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Underwater acoustic impacts of shipping management measures: Results from a social-ecological model of boat and whale movements in the St. Lawrence River Estuary (Canada)

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ABSTRACT

The recovery of whale species at risk requires the implementation of protection measures designed to mitigate the risks posed by various stressors. In the St. Lawrence Estuary (Canada), several whale species are threatened by navigation activities in various ways. Since 2013, seasonal voluntary ship strike mitigation measures, including a speed reduction area (SRA) and a no-go area, were implemented annually and largely adopted by the maritime industry to reduce the risks of lethal collisions with four species of baleen whales. While the endangered St. Lawrence beluga population is unlikely to be subject to collisions with large merchant ships, it is known to be negatively affected by vessel-generated underwater noise. To assess how these protection measures modify the beluga's soundscape throughout their critical habitat, we implemented an underwater acoustic module within an existing agent-based model (3MTSim) of ship-whale movements and interactions in the St. Lawrence Estuary. We ran multiple simulations for two scenarios 1) *without* and 2) *with* the protection measures to compare the level of noise received by belugas before and after 2013. Overall, the simulations showed a statistically-significant 1.6% decrease in the total amount of noise received by belugas in their critical habitat following the implementation of the protection measures. Although slowing down ships reduces instantaneous radiated noise, it also increases the total amount of acoustic energy released in the environment by extending the time spent in the SRA. Accordingly, our simulations showed a 2.4% increase in the cumulative noise from shipping received by beluga in the SRA. Conversely, belugas located in the Upper Estuary, mostly females and calves, *i.e.*, the most valuable individuals experienced a 5.4% reduction in the cumulative received level of shipping noise. Although refinements are required to improve the modelling of noise sources and propagation for finer scale projections in this complex nearshore environment, this agent-based modelling paradigm of 3MTSim proved informative for underwater acoustic impact assessments.

1. Introduction

The St. Lawrence River Estuary (SLE) in Canada is an important habitat for marine mammals year round, although mainly from May to October. Among them, the resident St. Lawrence beluga whale population (*Delphinapterus leucas*) along with the migratory Northwest Atlantic blue whale (*Balaenoptera musculus*) and the Atlantic fin whale population (*Balaenoptera physalus*) are listed under the Canadian Species At Risk Act (*Species at Risk Act (Canada)*, 2002). Two other baleen whale species along with several species of seals and odontocetes are also frequent visitors of the SLE during summertime, mainly for foraging purposes (Michaud et al., 1997a).

In addition to its rich biodiversity, the SLE is a major seaway linking the Atlantic Ocean to the Great Lakes. Each year, merchant ships conduct more than 7000 transits through the SLE to which are added thousands of trips by whale-watching boats, ferries and pleasure craft (Chion et al., 2009). The resulting co-occurrences between boats and whales have raised concerns about negative

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impacts including both collisions and exposure to underwater noise. While the negative impacts of collisions are obvious, underwater noise impacts on whales such as belugas include behavioral changes affecting foraging efficiency, e.g. avoidance and disturbance (Gomez et al., 2016), changes in vocalizing behaviour (Lesage et al., 1999), communication masking affecting an animal's ability to socialize and locate prey (Erbe et al., 2016) and hearing loss (Finneran et al., 2002; Schlundt et al., 2000). In the SLE, such threats are identified as potentially limiting the recovery of the North Atlantic blue whale (Beauchamp et al., 2009) and the St. Lawrence beluga population (Fisheries and Oceans Canada, 2012). Although avoidance behaviors have been observed in the study area, we know very little about frequency-dependent thresholds of noise levels that trigger such responses with potential long-term consequences (Gomez et al., 2016). Similarly, other potentially critical impacts of anthropogenic noise on belugas including the masking of their vital acoustic activities, e.g. echolocation, communication (Erbe et al., 2016) remain unclear at present.

The Saguenay-St. Lawrence Marine Park (marine park thereafter) is a marine protected area co-managed by Parks Canada and Parcs Québec located at the heart of the St. Lawrence beluga's critical habitat (Fisheries and Oceans Canada, 2012; Government of Canada, 1997). The marine park was initially designed to enhance the conservation of marine mammals with particular reference to the endangered beluga whale (cf. Fig. 1) and its regulations have been mainly designed with regard to managing the commercial and recreational whale-watching industry (Parks Canada, 2002). However, the issue of the risks of lethal ship strikes by merchant ships on large whales was not addressed by these regulations. Therefore, an interdisciplinary research project was initiated in 2006 to build decision support tools to inform the mitigation of ship-whale collisions in the SLE (Parrott et al., 2011). Following two years of collaboration, the Working Group for Maritime Transportation and Marine Mammal Protection (Working Group thereafter) involving stakeholders from the public, private, NGO, and academic sectors recommended in 2013 a set of voluntary protection measures to enhance marine mammal protection and considered compliance would not require mandatory regulations (Canadian Coast Guard, 2016). As it was determined that the risks of lethal collisions to large marine mammals increased with ship speed and the number of ship-whale co-occurrences (Laist et al., 2001; Vanderlaan and Taggart, 2007), the protection measures include a Speed Reduction Area (SRA), a No-Go Area (NGA), and a recommendation to navigate in the northern part of the SLE to keep transiting ships away from the south shore highly used by pods of female and young belugas (Fig. 1). These measures are intended to reduce the risks of lethal collisions between merchant ships and baleen whales without increasing the level of noise exposure for belugas (Parrott et al., 2016).

