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Exposure of the beluga (*Delphinapterus leucas*) to marine traffic under various scenarios of transit route diversion in the St. Lawrence Estuary

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The St. Lawrence Estuary (SLE) marine shipping lane currently overlaps with the main aggregation area for large baleen whales, male beluga and whale-watching activity, raising concerns for potential whale/ship or whale-watch vessel/ship collisions. Motivated by the desire to reduce collision risks, authorities from the Saguenay-St. Lawrence Marine Park and the future Marine Protected Area through the *Groupe de Travail sur le Trafic Maritime et la Protection des Mammifères Marins* (G2T3M) have proposed to the marine transport industry to reduce vessel speed to 10 kt within a particularly sensitive area at the head of the Laurentian Channel in the North Channel (NC), while leaving pilots the option of diverting their route to the South Channel (SC), thereby avoiding most of the speed-reduction zone and areas of whale aggregation. The present study indicates that commercial traffic transiting through the SLE exposes many times daily a substantial proportion (15-53%) of the SLE beluga population, of which the vast majority (72-81%) are females with calves or juveniles, to noise levels likely to induce negative behavioural responses in a majority of the exposed individuals. Diverting shipping to the South Channel not only increases the proportion of the population and its habitat (including designated Critical Habitat) exposed to noise levels in excess of the threshold for negative behavioural responses, but also contributes to the acoustic degradation of beluga habitat south of Île Rouge, previously relatively lightly exposed to shipping noise. We therefore conclude that maintaining or concentrating commercial traffic as much as possible in the NC constitutes the scenario which minimizes impacts on beluga and their habitat. A reduction in vessel speed or size, changes in vessel designs, or any other measure that might make vessels quieter, would contribute to reducing potential negative effects on SLE beluga.

Exposition du béluga (*Dephinapterus leucas*) au trafic maritime associée à divers scénarios de déviation des routes de transit dans l'estuaire du Saint-Laurent

RÉSUMÉ

La voie maritime dans l'estuaire du Saint-Laurent (ESL) chevauche actuellement les aires principales d'agrégation des grands rorquals, des bélugas mâles, et des activités d'observations en mer de mammifères marins, soulevant des préoccupations quant à de possibles collisions entre les navires et les baleines, ou entre les navires et les embarcations engagées dans des activités d'observations en mer. Motivés par la volonté de réduire les risques de collisions, les autorités du Parc Marin Saguenay-Saint-Laurent et celles de la future Aire Marine Protégée de l'ESL par l'entremise du *Groupe de Travail sur le Trafic Maritime et la Protection des Mammifères Marins* (G2T3M) ont proposé à l'industrie maritime du transport de réduire la vitesse des navires à 10 nœuds dans un secteur particulièrement sensible situé à la tête du Chenal Laurentien dans le Chenal Nord (CN), tout en laissant la possibilité aux pilotes de dévier leur course vers le Chenal Sud (CS), évitant ainsi presque toute la zone de réduction de vitesse et les aires d'agrégation de rorquals. La présente étude indique que le trafic commercial transitant dans l'estuaire expose plusieurs fois par jour une portion substantielle (15-53 %) de la population de bélugas de l'ESL, dont une grande majorité (72-81 %) sont des femelles accompagnées de veaux ou de juvéniles, à des niveaux de bruit susceptibles d'entraîner des réponses comportementales négatives chez une majorité des individus exposés. Une déviation du trafic vers le CS entraînerait non seulement une augmentation de la proportion de la population et de son habitat (incluant son Habitat Critique) exposés à des niveaux de bruits supérieurs aux seuils d'effets comportementaux négatifs, mais contribuerait aussi à la dégradation acoustique des habitats du béluga situées au sud de l'Île Rouge, jusqu'ici relativement peu exposés au bruit associé à la navigation. Nous concluons donc que de maintenir ou de concentrer autant que possible la navigation marchande dans le CN constitue le scénario qui minimise les impacts sur le béluga et son habitat. Une diminution de la vitesse des navires ou de leur taille, des changements dans leur design, ou toute autre mesure ayant pour effet de les rendre plus silencieux, contribuerait à réduire les effets négatifs sur les bélugas de l'ESL.

INTRODUCTION

The lower portion of the St. Lawrence River Estuary (SLE) is designated as an *Ecologically and Biologically Significant Area* of the St. Lawrence system. The particular hydrographical dynamics at the head of the Laurentian Channel promotes local productivity and prey aggregation, resulting in moderate to high species biodiversity (Savenkoff et al. 2007). At least 10 marine mammal species visit the area seasonally to feed, whereas the beluga (*Delphinapterus leucas*) and harbour seal (*Phoca vitulina*) use the Estuary throughout the year to feed, breed and rear their young (Lesage et al. 2007).

The beluga population is considered *Threatened* in Canada, and *At Risk of Extinction* under the Species at Risk Act (SARA). During summer, their distribution is centered on the Saguenay River mouth, but varies spatially depending on age- and sex-classes (Michaud 1993). Large white individuals presumed to be adult males, concentrate along the north shore of the Lower Estuary over the deeper and colder waters of the Laurentian Channel where baleen whales also aggregate. White animals, likely adult females, accompanied by calves and juveniles mainly occupy the shallower, warmer waters of the Upper Estuary and the south shore of the Lower Estuary, overlapping their distribution with male herds in and at the mouth of the Saguenay River (Figure 1a).

Marine mammals in the SLE are exposed regularly to commercial shipping, particularly along the north shore where the shipping lane is located (Chion et al. 2012). During summer, a fleet of approximately 40 whale-watching vessels offering several departures a day adds to the marine traffic in the Lower Estuary by concentrating their activities over the deeper waters of the Laurentian Channel (LC) and at the Saguenay River mouth. As a result, the traffic lane currently overlaps with the main aggregation area for large baleen whale, male beluga and whale-watching activity (Figure 1a), raising concerns for potential whale/ship or whale-watch vessel/ship interactions. Motivated by the desire to reduce collision risks for baleen whales, authorities from the Saguenay-St. Lawrence Marine Park and the future Marine Protected Area through the *Groupe de Travail sur le Trafic Maritime et la Protection des Mammifères Marins* (G2T3M) have proposed to the marine transport industry to reduce vessel speed to 10 kt within a particularly sensitive area at the head of the Laurentian Channel (Figure 1a), while leaving pilots the option of diverting their route to the South Channel (Figure 1b), thereby avoiding areas of whale aggregation. However, shifting commercial traffic to the South Channel (SC) will alter the pattern of exposure of SLE beluga to marine traffic, possibly increasing exposure of the females with calf/juvenile component of the population and their habitat compared to the current shipping route pattern (Figure 1c).

In this context, DFO Science was requested to examine exposure of SLE beluga to marine traffic under the proposed commercial shipping guidelines (hereafter known as the *Hybrid* scenario) as compared to current traffic conditions, and to assess the possible consequences for this SARA-listed population.

RATIONALE AND GENERAL APPROACH

Marine traffic can negatively impact marine mammals through collisions and generated noise. Collisions may result in mortalities or injuries, and depend on vessel type and speed, and a series of factors inherent to the exposed species such as their capacity to hear and avoid approaching vessels, motivation and behavioural activity (Laist et al. 2001; Parks et al. 2012; Allen et al. 2012). Pinnipeds and small odontocetes manoeuvre rapidly and swiftly, and thus are less prone to collisions with large vessels than mysticetes. This is supported by the lack of evidence in the literature for collision between large, slow moving ships and small odontocetes (Van Waerebeek et al. 2007) although it is acknowledged that the number of marine mammal interactions with vessels is largely underestimated. The beluga is a small cetacean with highly acute hearing in terms of directionality and critical ratio (Johnson et al. 1989; Erbe 2008; Mooney et al. 2008) and high manoeuvrability. As a result, we considered beluga at no risk of collision with large commercial ships given the generally low speed and predictable trajectory of these vessels. Consequently, changes in collision risk associated with alternate shipping route scenarios were not examined in this study.

Exposure to ship noise or overlap in distribution with shipping routes may or may not lead to injuries or other negative effects on marine mammal health, behaviour, and habitat use. The degree of reaction to noise and vessel traffic depends on a variety of factors (Richardson et al. 1995; Southall et al. 2007), and effects can be categorized as follows:

1. the noise may be too weak to be heard, i.e., below ambient level or the hearing threshold at the specific frequencies where noise is emitted;
2. the noise may be audible without eliciting negative behavioural or physiological response;
3. the noise may be audible and elicit a negative response that can range from temporary alertness, to active avoidance of the area for short to prolonged period of time;
4. the noise may mask components of incoming communication calls or interfere with calls or environmental sounds useful to some vital functions (e.g., foraging, navigation, finding mates or reproduction);
5. the noise can result in a progressive decrease in response as the animals habituate to it; or alternatively,
6. the noise can cause repeated and persistent disturbance or physiological stress if the animal remains in the area because of its importance for vital functions or because of a lack of alternate locations to fulfil essential biological needs; and,
7. the noise, if it is very strong, can lead to temporary or permanent hearing damage.

