Mapping cumulative noise from shipping to inform marine spatial planning

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Abstract: 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.

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1. Introduction

Anthropogenic ocean noise is increasingly considered a chronic, habitat-level stressor[1] requiring area-based management tools. Efforts are underway to compile information on human activities in the world's oceans to identify areas where anthropogenic activities most strongly overlap with vulnerable marine ecosystems.[2] Such large-scale (to global) conservation assessments have included a suite of anthropogenic stressors but have not yet considered ocean noise, perhaps due in part to a lack of simple analytical tools to provide reasonable predictions of man-made noise on large geographic scales.

The EU's Marine Strategy Framework Directive (2008/56/EC) specifies indicators to assess the environmental status of marine habitats[3] with respect to low-frequency, continuous sound: The annual average ambient noise level in the 1/3 octave bands centered at 63 and 125 Hz, as measured by a statistically representative set of observation stations, has been suggested not to exceed the baseline values of the year 2012 or 100 dB re 1 μPa root-mean-square (rms). Many other countries, including Canada, state qualitatively that critical habitats of acoustically sensitive species should incorporate acoustic attributes but do not yet specify thresholds or limits of acceptable change.

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Predicting such acoustic environmental indicators is difficult due to the large geographic scale, long duration (1-yr average), and multitude of noise sources. Detailed modeling of individual noise footprints is cost and time prohibitive and computationally infeasible. A more efficient modeling approach is needed; however, its error has to be assessed. We demonstrate one such tool for the example of Canada's Pacific Exclusive Economic Zone (EEZ).

2. Ship noise

Ship transits were derived from a geo-referenced database provided by the Vessel Traffic Operation Support System (VTOSS) program of the Marine Communications and Traffic Services (MCTS) of the Canadian Coast Guard. Figure 1(a) shows the cumulative hours of ship traffic in 2008 on a $5\,\text{km} \times 5\,\text{km}$ grid, integrated over all vessels. If two simultaneous vessels sailing in parallel took 20 min each to cross a cell, then this was counted as 40 min of traffic. The leap year 2008 had 8784 h. The cell with the maximum number of cumulative traffic hours (27 522) had on average three simultaneous vessels for every hour of the year.

The shipping source spectral density formulae from the Research Ambient Noise Directionality (RANDI) model[4] yielded representative ship source levels (SL) as a function of ship length and speed extracted from VTOSS. Vessels were grouped into five length classes with the largest class reflecting the fact that ship noise no longer increases with length for very large vessels.[5] The 1/3-octave band source spectra [Fig. 1(b)] represent mean SL, in terms of total radiated sound power, for each category of vessel. L1 vessels were modeled louder than L2 vessels due to their increased speed (Table 1).

The shape of the source spectra was corrected based on vessel size and propeller depth. Small vessels emit noise at higher frequencies than larger vessels due to their smaller, shallower propellers, which have higher blade rates, and increased surface-dipole cancellation at low frequencies. SL at wavelengths greater than four times the propeller depth were attenuated according to Eq. (4.1.24),[6] with propeller depth proportional to vessel length, up to a maximum depth of 6 m, which is a typical mean source depth for merchant shipping.[7] The attenuation was applied to the spectra on a relative basis only: The broadband SL for each category was preserved, so as not to underestimate SL for the smallest vessels.

3. Cumulative noise model

Bathymetry was extrapolated from the Etopo2 database,[8] the BC coastline from GSHHS.[9] Received levels (RL) were computed in 1/3 octave bands from 10 Hz to