More than 3 years after the implementation of the protection measures in the SLE, the risks of lethal collisions between large merchant ships and the five main species of baleen whales have decreased by up to 40% in the marine park from May to October (Chion, 2016). These gains in conservation are mostly due to the maritime industry's compliance with the voluntary SRA (Parrott et al., 2016), as shown in the Fig. A1d (Appendix A). For the Saguenay River and the Upper Estuary, no statistically-significant change in average ship speed was found after as compared to before the implementation of the protection measures (cf. Fig. A1a and b), confirming the absence of side-effects beyond their spatial boundaries.

These protection measures were intended to mitigate the risks of collision between large merchant ships and baleen whales in the SLE where these species mostly concentrate (Chion et al., 2012; Michaud et al., 1997b, 2008; Michaud and Giard, 1997). Beluga whales are considered subject to collisions with highly maneuverable and fast-moving boats (Fisheries and Oceans Canada, 2012) however, large merchant ships do not appear to be involved in mortality events attributed to ship strikes. This is possibly because collisions with large vessels are likely to result in a complete sectioning of the body, although this has not been documented (Lair et al., 2016). Nonetheless, the beluga is a toothed whale relying heavily on sound to communicate, as well as to locate and hunt their prey (Erbe et al., 2016; Lesage et al., 1999; Weilgart, 2007). By modifying some shipping-traffic parameters (mostly speed), compliance with the protection measures may have inadvertently modified the beluga's soundscape. Given the absence of any permanent acoustic monitoring system throughout the beluga's critical habitat, we proposed to combine agent-based modelling with acoustic sound-source and propagation models to assess the likely changes induced by the collision protection measures to the beluga's summer-habitat soundscape.

In the context of the Working Group's adaptive management process, our objectives were to assess the likely acoustic impacts of the voluntary protection measures on the SLE beluga's soundscape and to recommend further actions to investigate this emerging issue of the effects of anthropogenic noise. To this end, we report on the simulation results of a new version of the Marine Mammals and Maritime Traffic Simulator (3MTSim), an agent-based spatial model of boat and whale movements (Parrott et al., 2011) which has already been used to support management decisions in the SLE (Chion et al., 2012, 2013). This revised version of 3MTSim integrates acoustic models of both sound sources (*i.e.* merchant ships) and underwater noise propagation (*i.e.* transmission loss) to simulate the soundscape under various marine traffic scenarios. We first give an overview of 3MTSim described in previous publications (Chion, 2011; Chion et al., 2011; Lamontagne, 2009; Parrott et al., 2011) followed by a description of the acoustic models including the data used for calibration. We further present 3MTSim simulation results focusing on the changes in the beluga's soundscape with and without the ship-strike mitigation measures to detect any potential positive or negative side-effects. After a discussion of our results with regard to the known ecological characteristics of the beluga population, we conclude with some management implications of our results and identify future work to refine 3MTSim as an acoustic impact assessment tool.

2. Materials and methods

2.1. 3MTSim general overview

Relying on more than 25 years of data collection on whale ecology and the recent availability of data on navigation activities in the SLE and the Saguenay River (cf. map), 3MTSim was implemented using the agent-based modelling paradigm (Bonabeau, 2002; Grimm et al., 2005). 3MTSim simulates the movements of individual boats (2D) and marine mammals (3D) through the study area (cf. Fig. 1) at 1-min time intervals (Parrott et al., 2011). The primary goal of this social-ecological model is to assess how alternative scenarios of traffic management in the study area would potentially impact both marine mammals and navigation activities. The main indicators returned by the first version of 3MTSim were the transit times across the area for merchant ships, the activity budget for whale-watching vessels, the frequency of encounters between marine mammals and boats, and the risks of lethal ship strikes (see (Parrott et al., 2011) for a full description of the simulator and data). After several validation steps (Chion, 2011; Chion et al., 2011; Lamontagne, 2009), 3MTSim was used to inform various policy-making processes mostly related to the reduction of boat-whale close encounters (Chion et al., 2014, 2013) and the mitigation of ship strike risks (Chion et al., 2012).