Behavioural reactions to sound exposure occur primarily as a result of the physical characteristics of the noise, irrespective of period of exposure (Ellison et al. 2012, Götz and Janik 2011). However, behavioural reaction to noise has been shown to vary widely among studies (Southall et al. 2007), suggesting that environmental, operational and biological factors are likely to play a significant role in determining the probability and severity of the invoked reaction, particularly at low sound pressure levels (SPL) (Southall et al. 2007; Ellison et al. 2012). This dramatic variability among species and individuals makes it challenging to broadly characterize the impacts of shipping noise on marine mammal species (Ellison et al. 2012). As a result, there is a growing consensus that assessing likelihood of behavioural effects using received SPL alone according to a zone-of-influence or dose-response concept (Richardson et al. 1995), without taking into account context of exposure and receiver’s motivation, experience and conditioning, may not be appropriate (Southall et al. 2007, Ellison et al. 2012). However, there is little information available to assess these factors in an objective and a quantitative way. There is also no standards or criteria to estimate sound exposure levels (SEL) beyond which long-term effects may become important.

Furthermore, there are currently no data available to assess with any degree of certainty the proportion of the exposed marine mammals which will suffer from shipping noise to the point where detrimental effects on health, reproduction, or survival would be observed. One step towards estimating the significance of impacts is to determine the number of potential individual-exposures relative to total population size (e.g., Wood et al. 2012; Lawson and Lesage 2013). Another is to determine whether specific segments of the population are likely to be impacted more than others (e.g., calving females). This approach has been used as a standard by the National Marine Fisheries Service (NMFS, US) when assessing potential impacts of various types of projects and noise sources on marine mammals, including impulsive or more continuous/chronic sound sources such as shipping noise.

The proportion of a population that will be exposed to a given level of noise is a function of their local density, as well as shipping traffic volume, trajectory and source level, whereas duration of exposure will also depend on residency time and behaviour, as well as vessel speed. The number of individual-exposures per year for a population of interest can be estimated by multiplying the zone of influence (ZOI) around a ship track by local population density estimates and number of ship transits during periods of overlap, corrected for seasonal use of the area. Note that individual-exposures are not equivalent to the number of individuals exposed; it is assumed that the individual-exposure metric includes the likely repeated exposure of the same individuals over a given period. A ZOI is defined as the area around a ship track where 50% of the exposed animals are expected to react negatively to the noise source. The ZOI around a ship can be estimated using sound propagation models parameterized specifically for the noise source being evaluated or alternatively, for similar sound sources and environments. For continuous sources of noise (e.g., shipping, drilling, dredging), negative responses ranging from alertness, to minor to strong avoidance of the ensonified area, have been observed at received sound pressure levels (SPL) as low as 90-120 dB re 1 μPa rms for mid-frequency cetaceans such as the beluga, while in other field settings, individuals of this functional hearing group failed to exhibited such responses at SPL below 150 dB re 1 μPa rms (reviewed in Southall et al. 2007).

In their evaluation of acoustic effects of development projects on marine mammals, the US National Marine Fisheries Service (NMFS) has set the threshold where it is expected that 50% of the exposed individuals will react negatively to a continuous noise source at 120 dB re 1 μPa rms, based largely on the findings from Malme et al. (1984) and Richardson et al. (1990). More recently, Southall et al. (2007) suggested taking into account the auditory capacity of the species of concern in calculating exposure. Several frequency-weighting functions are available, with some being more conservative than others (reviewed in McQuinn et al. 2011; Finneran and Jenkins 2012). To examine the possible degree of exposure of the beluga population, we used 1) the NMFS criteria, i.e., 120 dB re 1 μPa rms, without correction for beluga auditory capacity, and 2) the same criteria to which we applied two different frequency-dependent weighting functions (M-weighting and C-weighting; see below). Frequency-dependent weighting functions are usually applied to the measured sound pressure before calculation of the overall SPL. These functions essentially de-emphasize frequencies where the receiver's sensitivity is lower. In the absence of comprehensive data for marine mammals, Southall et al. (2007) derived theoretical M-weighting functions for the various functional marine mammal hearing groups, based loosely on the human C-weighting equations, and known or estimated auditory sensitivity of these groups, to model their perception of sound loudness at different frequencies. This modeled approach assumed a relatively flat response over the receiver's optimal hearing range, and simulated the reduction in hearing sensitivity in the non-optimal frequency band. These auditory functions are expected to be precautionary as they are intentionally wide and thus, likely overestimate detected sound levels at the low and high end of the functional hearing band. More recently, a combination of the M-weighting functions of Southall et al. (2007) and C-weighting functions based on experimental equal loudness contours of Finneran and Schlundt (2010; 2011) were used to derive what was called Type II weighting functions in the context of an analysis of U.S. Navy acoustic and explosive effects (Finneran and Jenkins 2012). McQuinn et al (2011) used both C- and M-weighting separately in a study comparing the two approaches on noise levels in the St. Lawrence beluga habitat.

Impacts can be measured in terms of the proportion of the population exposed, or of the available habitat ensonified, with or without taking into account the duration aspect of the exposure. In order to qualify impacts, segments of the population (e.g., females with calves vs adult males) affected by noise exposure can also be assessed.

MATERIALS AND METHODS

The period of concern for elevated collision risks between commercial vessels and large baleen whales is from May to October, the main feeding season for large whales in the SLE. Available data for this period to characterize beluga habitat use, vessel traffic and acoustic properties and the environment included beluga spatial densities, shipping volume, site-specific sound propagation parameters, and vessel acoustic signatures and source levels. However, there are no reliable data available regarding beluga residency time and site-specific behavior.

BELUGA DENSITIES

The number of individuals exposed to noise levels likely to cause behavioural disruption was derived from beluga spatial densities obtained from 35 replicate systematic aerial surveys conducted in late August between 1988 and 2009 (A. Mosnier and J.-F. Gosselin[1], unpublished data). Briefly, these surveys were conducted using two planes flying systematic transect lines perpendicular to the axis of the Estuary, and covering the summer distribution of SLE beluga. Flying altitude was 1000 to 1500 ft (305 and 457 m) in the case of visual surveys, and 4000 ft (1219 m) in the case of photographic surveys, resulting in a sampling coverage of up to 50% (Gosselin et al. 2014, and references therein). Local mean densities were estimated using the fixed kernel method and grids with a cell size of 1000 x 1000 m (A. Mosnier and J.-F. Gosselin unpublished data) (Figure 1c). Beluga densities at the end of August were assumed to be representative of the beluga distribution during the summer period and thus, during most if not all of the period of interest (May to October).

TRANSIT ROUTES

The vast majority of commercial traffic transits by the current two-lane North Channel route (Figure 1a), as adopted by the International Maritime Organization. With the instauration of a voluntary 10 kt speed limit at the head of the Laurentian Channel, as proposed by the SSLMP and MPA authorities through the *Hybrid* scenario (Figure 1b), it is suspected that a proportion of that North-Channel traffic will choose to take the longer, but less-restricted South Channel,

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thereby increasing traffic in an area which previously has had very little commercial shipping (Figure 1a, b).

TRAFFIC STATISTICS

Information on vessel type, and temporal and spatial density of traffic was obtained from the INNAV database (Canadian Coast Guard). The transit analysis does not consider seasonal effects and is based on the total number of transits over the period from May to October along the North and South Channels from 2002 to 2007, and in 2012 (Table 1).

SOUND AND VESSEL TRACK RECORDINGS

Acoustic data used for these analyses were acquired from the study area in 2004-2005 as part of a project describing the ambient and vessel-generated noise characteristics in the SLE, specifically targeting beluga habitat (McQuinn et al. 2011). As part of that study, noise signatures of various vessel types including merchant ships plying the SLE were recorded on a calibrated, surface-deployed, passive-acoustic system (RUSTLER) to determine the frequency composition and source levels of passing vessels (see McQuinn et al. 2011 for specifications). Sound levels were recorded during 10-min sampling periods, some of which were adjacent to the shipping lanes (Figure 1c). Simultaneously, the estimated bearing, range – mostly by radar - and time relative to the start of the sound recording of all visible vessels (commercial and recreational) were logged. In addition, when vessels passed close by the recording station (within 2 km, and at times 10-100's of m), the vessels were actively tracked by logging their coordinates (range, bearing and time) at regular intervals, e.g. every 30 s or so. The ship's trajectory and speed were determined from these data. Information on the vessels' identity and characteristics were obtained from the Canadian Coast Guard pilot station at Les Escoumins.

Although hundreds of vessel sighting and signatures were recorded, not all sightings were suitable for source level estimation. To effectively measure a vessels source level, certain criteria had to be met to avoid contamination from other noise sources, primarily other vessels. Also, because accurate estimates of vessel range are important for the accurate evaluation of source level, we attempted to validate range estimates where possible by calculating vessel speed from multiple range-bearing-time fixes. A subset of vessels was thus chosen for further analyses if they respected the following selection criteria:

- The vessel was the closest to the recording platform,
- There was no other commercial vessel was within 6 km of the recording platform,
- At least 2 positions were logged,
- The vessel was within 3 km of the recording platform at CPA.

In addition, sound propagation measurements were made to determine transmission losses at the various sites using pure tones generated from a calibrated projector at frequencies ranging from 1000 to 6000 Hz (McQuinn et al. 2011). With these two sources of locally-derived measurements, we were able to parameterized simple 1-D horizontal sound-propagation models to determine site-specific ZOIs around ship tracks where threshold noise levels were reached.