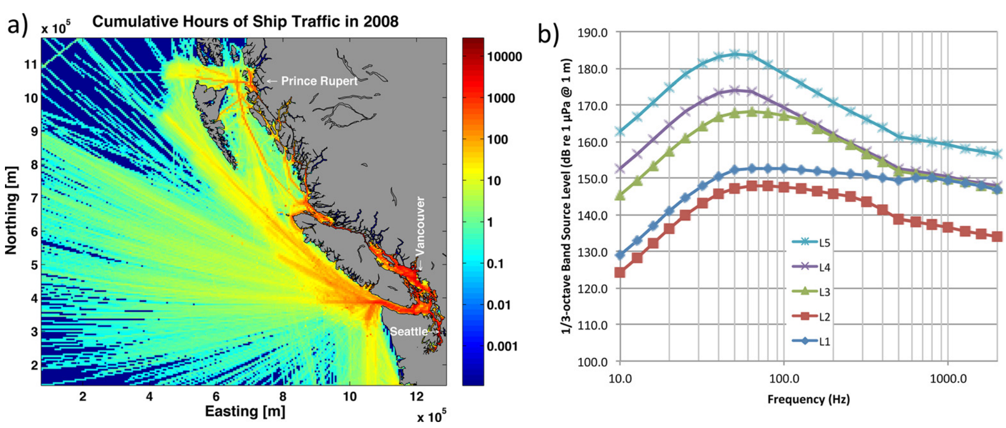

Fig. 1. (Color online) (a) Total hours of shipping for the year 2008. (b) Mean 1/3-octave band source levels for the five vessel length classes.

Table 1. Modeled properties for the five vessel length classes in the shipping traffic database.

Vessel Class	L1	L2	L3	L4	L5
Lengths represented (m)	≤10	10–25	25–50	50–100	≥100
Modeled length (m)	7.8	18.6	38.9	77.8	155.6
Modeled speed (kts)	15.6	9.1	14.6	13.6	15.0
Modeled source depth (m)	0.5	1.25	3.0	6.0	6.0
Broadband SL (dB re 1 μPa @ 1 m)	163.6	157.2	176.4	181.1	190.8

2 kHz, as SL-TL, using a geometric transmission loss (TL) model accounting for spherical spreading (20 log R) to the maximum water depth along the modeling radius (R), and cylindrical spreading (10 log R) for the remainder of the radius. Frequency-dependent, volumetric absorption was also included.[10,11] RL were computed from each cell with ship counts over a circle with 100 km radius. RL beyond 100 km did not contribute significantly to the cumulative noise map based on the modeling of individual radii. Considering the ocean an acoustic waveguide, in the case of a hard (reflective) seafloor, the minimum frequency that can propagate has a wavelength of four times the minimum water depth $D_{\min}$. For each radius, $D_{\min}$ was found and a high-pass filter imposed. RL in a source cell was computed as SL-TL for an average R to the cell center of 1.9 km in a 5 km × 5 km cell, plus the contribution from sources outside of this cell.

Sound exposure levels (SEL) were computed by adding 10 log T to RL, where T was the time (in seconds) a vessel type spent in each source cell. Received energy was integrated over all ships for the 12 months of 2008 [Fig. 2(a)]. Noise levels (10–2000 Hz) were highest in the Straits of Georgia and Juan de Fuca near the ports of Vancouver and Seattle, then Prince Rupert. The maximum modeled sound exposure level was 215 dB re 1 μPa^{2}s near Seattle. These areas of high exposure form part of critical habitat for resident killer whales.

The average sound pressure level from shipping was estimated from the cumulative SEL map by dividing the energy by the total number of seconds in 2008 [equivalent to subtracting 75 dB from the cumulative noise map in Fig. 2(a)]. Considering energy only in the two 1/3 octave bands centered at 63 and 125 Hz gave an estimate of ambient levels at frequencies that are monitored in Europe. Figure 2(b) shows in pink the regions where the annual average noise level from shipping was predicted to exceed the suggested European target of 100 dB re 1 μPa in either the 63 or 125 Hz 1/3 octave band.

