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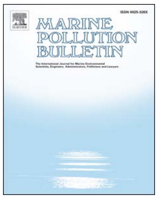

Effects of shipping on marine acoustic habitats in Canadian Arctic estimated via probabilistic modeling and mapping

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ABSTRACT

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.

1. Introduction

Shipping has been identified as a major contributor to ocean noise (Hildebrand, 2009; NRC, 2003). In some parts of the world, shipping noise (SN, see Table 1 for acronyms) is estimated to have approximately doubled every decade since the 1960's, as a consequence of the increase of world shipping and economic activity (Andrew et al., 2011; Frisk, 2012; McDonald et al., 2006). World shipping is essentially distributed around the mid-latitudes with very low traffic in Polar regions (Wu et al., 2017). Present shipping in Canada follows this general pattern (Simard et al., 2014a, c, b). This state may however change in Arctic and Subarctic regions in the coming decades as a result of the melting of the Arctic ice cap (Overland and Wang, 2013) and the subsequent opening of regional and inter-continental seasonal ice-free routes (Dawson et al., 2016; Eguíluz et al., 2016; Gavrilchuk and Lesage, 2014; Melia et al., 2016; PEW, 2016).

The opening of routes and significant traffic increase in the relatively pristine Arctic, i.e. relatively free from industrial activities in comparison with mid-latitude regions, could affect the underwater habitats by introducing stressors related to human presence alike moving or still objects (ships, nets, buoys…), chemicals from spills, or radiated acoustic energy. Indeed, one of the intrinsic properties of wildlife habitats is their soundscape (Moore et al., 2012; Pijanowski et al., 2011). Sounds convey key information about the ecosystem (e.g. wind, rain) and its inhabitants (e.g. presence of conspecifics, predators or preys) (Au and Hastings, 2008; Coquereau et al., 2016; Pijanowski et al., 2011; Wale et al., 2013; Webb et al., 2008; Wenz, 1962). It is used by most marine fauna, from invertebrates and fish to marine mammals, to accomplish vital functions such as acoustic sensing, communication, navigation and feeding (Au and Hastings, 2008; Coquereau et al., 2016; Pijanowski et al., 2011; Wale et al., 2013; Webb et al., 2008; Wenz, 1962). Large-scale chronic anthropogenic noise (e.g. shipping, marine renewable energy plant) may impact marine habitats, by interfering with these functions and altering the ecosystem (Boyd et al., 2011). This eventuality has raised worldwide concerns from several regulatory organisations and initiated studies to better estimate and monitor this SN threat in different regions of the world, and propose ways to reduce its effects and reverse the increasing trend (Gedamke et al., 2016b; IMO, 2014; UNEP-CBD, 2014; Van der Graaf et al., 2012). For instance, the Canadian Species at Risk Act (Canada, 2002) protects species at risk from the degradation of their critical habitat, including their soundscape.

Characterizing SN and its environmental effects over large-scale 3D basins and extended periods of time is particularly challenging. It is a

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Table 1
Acronym table.

ANL	Ambient noise level
ANL_0	Ambient noise level reference
BRT	Behavior response threshold
cdf	Cumulative density function
PTS	Permanent auditory threshold shift
pdf	Probability density function
RAM	Range-dependent Acoustic Model
RRF	Range reduction factor
SL	Source level
SN	Shipping noise
SNL	Shipping noise level
SPL	Sound pressure level
SPL_0	Sound pressure level threshold reference for a given effect
TTS	Temporary auditory threshold shift

highly multi-dimensional problem depending on time, space and frequency, as well as studied species or biological functions (e.g. communication, mate selection, echolocation, foraging, and predation).

Habitat-centric approaches (Williams et al., 2014), using direct measurements at strategic locations, have been suggested to monitor the SN contribution to soundscapes (Merchant et al., 2014), identify problematic sound levels and estimate the risk of masking (Gervaise et al., 2012; Simard et al., 2010), i.e. the risk that SN covers useful sounds to marine life. To assess habitat quality at the larger scales required for marine spatial planning, numerical acoustic propagation modeling has been used to map the instantaneous sound field of individual ships (Matthews et al., 2010), fleet SN average, cumulative exposure (Erbe et al., 2012; Gedamke et al., 2016a; Porter and Henderson, 2013; Redfern et al., 2017) or percentiles (Audoly et al., 2016; Gervaise et al., 2015). SN potential effects or impacts to marine animals were estimated by mapping SN excess relative to species audiograms to circumscribe noise hotspots (Erbe et al., 2014) or quiet areas (Williams et al., 2015), or relative to threshold criteria for temporary and permanent threshold shifts (TTS and PTS) (NMFS, 2016; Southall et al., 2007), behavioral responses (Gomez et al., 2016; Southall et al., 2007), masking (Clark et al., 2009; Erbe et al., 2016), or relative to pristine ambient noise levels in biologically important areas (Gervaise et al., 2012; Redfern et al., 2017).