ESTIMATION OF ZOI

The vessel tracks were reconstituted and merged with the normalized sound files in a GIS framework. Source levels (*SL*) were estimated from receive levels (*RL*) for each recorded vessel as follows:

$$SL = RL + TL$$

by assuming that transmission loss (*TL*) was described by the following function:

$$TL = 20 \log_{10} (r_1) + c \log_{10} (r - r_1) + \alpha r \quad (1)$$

where r is the range (m) of the vessel to the receiver, r_1 is the range of the near field (approximately equal to 3 times the bottom depth) in which 20 log r or spherical-spreading losses would be expected, c is the site-specific spreading-loss coefficient determined from the propagation experiments at 1000 Hz (McQuinn et al. 2011) and α is the absorption loss coefficient equal to 0.06 dB per km. Source level was determined for the time segment closest to CPA while being beyond the near field.

From the vessel-specific source levels, projected receive levels from each vessel were estimated using eq. 1 in reverse, where the value of c was taken from McQuinn et al. (2011) for the corresponding sector of the Estuary (Upper Estuary = 16.8; southwest of Ile Rouge = 17.2; head of LC = 18.0). The ZOI for a given route was determined as the area around the vessel (e.g. Figure 2) where theoretical sound levels exceeded the chosen criteria, i.e. 120 dB (see RATIONALE AND GENERAL APPROACH).

Sound exposure levels (SEL) were also estimated by spatially integrating the projected SPL emanating from a vessel for every point surrounding a given vessel’s trajectory, i.e. the total cumulative exposure for the vessel transit (Figure 2). A vessel transiting at half speed would thus produce levels of 3 dB higher (double the intensity) due to the doubling of the exposure (double the time for the same distance travelled).

As part of the mitigation strategy by the G2T3M to avoid harmful whale/ship interactions, the *Hybrid* scenario proposes a speed-reduction zone of 10 kt along the NC between the pilot station at Les Escoumins and Ile Rouge (Figure 1a). Therefore vessels which remain along the NC and reduce speed to 10 kt will also decrease their acoustic footprint by decreasing their SL. McKenna et al. (2013) derived a simple model relating the decrease in noise generation with a reduction of vessel speed for container ships off the southern Californian coast. This relationship was used in our simulations to account for this speed-related noise reduction. Accordingly, the SL for container ships was decreased by 3.5 dB to simulate compliance with the 10 kt speed limit in the *Hybrid* zone, no matter which route was taken.

AUDIOGRAM AND WEIGTHING FUNCTIONS

The beluga is a cetacean which belongs to the mid-frequency hearing functional group (Southall et al. 2007), with a hearing frequency range of 150 to 160,000 Hz. To determine audible levels for beluga throughout the study area, McQuinn et al. (2011) applied both an M-weighting function based on a theoretical mid-frequency hearing odontocete (Southall et al. 2007) and a C-weighting function based on an experimental mid-frequency odontocete audiogram and equal-loudness curves (Finneran and Schlundt 2011). However, since the C-weighting method assumes that *ex situ* hearing experiment results conducted on captive animals are transferable to the wild SLE beluga population, we also estimated the more conservative M-weighted audible levels, as well as an un-weighted broadband (10-24000 Hz) receive level.

Further, there are no criteria in the literature with which to compare frequency-dependent weighted received levels for an indication of possible impacts on marine mammals. Yet, in some studies, such weighting functions have been applied against un-weighted criteria when evaluating impacts of man-made noise on marine mammals. As an example, we calculated the projected M-weighted and C-weighted ZOI for a container ship along the SC route and the NC route, respectively, to compare with the un-weighted broadband ZOIs.

EXPOSURE

To estimate the change in exposure of the SLE beluga population due to a change in traffic routes, we first estimated the population's current exposure per passage and vessel group. Projected ZOIs throughout the beluga summer distribution were overlaid with the estimated local beluga densities (see 'Beluga densities' above). In addition, beluga densities were subdivided into herds of females accompanied by calves or juveniles (FCJ), adults only (presumed to be males), and mixed herds (adults only or FCJ) (Michaud 1993). We then re-estimated the proportion of the population (by mixture group) exposed to a vessel's acoustic footprint for (a) the NC route (upstream and downstream) with reduced vessel speed in the *Hybrid* zone, (b) the SC route (downstream), south of Ile Rouge and back to the north shore (hereafter known as the *Provisional* scenario), and (c) the SC route (downstream), south of Ile Rouge and following the boundary of the *Hybrid* zone before heading due north back to the pilot station on the north shore (Figure 1b). Changes in exposure as a function of route, scenario and vessel group was quantified in terms of the proportion of the population, as well as the amount of their habitat, exposed to noise levels likely to induce negative behavioural responses. Habitat exposure was described with two metrics, i.e., amount of area used by the different mixture groups, and amount of the designated Critical Habitat, which essentially corresponds to areas used by FCJ or mixed herds (DFO 2012).

RESULTS

VESSEL TRAFFIC

Between 2002 and 2007, 90-94% of all commercial vessel traffic followed the North Channel of the SLE (Table 1), either upstream in the north lane or downstream in the south lane (Figure 1a). Both these lanes pass on the north side of Ile Rouge (Figure 1b). During the same period, 6-10% (196-433/year) of the total vessel traffic took the South Channel, southeast of Ile Rouge (Table 1). Of those vessels which took the SC, most were barges and tugs, followed by bulk carriers and container ships.

A preliminary analysis of the possible effects of the voluntary speed limits on the choice of route taken by pilots (Chion et al. 2012) suggested that it would not be advantageous to choose the SC unless the vessels operating speed exceeded 14 kt. A further analysis showed that of the merchant vessels which had chosen the NC in 2007, 18.4% (502/2734) navigated at speeds exceeding this limit, (Chion 2013), with container ships dominating (88%) this category of traffic.

There is therefore a potential for an increase of 502 vessel passages via the SC, or 3 times the current traffic. However, between 2005 and 2007, 65-67% of the vessels choosing to transit by the SC were travelling downstream (Chion 2013), mainly due to logistical considerations. Therefore vessels in this group traveling downstream would have twice the probability of choosing the SC compared to vessels transiting upstream. Assuming that 50% of vessels travel in the downstream direction and 50% travel upstream, and that all the vessels travelling downstream at speeds > 14kt chose the SC, and half the vessels upstream did the same, the projected potential increase would be 375 vessels or 2.5 times current traffic.

SOURCE LEVEL

Of the hundreds of vessel sightings recorded from > 60 different commercial vessels, at least 13 exceeded the selection criteria (Table 2), including 2 general cargo vessels, 5 bulk carriers, 4 tankers (oil/chemical/general) and 2 container ships. These ships were recorded from various stations along the SLE (Figure 1c). Estimated SL varied from 180.0 to 190.0 dB re 1 µPa rms, with the mean at 185.4 dB and a SL distribution centered at 184-186 dB (Figure 3). These levels are similar to SLs measured by Hatch et al. (2008) and McKenna et al. (2013). There was a tendency for container ships to have a higher SL than the other ships in the main group, however the sample size was small (n=2).

Source level showed weak but increasing trends with vessel length, speed and gross tonnage (Figure 4a,b,c) although little relationship with the vessel's age (Figure 4d). However, since there is obviously autocorrelation between these variables, as can be seen between vessel length and speed (Figure 4e), we can conclude that in general, bigger, faster vessels are the loudest, in agreement with McKenna et al. (2013).

Spectral composition was concentrated in the low-frequency band (Figure 5), with the dominant tone generally below 100 Hz (Table 2) and the majority of the acoustic energy below 1000 Hz (Figure 5).

ZOI

Given the distribution of SLs (Figure 3), we ran simulations for three groups of vessels: (1) relatively quiet vessels, including general cargo and bulk carriers (~180 dB), (2) medium-noise vessels – bulk carriers and tankers (~185 dB) and (3) noisy vessels – container ships (~190 dB). From these simulations, the ZOIs around the SC showed a clear dependence on the individual ships SL (Table 2). The ZOI width increased nearly 4-fold between the relatively quiet and noisy vessel groups, ranging from 1,504 m to 5,709 m from the quietest to the noisiest vessel (Table 2).

BELUGA EXPOSURE

The increase in the ZOI with vessel SL (e.g., Figure 6) resulted in a concomitant increase in the number of beluga, as well as the amount of their habitat that would be exposed to noise levels in excess of the threshold where negative behavioural responses may be expected to occur. Exposure of beluga and its habitat increased roughly three-fold between the quietest and noisiest vessels (Table 3).

Current scenario

From our simulations, a commercial ship transiting by the current NC shipping route with no speed reduction exposes 15–48% of the beluga population to noise of 120 dB re 1 µPa rms or more depending on its SL and direction of transit, of which 72-80% would be FCJ (Table 3). Vessels currently diverting part of their path toward the SC with no speed reduction increase beluga exposure to noise of this magnitude by 7–11% per transit compared to those staying in the NC, with 16 to 53% of the population exposed depending on the SL (or vessel group) and direction of transit, again the majority of which (79-81%) being FCJ.

In terms of habitat exposure, a commercial ship transiting by the current NC shipping route with no speed reduction exposes between 579 and 1892 km^2 of the beluga areas of concentration, depending on direction of transit and SL, with 59-71% of the areas being used by FJC (Table 3). Vessels using the SC during part of their transit reduce their overall encroachment on the beluga areas of concentration by 2-3% depending on SL, but increase exposure of areas of concentration of FCJ as well as beluga designated Critical Habitat by 3%.