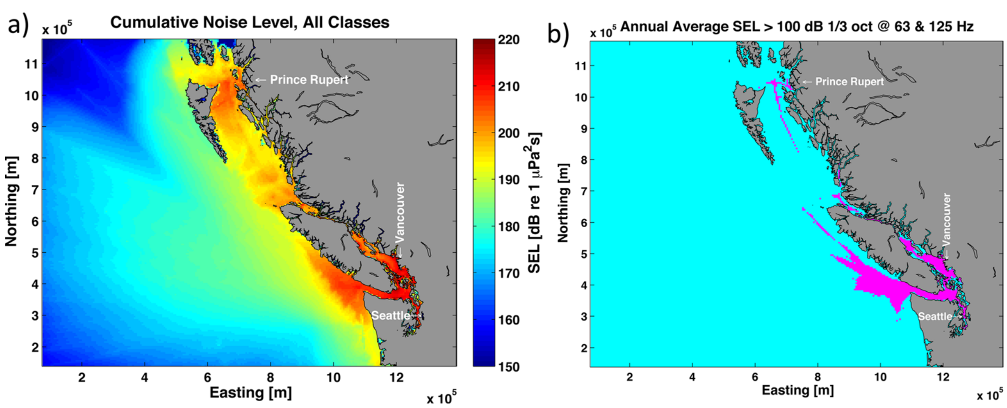

Fig. 2. (Color online) (a) Cumulative sound exposure level from vessel traffic from Jan to Dec 2008. (b) Areas where the estimated annual average sound pressure level (*SPLrms*) exceeded the EU Marine Strategy Framework Directive of 100 dB (*SPLrms*) in 1/3-octave bands centered on 63 or 125 Hz.

4. Error analysis

Error analysis consisted of (1) a comparison of the simple TL model to a range- dependent parabolic equation (PE) model[12] along 10 radii spanning the EEZ, (2) a sensitivity study of the noise map to variability in seafloor and water column parameters, and (3) a comparison to field measurements. Of the 10 radii, two were in offshore deep water, two on the continental slope, and six lining the inshore waters between the mainland and Vancouver Island and the Queen Charlotte Islands (Haida Gwaii). For each radius, two extremes (= the range) of the local geoacoustic parameters were modeled: One acoustically hard (= more reflective) and the other acoustically soft (= less reflective). Seabed geoacoustics were based on sediment samples from the Geological Survey of Canada (GSC), supplemented by the BC Marine Ecological Classification (BCMEC) maps of the Ministry of Sustainable Resource Management.[13] The grain-shearing model of Buckingham[14] was used to compute geoacoustic properties of the sediments from these databases.

For continental shelf areas, the effect of surficial sediment thickness on transmission loss was considered by varying the depth to the acoustic basement in the geoacoustic model according to Huntec cross sections and core data.[15–18] The acoustic basement below the sediments was assumed to consist of lithified tertiary sediments with associated geoacoustic properties.[19] To quantify the influence of sound speed profile variability in the water column on TL, both winter and summer conditions were modeled for all 10 radii. Range-dependent profiles of mean ocean temperature and salinity were interpolated from the Global Digital Environmental Model (GDEM) database[20] and used to compute sound speed.[21]

The ensemble of TL curves for all 10 radii was analyzed statistically. For each frequency, TL percentile levels (5%, 25%, 50%, 75%, and 95%) were computed providing an estimate of the range-dependent probability density for TL off western Canada (Fig. 3). Uncertainty in TL increased with range and was generally greater at higher frequencies. Below 40 Hz, the median (= 50th percentile) TL followed a spherical spreading law very closely (to within 3 dB) over ranges <30 km. At higher frequencies, the median TL started out spherical (slope 20 dB/decade in range) and turned to cylindrical (slope 10 dB/decade in range). This conversion from spherical to cylindrical was therefore included in the simple TL model. Offshore, in deep water, TL followed the geometric model very closely thanks to a lack of environmental variability and a lack of seafloor interaction. The extremes of high TL corresponded to soft-sediment inshore radii during summer when the water was downward refracting, increasing the