But animal responses to sound have been shown to be highly variable (Gomez et al., 2016) depending on life stage, individual (Erbe et al., 2016) or context (DeRuiter et al., 2017; Ellison et al., 2012). Underwater transmission losses also highly depend on variable environmental parameters. Therefore, ocean environment, animal characteristics and context are rarely known with enough precision and high resolution over large scales to precisely characterize SN and its effects without a range of uncertainty (Gisiner et al., 2006). Trade-offs between computational costs and approximations in numerical simulations with ocean propagation models (Farcas et al., 2016) also add to uncertainties. To deal with variability and uncertainties, animal-centric approaches simulate multiple realizations of individual exposure with animat models and Monte-Carlo methods (Frankel et al., 2002; Frankel et al., 2016), leading to individual-based stochastic dynamic risk modeling (Schwarz et al., 2016). In habitat-centric modeling and mapping, accounting for intrinsic variability and uncertainties is still a challenge and validation with in situ measurements remains a critical step.

In the present study, we develop a probabilistic framework, called RAMDAM, to estimate, map and compare the SN effect probabilities within four large-scale regions of the Canadian Arctic and Subarctic archipelago (Fig. 1). This probabilistic framework integrates models of ship source levels (SL), present shipping traffic data and underwater acoustic propagation theory, and takes into account intrinsic variability and uncertainties of these quantities, in the estimate of shipping noise level (SNL) statistical distributions. The European Marine Strategy Framework Directive recommends the analysis of the 63-Hz and the 125-kHz one-third-octave band for shipping noise monitoring (Van der Graaf et al., 2012). To limit the computation time, simulations were carried out in the first place for the predominant 63-Hz one-third-octave band characterizing shipping noise and merchant ship source levels (Simard et al., 2016). In the context of Arctic sea ice decreasing trend, RAMDAM is also exploited to simulate the hypothetical future scenario of a tenfold traffic increase. Then, the probabilistic approach is used to compare "present" and "future" shipping noise distributions to the typical Arctic ambient noise level distribution and to the ~100-times busier southern traffic of the St. Lawrence Seaway. Lastly, a set of probabilistic metrics are derived to discuss the potential effects of shipping noise on marine acoustic habitats. In particular, we illustrate how the simulation results could be used to assess the potential acoustic effects of a traffic increase in some of the northern Canadian ecologically and biologically significant areas (EBSAs) (DFO, 2011, 2014, 2015; Paulic et al., 2014).

2. Material and methods

Four large-scale sites along the present shipping routes and forecasted marine corridors in Canadian Arctic and Sub-Arctic archipelago (Dawson et al., 2016) were selected because of their overlap with identified ESBAs (DFO, 2011, 2014, 2015; Paulic et al., 2014). Acoustic simulations were performed to get three-dimensional (3D) SNL time series at each site from the transiting ships. The results provided a SNL probability density function (pdf) and a cumulative density function (cdf) for each cell of the 3D simulation grids, which were then used to compute and map the risk to exceed given sound pressure level (SPL) thresholds. The acoustic propagation was performed on a high resolution grid over the whole water column. The resulting acoustic field was interpolated on a 1 km × 1 km horizontal resolution grid, and ten depth layers: 10, 25, 50, 75, 100, 150, 200, 250, 300, and 350 m. SNL snapshots were computed at regular time steps of 5 min in order to capture the SPL variations associated with every single ship transit.

The simulation outputs were SNL pdf and did not include any ANL component unless mentioned.

2.1. Data input

The shipping traffic was extracted from 2013 DFO-Coast Guard shipping dataset for Canadian North. A quality control step was necessary before using these ship positions (see Appendix A for more details). The trajectories were interpolated to 1-min steps to feed the ocean acoustic propagation model.

Ship SLs were taken from Simard et al.'s (2016) model of merchant ship SLs, which included some ships transiting in the Canadian Arctic. The SL model uncertainty was taken into account and integrated in the SNL pdf using pdf convolutions (Gervaise et al., 2015). The depths of the sources were derived from ship lengths according to Gray and Greeley (1980).

Water temperature and salinity were taken from operational TOPAZ4 Arctic Ocean model estimates from ocean dynamics modeling and data assimilation (Bertino et al., 2008). The daily average temperature and salinity fields were provided with a 12.5-km horizontal resolution at 12 depths: 5, 30, 50, 100, 200, 400, 700, 1000, 1500, 2000, 2500, and 3000 m. For the present work, we used the July 1st, 2013 3D sample of the temperature and salinity fields. Typical, sound-speed minimum were located at the surface in the Amundsen Gulf and Foxe Basin, 75 m in the Hudson Strait and 20 m in Lancaster Sound (Fig. 7)

Bathymetric data were taken from the General Bathymetric Chart of the Ocean (GEBCO) 30-arc-second-resolution dataset (http://www.gebco.net/) (Fig. 2). In absence of detailed and available geo-acoustical data of the Canadian Arctic, only one geo-acoustical model per study site was considered. Marine bottom and sub-bottom geo-acoustical properties (density, compressional- and shear-wave speed, and