Note that none of the ZOIs of vessels transiting exclusively through the NC exposed the beluga habitats along the south shore of the Upper Estuary. This included the high-noise ZOI which was shadowed by the islands along the SE boundary of the Upper Estuary (Figure 6). The footprint of the ZOIs was different for vessels using the SC route during part of their transit with no speed reduction, all of which encroached to some degree on previously weakly-impacted beluga habitat whether considering low-, medium- or high-noise vessels (Figure 7). Maximum exposure of the south shore habitat would however be felt along an alternative, yet occasionally used SC route, which runs along the south shore of the estuary (Figure 7d), where numerous mixed social group habitats are found. Taking this alternate route compared to the NC results in a 12% decrease in adult beluga habitat exposure, but a 32% increase in exposure of habitat along the south shore used by a mix of herds composed of adults or of FJC, overall increasing exposure of FCJ and the SLE beluga Critical Habitat by 5% and 18%, respectively (Table 3).

Hybrid and Provisional scenarios

Under the proposed *Hybrid* scenario where a reduction of speed to 10 kt is proposed (Figure 1b), it is expected that at least some of the current NC traffic will deviate to the SC resulting in an increase in vessel noise exposure of beluga along the south shore. However, there will also be a reduction of noise throughout the speed-limited zone as vessels slow down, resulting in reduced noise emission and improvement of the acoustic environment in this area. To quantify these effects, we ran simulations assuming the implementation of the *Hybrid* scenario for the case of a container ship, given that this was the vessel class most likely to affect the SC sound environment and also the most likely to deviate its course to the SC.

For those noisy ships which remain in the NC, there would be a 12% and 10% lesser exposure of the beluga population, along the upstream (Figure 8a) or downstream (Figure 8b) directions, respectively, simply by the effect of reducing speed. The concomitant reduction in exposure for beluga areas of concentration would be 12 and 16% for vessels in upstream and downstream transits; for Critical Habitat, reductions in exposure as a result of speed reduction in the NC would be 7 and 11% for vessels transiting upstream and downstream, respectively (Table 3). For those ships which choose the most probable *Hybrid* route (Figure 8c) so to spend the least time in the speed-reduced zone, the effect would be to increase the exposure of beluga by 21%, and exposure of their areas of concentration and Critical Habitat by 10% and 17%, respectively, relative to the NC route with reduced speed, i.e., without deviation to the SC. As with other deviations to the SC, this scenario reduces exposure of herds of adult beluga and their habitat, but increases exposure of FCJ and the habitat they use.

For those ships which take the SC along the *Provisional* route (the shortest overall route although longer in the 10 kt speed-limit zone), exposure of beluga would be 4% less than with the *Hybrid* scenario with a SC channel deviation, and 16% higher than with a *Hybrid* scenario without deviation to the SC. (Figure 8d). As a corollary, exposure of beluga areas of concentration and Critical Habitat would decrease by 4% and 6% under the *Provisional* scenario with a SC deviation, which would still be 6% and 10% higher exposure than if traffic was maintained in the NC under the *Hybrid* scenario (i.e., with a speed reduction). This *Provisional* scenario would also increase exposure of FCJ by 3%, with this type of herd representing 76% of the beluga exposed to vessel noise.

Audiogram and weighting functions

The projected M-weighted (Figure 9) and C-weighted (Figure 10) ZOI for a container ship along the SC route and the NC route, respectively, was calculated to compare with the un-weighted broadband ZOIs (Figures 7c and 6c). The use of these frequency-dependent weighted received levels considerably reduced beluga and habitat exposures; in the case of M-Weighing, beluga and habitat exposures were approximately equivalent to those predicted for vessels with a source level 10 dB quieter (Table 3).

DISCUSSION

This study is the first attempt at quantifying the exposure of SLE beluga to marine traffic. Our results indicate that a commercial vessel transiting through the SLE exposes a substantial proportion of the beluga population (range 15 to 53%) to noise levels susceptible to induce negative behavioural responses, depending on source level and whether they use exclusively the NC or the SC for part of their transit. Of the animals exposed to shipping traffic, the vast majority (approximately 72–81%) are females with calves or juveniles (FCJ), assuming that half of the beluga in areas with mixed herds are FCJ. Using criteria developed for evaluating impacts of seismic pulses on marine mammals in California (Wood et al. 2012), but adapted to non-pulsed noise sources (see Lawson and Lesage 2013), the magnitude of impact of a single ship transit through the NC of the SLE would be considered high as it exposes more than 2.5% of a SARA-listed population. The increase in exposure of the population (7–11%) associated with the shift of transit route to the SC alone exceeds this threshold. This is also true when considering only the increase of FJC noise exposure (3-4%) for the vessel class most likely to use the alternate route (e.g., container ships), regardless of the scenario used (SC with or without speed reductions).

The alternate SC shipping route changes little the total footprint of shipping in the SLE beluga habitat. However, while the shipping footprint is generally reduced in the adult herd (presumably male) habitat, diverting traffic to the SC systematically increases the footprint in FCJ habitat, resulting in an overall increase of the shipping footprint in what is designated the *Critical Habitat* of SLE beluga(DFO 2012). The partial diversion of shipping towards the SC will also contribute to the acoustic degradation of areas of beluga concentration south of Île Rouge, which previously were relatively lightly exposed to shipping noise. McQuinn et al. (2011) showed that the area southeast of Ile Rouge had a median sound level of 103.8 dB re 1 µPa (rms), compared to 111.4 dB re 1 µPa (rms) for the head of the Laurentian Channel in the shipping lane. Extending these findings to encompass total commercial transits results in each beluga being exposed several times daily to commercial traffic. Considering only those vessels whose cruising speed exceeds 14 kt, there is a potential for almost a tripling of the frequency of exposure of FCJ in this lightly exposed habitat.

These results were obtained using the acoustic footprint of the loudest vessels transiting through the SLE, and the NMFS exposure criteria of 120 dB re 1µPa (rms), i.e., uncorrected for the beluga auditory sensitivity. We feel that these are reasonable assumptions for estimating the impacts of traffic diversion to the SC, given that container ships will be the class of vessels most often transiting via the SC. While sample size to estimate their acoustic footprint was small (n=2), our estimate is similar to that obtained by McKenna et al. (2013) for the same type of vessel.

Intuitively, the use of an impact threshold corrected for the auditory sensitivity of species of concern makes sense, as animals are unlikely to react to sounds they can't hear or feel. However, the type of weighting that should be used for behavioural responses are still debated, and there has been no validation as to the adequacy of M-, C- or A-weighting when assessing the potential for underwater noise to cause behavioural disturbance (Southall et al. 2007; NSF 2011). Noise levels eliciting reactions from exposed animals have been determined in the vast majority of studies without accounting for auditory sensitivity (reviewed in Southall et al. 2007). The 120 dB re 1 µPa (rms) threshold was established specifically for the mid-frequency cetacean functional hearing group without frequency weighting, and thus should be suitable for measuring noise exposure of beluga. Using weighting curves with impact thresholds established based on reactions not taking into account hearing sensitivity would bias the ZOI downward (Table 2, Figures 9, 10). However, this is inconsistent with other evidence that beluga and other cetaceans with hearing sensitivity similar to beluga can detect and react to commercial vessels at distance in the 10's of kilometers and at received levels equivalent to those uncorrected for hearing sensitivity. We provided the ZOI with and without application of a weighting function to illustrate the effect of various methods on the assessment of exposure. In the absence of data to re-evaluate impact thresholds for behavioural disturbance while taking into account hearing sensitivity, we consider the un-weighted results as the most applicable.

To evaluate the effects of a change in shipping route on SLE beluga, one needs to determine impacts of current shipping traffic. While a large body of literature exists documenting short-term effects of noise exposure on marine mammal hearing and behaviour (reviewed in Richardson et al. 1995; Southall et al. 2007), demonstrated long-term effects on individuals or populations are much more scarce as this requires establishing cumulative effects having an incidence on individual health, probability of reproduction or survival (NRC 2005). Major initiatives in the US and UK are currently underway to identify species-specific criteria in terms of duration of exposure and interruption of critical behaviour that are likely to result in a reduced probability of reproduction or survival (e.g. feeding, nursing, etc.). In the meantime, effects of noise on marine mammals have been quantified in terms of the number of individuals exposed to noise levels likely to cause injuries or behavioural reactions in a majority (>50%) of individuals, but without criteria to determine the proportion of those individuals for which exposure is likely to result in impacts on reproduction, health or survival (e.g. Southall et al. 2007; Wood et al. 2012).

One can also take the inverse approach and assess the capacity of the population to support further stress or changes to its environment. The SLE beluga population is currently exposed to regular traffic in the majority of their habitat (Chion et al. 2012 and Figure 1c). Median noise levels are highest in habitat along the north shore of the SLE (109-117 dB) where most of the traffic is currently located (McQuinn et al. 2011). Diverting shipping to the SC where median noise levels are presently low (102-104 dB) would increase the proportion of the population and its habitat exposed to higher levels of noise, regardless of vessel route or speed.

Exposure to noise might result in temporary or persistent physiological (stress) and behavioural responses for a portion of the individuals exposed to anthropogenic noise sources. Behavioural changes can include habitat abandonment, disruption of foraging activity, suppression or alteration of vocalization, or other effects, and lead to chronic stress and population-level impacts (Richardson et al. 1995; Nowacek et al. 2007; Weilgart 2007; Joint Working Group on Vessel Strikes and Acoustic Impacts 2012; Rolland et al. 2012). Until recently, it was not known if exposure to shipping noise could result in physiological responses that may lead to significant consequences for individuals or populations. Rolland et al. (2012) showed that reduced ship traffic in the Bay of Fundy following the terrorist events of 11 Sept. 2001, resulted in a 6 dB decrease (a halving of sound levels) in underwater noise, with a significant reduction at low frequencies. This noise reduction was associated with decreased levels of stress-related faecal hormone metabolites in local North Atlantic right whales (*Eubalaena glacialis*). This is unique 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 (Rolland et al. 2012).