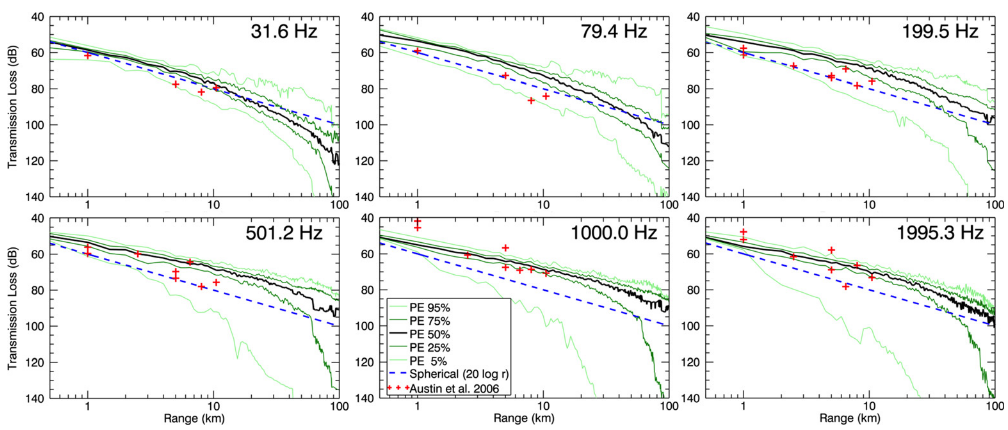

Fig. 3. (Color online) Transmission loss versus range statistics at six frequencies, as computed from the ensemble of PE model transects. Solid lines show the 5th, 25th, 50th, 75th, and 95th percentile transmission loss contours. Crosses are transmission loss measurements. Dashed line indicates spherical spreading transmission loss.

interaction of the sound with the seafloor. Wind-driven mixing combined with atmospheric cooling in winter results in a mild surface-duct profile reducing seafloor losses.

Field measurements of TL were collected off the north coast in late Sept. 2005 (Ref. 22) using a controlled sound source and bottom-mounted hydrophones. TL roughly followed a geometric model with variability increasing with frequency.

The standard deviation of the simple geometric model (combining spherical and cylindrical spreading) from the median PE and measured TL was 10 dB at 80 km (less at shorter ranges). The mean error in SL was estimated to be <7 dB based on measured standard deviations of 3–7 dB elsewhere.[7,23] Based on error propagation ($\sigma_{RL} = \sqrt{\sigma_{SL}^2 + \sigma_{TL}^2}$), the mean error in RL was <12 dB (less at shorter ranges).

5. Conclusion

We developed and assessed a simple tool to derive a large-scale noise map, which can be overlain with wildlife distribution maps, so that ocean noise can be better integrated into marine spatial planning. This represents an exciting opportunity for the marine conservation community because it suggests that simple and readily accessible transmission models provide an accurate enough picture as a starting point to identify areas where noise is likely to be and likely not to be a problem.

AIS data are increasingly being used for ship noise assessments,[23] yet only provide a minimum estimate, as small vessels are not required to log their position, but far outnumber large vessels in certain regions. Sources other than shipping (pile driving, seismic surveys, etc.) can easily be included in our model, but these are not prevalent in Canada's Pacific EEZ. The United States has formed an Underwater Sound Field Working Group to map underwater noise throughout the waters of the US EEZ. This represents a tremendous step forward in terms of integrating noise into the US commitment to marine spatial planning.

Overall, our maps provide a simple, visual tool to allow managers and stakeholders to see where we have an opportunity to keep quiet areas quiet and where mitigation measures may be needed to make noisy areas quieter.

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References and links

[1]W. Ellison, B. Southall, C. Clark, and A. Frankel, "A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds," Conserv. Biol. **26**(1), 21–28 (2012).

[2]B. S. Halpern, S. Walbridge, K. A. Selkoe, C. V. Kappel, F. Micheli, C. D'Agrosa, J. F. Bruno, K. S. Casey, C. Ebert, H. E. Fox, R. Fujita, D. Heinemann, H. S. Lenihan, E. M. P. Madin, M. T. Perry, E. R. Selig, M. Spalding, R. Steneck, and R. Watson, "A global map of human impact on marine ecosystems," Science **319**, 948–952 (2008).

[3]M. L. Tasker, M. Amundin, M. Andre, A. D. Hawkins, W. Lang, T. Merck, A. Scholik- Schlomer, J. Teilman, F. Thomsen, S. Werner, and M. Zakharia, "Marine Strategy Framework Directive: Task Group 11 Report: Underwater noise and other forms of energy," European Commission and International Council for the Exploration of the Sea, Luxembourg, 2010.

