induce stress responses, degrade their environment and, in the more extreme cases, lead to permanent hearing damage, or even death. The extent to which noise from human activities impacts populations of marine mammals has been highly debated. However, there is increasing evidence that the myriad of sound introduced into the oceans by humans is collectively damaging the health and reproductive capabilities of these animals in various ways. Furthermore, there are now a number of solid indications that what is currently known about the severity of the impact of human noise exposure on populations of marine mammals, as well as on individuals, is likely to be only the "tip of the iceberg" (one of two possible options presented by the U.S. National Research Council, NRC, 2005). This is due to the multi-faceted, and often subtle, range of effects that noise can have on the lives of marine animals. Despite this, some argue that the impacts of noise are negligible in contrast to the expected consequences of climate change and other threats such as bycatch of marine mammals in fishing gear. However, the aggregated impacts of noise on marine mammals also combine with the effects of climate change and other human pressures. For example, marine mammals are exposed to chemical pollutants through their diet and store many of these in their blubber due to the interaction of these chemicals with the fats. This limits circulating levels of the chemicals (often called contaminants) as well as their total impact on the individual. However, in times of high energy use (e.g., pregnancy) or low energy availability (perhaps due to overfishing or avoidance of a feeding area due to high noise levels) these fat stores are metabolized, thus releasing the chemicals into the bloodstream, leading to increased circulating levels at times of vulnerability.