The SLE beluga population has been greatly reduced by past overhunting, and has failed to show signs of recovery despite 30 years of protection (Hammill et al. 2007). They are highly contaminated (reviewed in DFO 2012), and are currently experiencing profound changes in their physical and biological environment, which appear to be detrimental to recruitment (Plourde et al. 2014; Mosnier et al. 2014). While local studies have indicated that SLE beluga are more tolerant to marine traffic (Blane and Jaakson 1994; Lesage et al. 1999) than their counterparts in the Arctic where shipping is practically non-existent (Finley et al. 1990), short-term behavioural effects have been documented in SLE beluga as a result of exposure to marine traffic. Abandonment of sectors such as Tadoussac Bay following the construction of a marina is also suspected to be related to increased vessel traffic. These observations indicate that SLE beluga are not immune to disturbance. In the current context where the beluga population appears to be evolving in a changing and possibly sub-optimal environment, an increase in exposure of females, calves and juveniles and their habitat to shipping are likely to have negative, at best neutral, effects on SLE beluga recovery as it increases the vessel-noise footprint in FCJ habitats, and the beluga Critical Habitat, and contributes to the acoustic degradation of some areas of concentration previously only lightly exposed to shipping noise. However, we are unable to determine the number of individuals and proportion of the population that will be negatively affected by the proposed change.

In conclusion, commercial traffic transiting through the SLE exposes many times daily a substantial proportion of the SLE beluga, of which the vast majority are females with calves or juveniles, to noise levels likely to induce negative behavioural responses in a majority of exposed individuals. Maintaining or concentrating as much as possible commercial traffic in the NC constitutes the scenario which minimizes impacts on beluga and their habitat. A reduction in vessel speed or size, changes in vessel designs, or any other measure that might make vessels quieter, would contribute to reducing potential negative effects on SLE beluga.

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Table 1. Numbers of vessels transiting the North Channel (NC) and the South Channel (SC) as well as the percentage choosing the SC from May to October between 2002 and 2007 according to the INNAV database. The estimate for 2012 came from a preliminary analysis of AIS data.*

Year	NC	SC	% SC
2002	3724	433	10.4%
2003	3071	313	9.2%
2004	3185	196	5.8%
2005	2595	200	7.2%
2006	2341	243	9.4%
2007	2734	249	8.3%
2012*	-	-	12.0%

Table 2. Source levels (SL) estimated from sound recordings of individually tracked commercial vessels transiting the SLE in 2004-2005, their physical characteristics (DWT=deadweight) and transiting speed logged by the Coast Guard (CG), and measured performance (max/cruising). Noise measurements include the year of recording, source level (SL) in dB re 1 µPa @ 1 m, and the frequency (Hz) of the dominant tone. ZOI width at 120 dB re 1 µPa rms was estimated using broadband (BB), M-weighted (M_{wt}) and C-weighted (C_{wt}) filters.

									Speed (kt)			Noise Measurements				ZOI width (m)		
Vessel	Category	Year built	th (m)	Beam (m)	Draught (m)	Keel (m)	Gross tonnage	DWT	CG	Max/ Cruising	Study	Year	SL	Dominant tone	Group	BB	M_{wt}	C_{wt}
Yankcanuk	General Cargo	1963	99	15	6.6	7.9	3,280	4,760	9.1	10.0	-	2004	180.7	36	Quiet			
Kemeri	Oil/chemical Tanker	1985	152	22	9.0	12.2	10,944	17,610	12.8	15.6	11.0	2005	182.1	53	Quiet	1971		
Team Leopard	Chemical Tanker	1985	172	32	8.2	17.9	26,113	46,100	13.1	13.0	15.3	2005	185.5	120	Median			
Cherkassy	General Cargo	1984	177	23	10.1	14.0	16,794	23,181	14.6	17.2	14.3	2005	183.5	53	Median			
Pomorze Zachodnie	Bulk Carrier	1985	180	23	9.9	13.9	16,697	26,696	11.5	11.6	13.6	2005	180.0	33	Quiet	1504		
Taintless	Crude Oil Tanker	1999	183	-	12.2	18.2	27,645	46,217	13.7	16.4	20.0	2005	185.4	42	Median	3064		
Federal Yoshino	Bulk Carrier	2001	190	23	10.6	15.2	19,215	32,845	12.3	13.4	12.7	2005	185.8	50	Median	3223		
Maersk Perth	Container	2001	211	32	12.0	19.0	32,322	39,128	14.0	22.5	19.5	2005	188.6	21	Noisy	5402		
Algoisle	Bulk Carrier	1963	223	23	8.2	11.9	18,126	27,199	10.7	17.0	16.5	2005	184.5	56	Median	3177		
Valgocen	Bulk Carrier	1968	223	22	8.3	12.1	18,089	28,499	8.9	-	12.3	2004	186.2	71	Median	3398		
CSL Assiniboine	Bulk Carrier	1977	224	23	9.0	14.2	23,445	33,309	10.2	10.6	10.8	2005	182.0	57	Quiet			
Cap Romuald	Crude Oil Tanker	1998	224	48	8.4	22.8	81,148	146,639	14.3	-	10.5	2005	184.9	56	Median	2889		
CP Venture	Container	2003	294	32	10.8	21.5	55,994	47,840	18.9	19.8	15.6	2004	190.0	45	Noisy	5709	1564	206

Table 3. Proportion of the SLE beluga population, and habitat area by social group exposed to received levels (broadband – 10-24,000 Hz – and M-weighted) of at least 120 dB re 1 µPa rms for three classes of vessels with different source levels (SL) transiting along the North Channel (NC) (upstream (Up) and downstream (Down)) or the South Channel (SC), under the current, South Shore (S. Shore), Hybrid, Provisional scenarios. Scenarios and specific trajectories are presented in Figure 1b.

						Proportion of the population				Area by zone (km²)				Critical Habitat (km²)
Receive Level	SL (dB)	Scenario	Direction	Trajectory	Distance at 10 kt	Adult & young	Mixed	Adult	Total	Adult & young	Mixed	Adult	Total	
Broadband	190	Current	Down	NC	0.0	0.326	0.104	0.048	0.478	861	481	550	1892	1167
(10-24,000 Hz)				SC	0.0	0.352	0.131	0.048	0.531	913	452	485	1849	1245
		S. Shore		SS	0.0	0.352	0.161	0.024	0.537	908	633	381	1923	1378
		Hybrid		NC	33.0	0.326	0.065	0.037	0.428	862	298	422	1581	1036
				SC	20.0	0.353	0.131	0.033	0.517	914	429	402	1745	1216
		Provisional		SC	28.0	0.352	0.111	0.033	0.496	913	357	406	1676	1142
		Current	Up	NC	0.0	0.286	0.073	0.089	0.448	792	160	669	1620	931
		Hybrid		NC	34.2	0.286	0.036	0.070	0.392	792	96	535	1422	864
	185	Current	Down	NC	0.0	0.205	0.060	0.030	0.295	543	198	329	1070	669
				SC	0.0	0.220	0.069	0.027	0.316	563	188	288	1040	708
	180	Current	Down	NC	0.0	0.102	0.025	0.019	0.146	303	84	192	579	353
				SC	0.0	0.108	0.037	0.016	0.161	312	78	171	561	372
M-weighted	190	Current	Down	NC	0.0	0.107	0.026	0.019	0.152	314	88	199	602	368
				SC	0.0	0.113	0.038	0.017	0.168	324	82	177	583	388