[4]J. E. Breeding, L. A. Pflug, M. Bradley, M. Herbert, and M. Wooten, *RANDI 3.1 User's Guide* (US Naval Research Laboratory, White Oak, MD, 1994).

[5]M. F. McKenna, D. Ross, S. M. Wiggins, and J. A. Hildebrand, "Underwater radiated noise from modern commercial ships," J. Acoust. Soc. Am. **131**(1), 92–103 (2012).

[6]L. M. Brekhovskikh and Y. P. Lysanov, *Fundamentals of Ocean Acoustics*, 3rd ed. (Springer, New York, 2003).

[7]P. Scrimger and R. M. Heitmeyer, "Acoustic source-level measurements for a variety of merchant ships," J. Acoust. Soc. Am. **89**(2), 691–699 (1991).
[8]U.S. Department of Commerce, "Two-minute Gridded Global Relief Data (ETOPO2v2)," National Oceanic and Atmospheric Administration, National Geophysical Data Center (2006).
[9]P. Wessel and W. H. F. Smith, "A global self-consistent, hierarchical, high-resolution shoreline database," J. Geophys. Res. **101**(B4), 8741–8743, doi:10.1029/96JB00104 (1996).
[10]R. E. François and G. R. Garrison,"Sound absorption based on ocean measurements: Part I: Pure water and magnesium sulphate contributions," J. Acoust. Soc. Am. **72**(3), 896–907 (1982).
[11]R. E. François and G. R. Garrison, "Sound absorption based on ocean measurements: Part II: Boric acid contribution and equation for total absorption," J. Acoust. Soc. Am. **72**(6), 1879–1890 (1982).
[12]M. D. Collins, R. J. Cederberg, D. B. King, and S. Chin-Bing, "Comparison of algorithms for solving parabolic wave equations," J. Acoust. Soc. Am. **100**(1), 178–182 (1996).
[13]D. E. Howes, M. A. Zacharias, and J. R. Harper, *British Columbia Marine Ecological Classification: Marine Ecosections and Ecounits* (Province of British Columbia Resource Information Standard Committee, Victoria, BC, 1997).
[14]M. J. Buckingham, "Compressional and shear wave properties of marine sediments: Comparisons between theory and data," J. Acoust. Soc. Am. **117**(1), 137–152 (2005).
[15]J. V. Barrie and B. Bornhold, "Surficial geology of Hecate Strait, British Columbia contintental shelf," Can. J. Earth Sci. **26**, 1241–1254 (1989).
[16]J. V. Barrie and P. R. Hill, "Holocene faulting on a tectonic margin: Georgia Basin, British Columbia, Canada," Geo-Mar. Lett. **24**, 86–96 (2004).
[17]J. V. Barrie, J. L. Luternauer, K. W. Conway, and A. Caltagirone, *Surficial Geology of the Queen Charlotte Basin*, GSC Open Files 2193, 2195, 2196, 2197, Geological Survey of Canada, 1990.
[18]B. Bornhold and J. Barrie, "Surficial sediments on the Western Canadian continental shelf," Cont. Shelf Res. **11**, 685–699 (1991).
[19]A. O. MacGillivray, *An Acoustic Modelling Study of Seismic Airgun Noise in Queen Charlotte Basin* (University of Victoria, B.C., 2006).
[20]M. R. Carnes, "Description and Evaluation of GDEM-V 3.0," NRL Memorandum Report 7330-09-9165 (US Naval Research Laboratory, White Oak, MD, 2009).
[21]S. Clay and H. Medwin, *Acoustical Oceanography* (Wiley, New York, 1977).
[22]M. Austin, A. MacGillivray, D. Hannay, and M. Zykov, "Enbridge Northern Gateway Project," Marine Acoustics Technical Data Report, JASCO Applied Sciences, Victoria, B.C. (2006). The report is available from the Canadian Environmental Assessment Agency (CEAA) registry, http://www.ceaa.gc.ca/050/document-eng.cfm?document=46395.
[23]L. Hatch, C. Clark, R. Merrick, S. Van Parijs, D. Ponirakis, K. Schwehr, M. Thompson, and D. Wiley, "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. (N.Y.) **42**(5), 735–752 (2008).