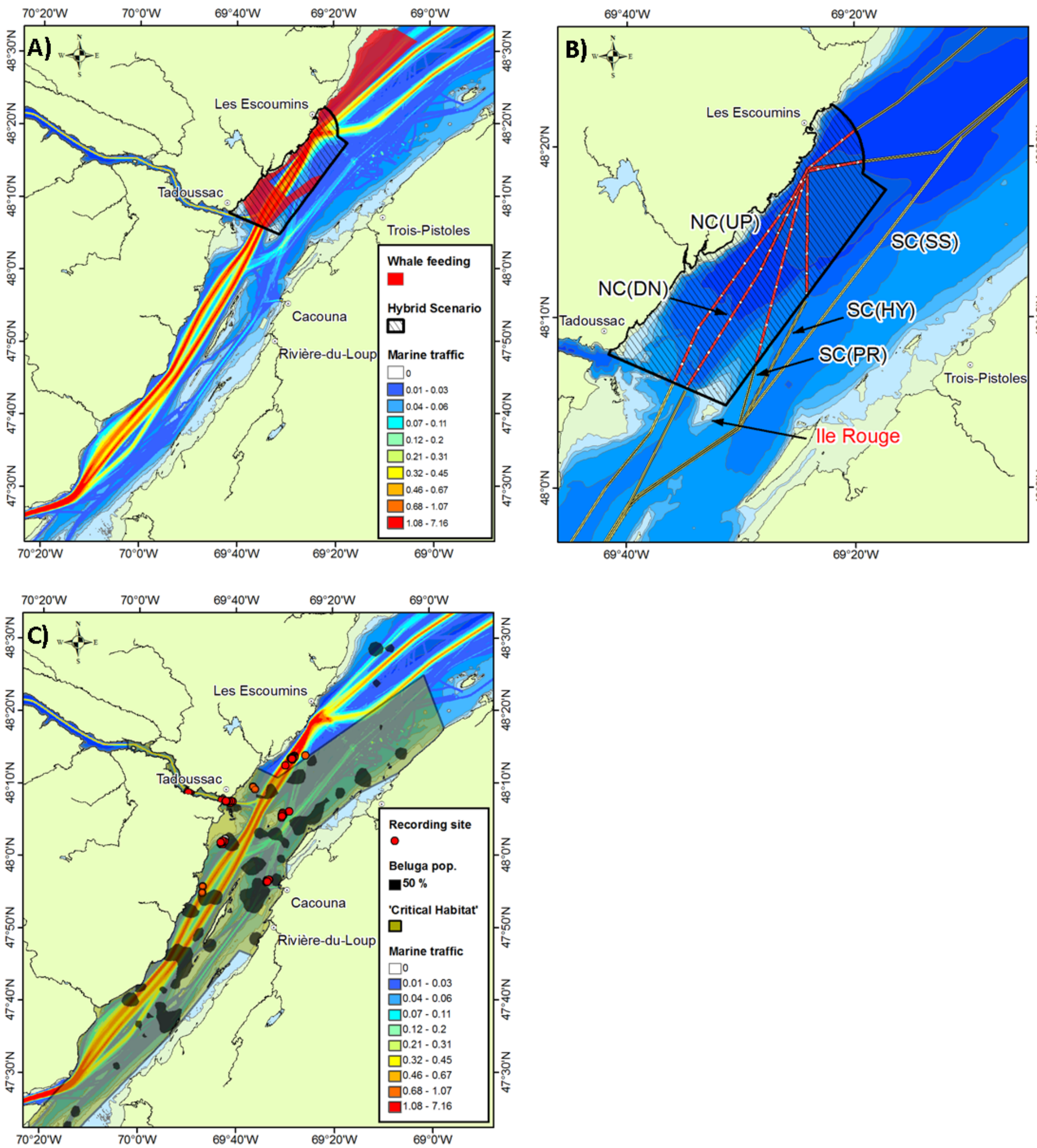

Figure 1. Study area in the St. Lawrence Estuary. (a) Marine traffic as indicated by AIS tracking data, the baleen whale feeding area and high collision risk zone (red zone), and the area of reduced speed (10 kt) under the Hybrid scenario (hashed zone). (b) The North Channel upstream (NCUP), downstream (NCDN), South Channel Provisional (SCPR), Hybrid (SCHY) and south shore (SCSS) traffic lanes are indicated along with the area of reduced speed under the Hybrid scenario (hashed zone). (c) The sites at which acoustic recordings were obtained and areas where 50% of the beluga population resides relative to its 'Critical Habitat'.

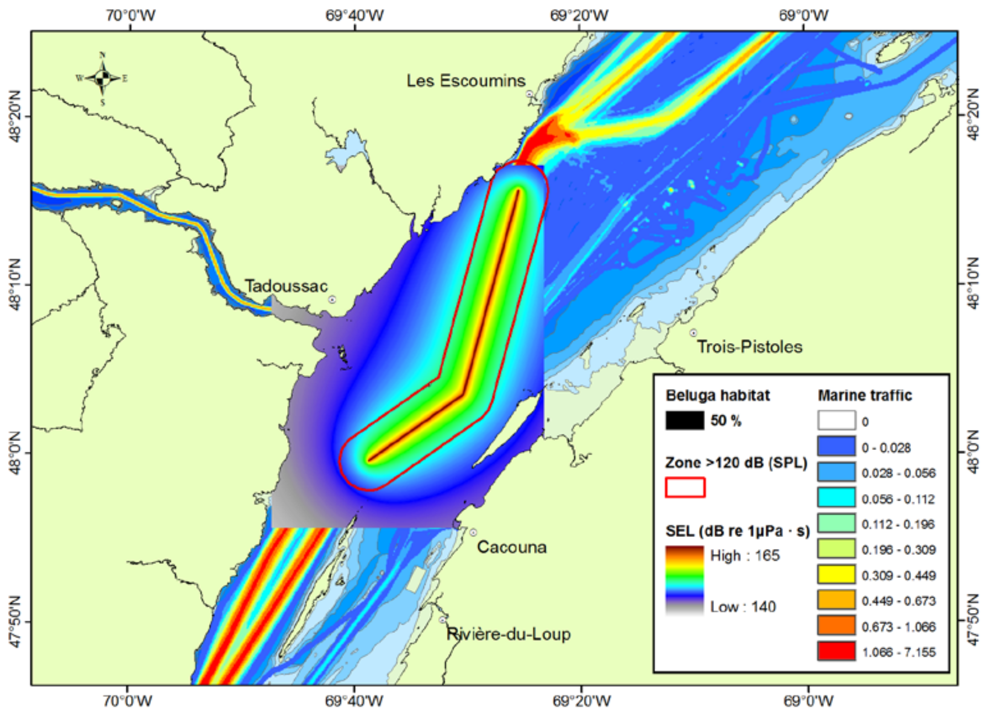

Figure 2. Simulated ZOI (SPL of 120 dB, and SEL) produced by a bulk carrier (Federal Yoshino) transiting the South Channel Provisional trajectory at a constant speed.

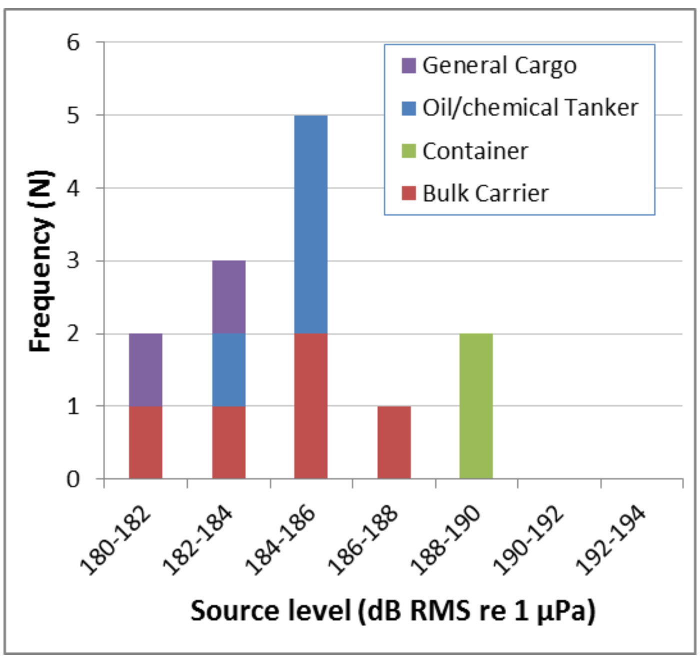

Figure 3. Distribution of source level (dB re 1 µPa @ 1m) estimates by commercial vessel category.

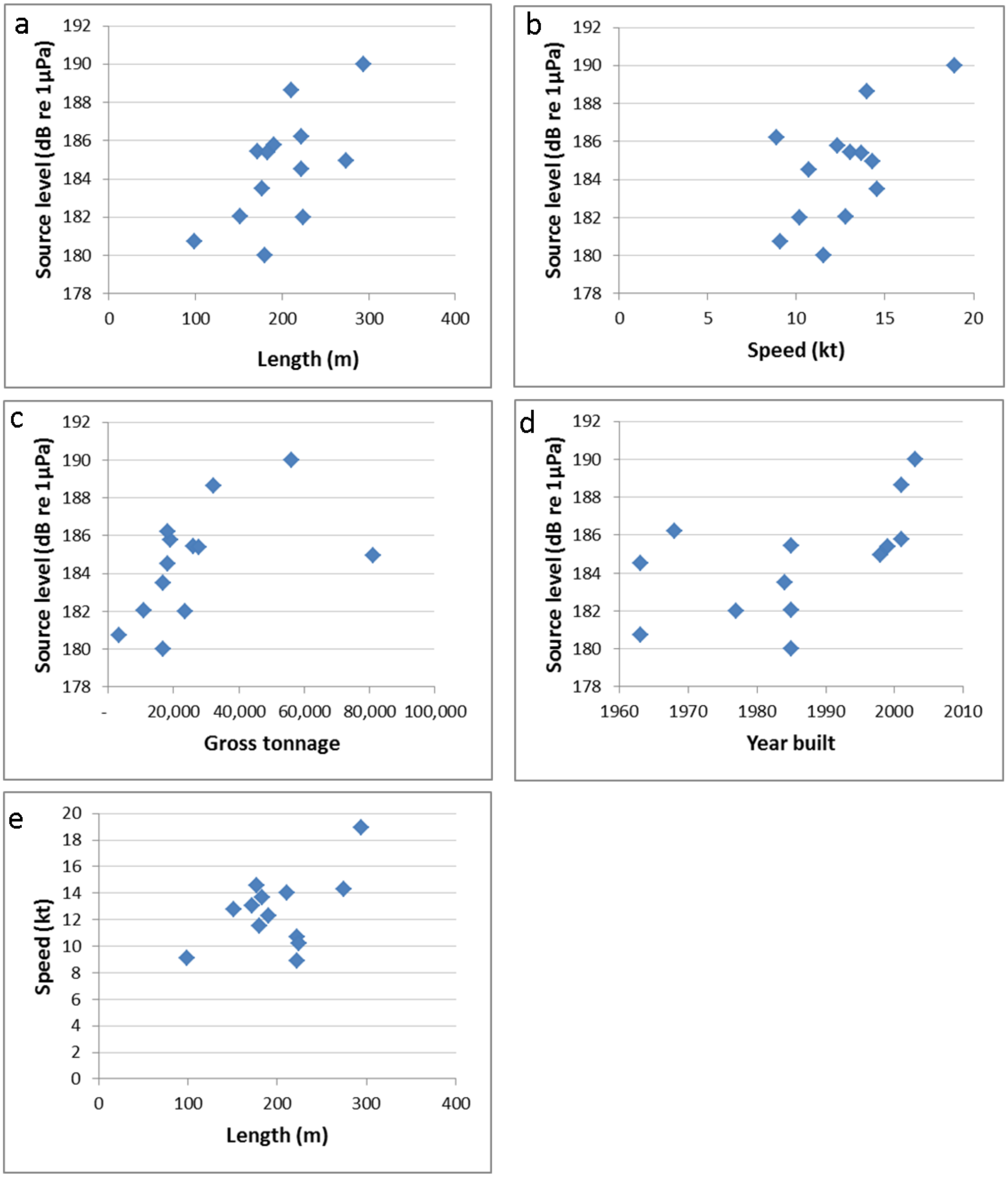

Figure 4. Relationships between physical vessel characteristics and source level (dB re 1 µPa @ 1m) as well as the correlation between length and speed.

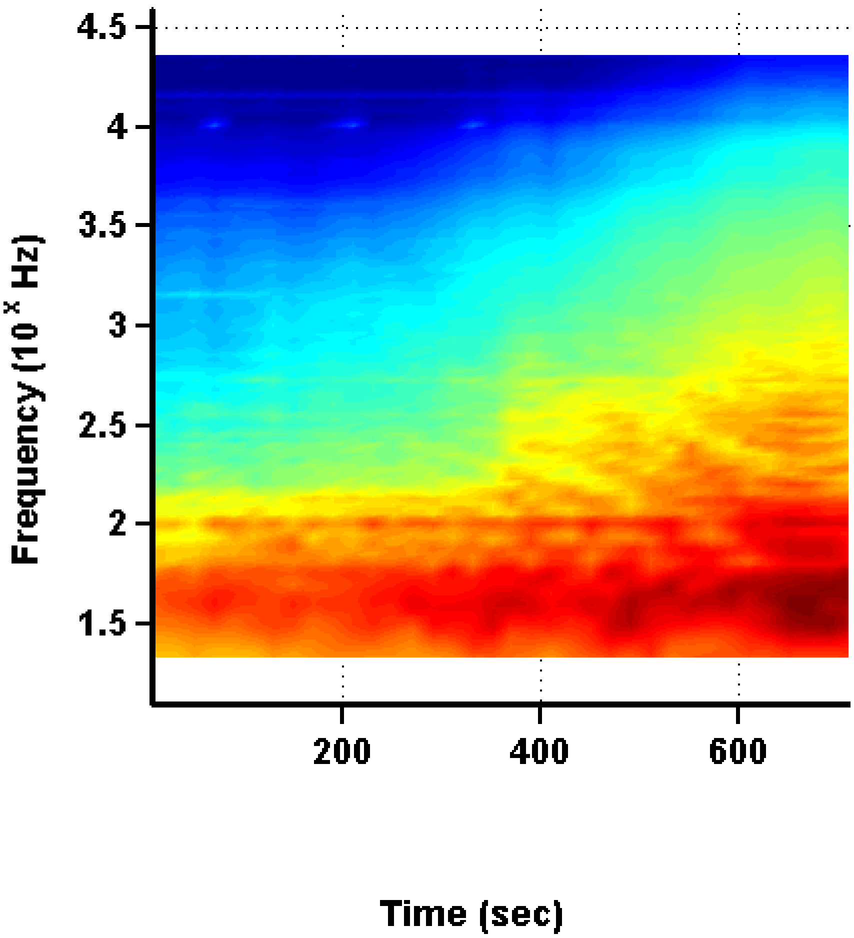

Figure 5. Power spectral density (dB re 1 μPa²/Hz) in 1/12 octave bands (blue = low; red = high) of an approaching container ship (CP Venture) recorded in the SLE in 2004.

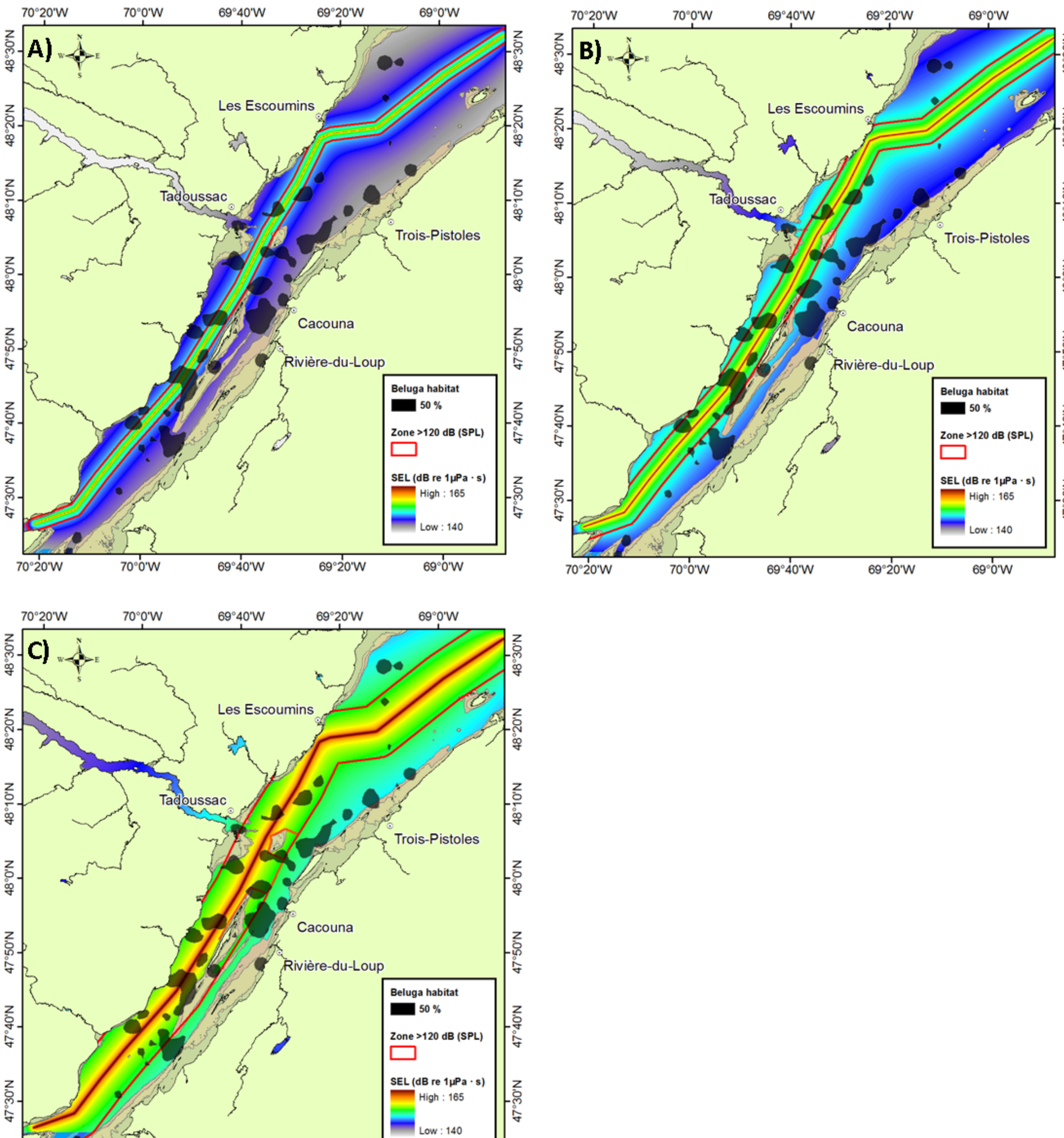

Figure 6. Simulated ZOI (SPL of 120 dB and SEL) produced from (a) a low-noise bulk carrier (b) a medium-noise crude-oil tanker and (c) a high-noise container ship transiting downstream by the North Channel relative to beluga core (50%) areas of concentration. Note the shadowing from Île Rouge and the islands along the SE boundary in (c).

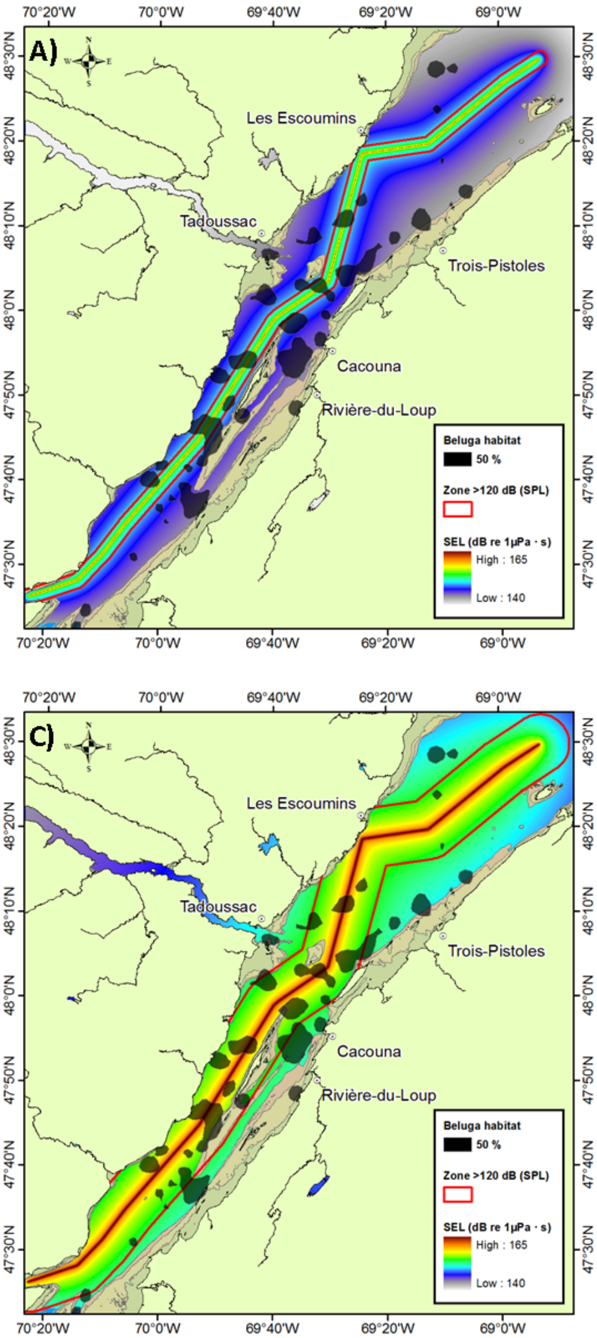

Figure 7. Simulated ZOI (SPL of 120 dB and SEL) produced from (a) a low-noise bulk carrier (b) a medium-noise crude-oil tanker and (c) a high-noise container ship transiting by the South Channel relative to beluga essential habitat where 50% of the population resides.

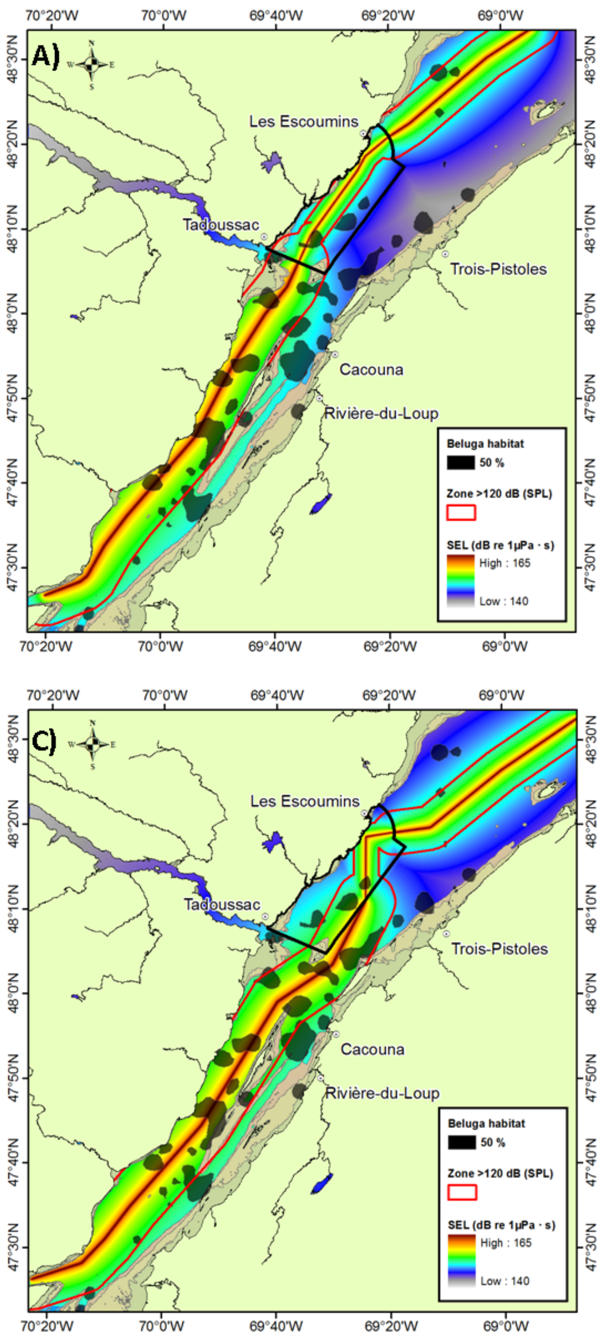

Figure 8. Simulated ZOI (SPL of 120 dB and SEL) produced from a high-noise container ship with reduced speed in the proposed Hybrid speed-reduction zone (contoured in black) transiting by (a) the NC upstream lane, (b) the NC downstream lane (c) the SC proposed Hybrid route and (d) the SC Provisional route relative to beluga essential habitat where 50% of the population resides.

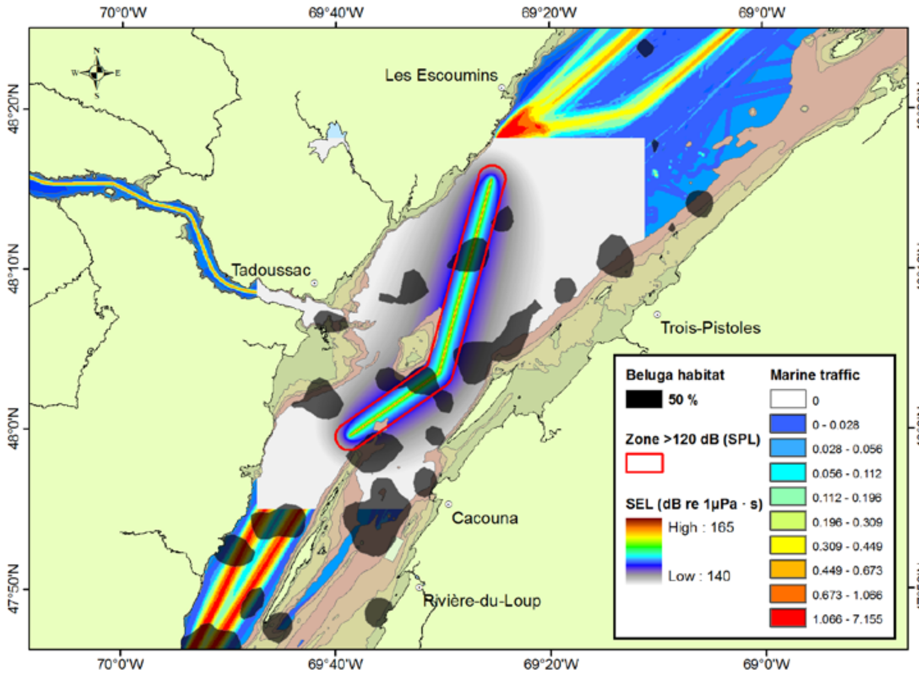

Figure 9. ZOI (M-weighted SPL of 120 dB and SEL) produced from a high-noise container ship transiting by the South Channel relative to beluga essential habitat where 50% of the population resides.

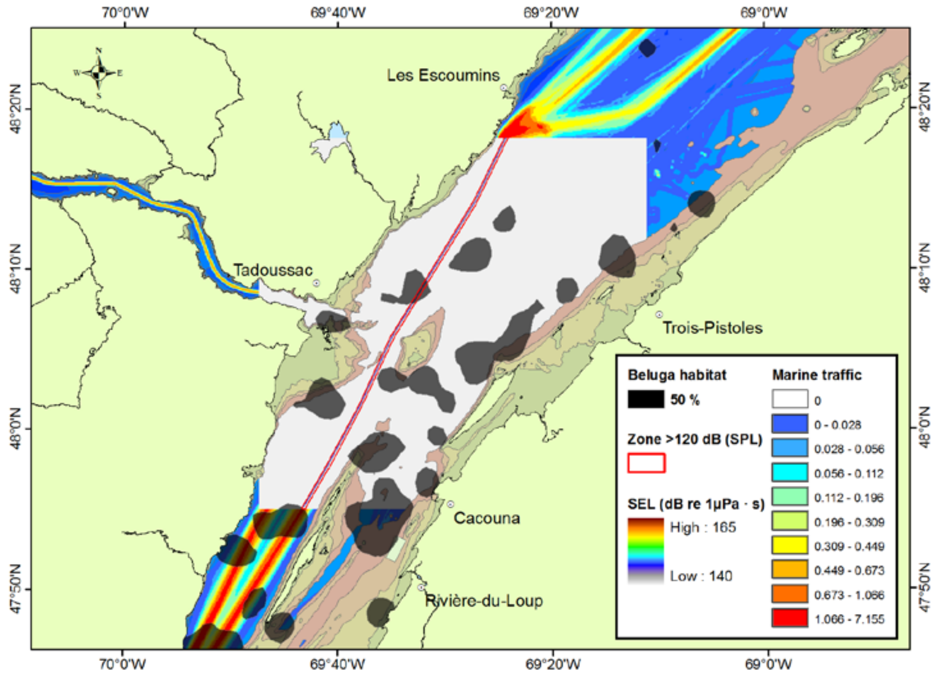

Figure 10. ZOI (C-weighted SPL of 120 dB and SEL) produced from a high-noise container ship transiting.