An Analysis of Regional Ocean Noise Contributors

The Enhancing Cetacean Habitat and Observation (ECHO) Program commissioned a study to better understand the contributions of various vessel types to underwater noise in the Salish Sea.

This summary document was prepared to describe why the study was conducted, its key findings and conclusions, and how the results are planned to be used by the ECHO Program to help manage the impact of shipping activities on at-risk whales throughout the southern coast of British Columbia.

What questions was the study trying to answer?

Endangered Southern Resident Killer Whales (SRKW) and other at-risk whale species frequent the Salish Sea, which also hosts commercial and recreational vessel activities. Noise from vessel traffic combines to increase ambient underwater noise levels and can interfere with the ability of animals to hunt their prey and communicate with one another.

The noise contribution of various vessel categories depends on several operational and environmental factors.

Previous studies have quantified underwater noise generated by vessels in the region, but data available at the time did not include all vessel types or provide enough detail to fully understand the contribution of various vessel categories in the critical habitat of the SRKW.

The noise contribution of a given vessel category (such as tanker, ferries, container ships, recreation boats) varies depending on: the noise characteristics of the specific vessels; the intensity (loudness) of the vessels; the number of vessels of that category transiting; the amount of time a vessel spends in a given area; and the environmental conditions that affect how sound travels in water.

The ECHO Program commissioned a study to answer the following questions:

- How much underwater noise do different commercial vessel sectors (e.g., commercial deep-sea vessels, passenger ferries, tug boats etc.) contribute in the region?
- How much noise do recreational, fishing and whale watching boats contribute in the region?
- Does the noise contribution of different vessel categories vary throughout the year and throughout the region?

Who conducted the study?

JASCO Applied Sciences Ltd. (JASCO) was selected to undertake this study based on their expertise in underwater noise and existing tools (models) they have developed specifically for this region.

What methods were used?

JASCO used an existing regional acoustic model and vessel information from 2015 to produce more detailed and fulsome noise estimates in the region. Information used to create the noise model includes:

1) Automated Identification System (AIS) information from vessels transiting the region in winter (January) and summer (July) of 2015 (e.g., vessel type, route and speed) as well as and simulations of whale watch vessel traffic (whale watch boats are not AIS-equipped);
2) information on vessel-generated noise for different vessel types; and
3) environmental data such as water temperature, salinity etc. that governs how sound travels through water.

The results of the updated acoustic model were used to create noise maps, pie-charts and ranking tables which display underwater noise levels and the relative contributions of different vessel categories to overall underwater noise levels. The noise information was represented by vessel category (using 11 categories), season (winter and summer) and sub-region (6 smaller geographic areas within the Salish Sea).

What were the key findings and conclusions?

The study generated the average total sound levels within the Salish Sea for a month in summer and a month in winter, based on noise generated by transiting vessels using 2015 data. The study found that:

- Sound generally travels faster and further through the colder waters in winter than in the warmer waters in summer and therefore underwater noise levels in the region are typically higher in winter despite the lower winter vessel traffic volumes;
- The commercial vessel sector (commercial deep-sea vessels, ferries, tugs etc.) is the main contributor of underwater noise in the region;
- Vessel categories with the largest overall noise contributions in the study area are those that spend the most time travelling in the region (i.e., tugs and ferries);
- Commercial deep-sea vessels make a relatively large contribution to underwater noise, mostly along the international shipping lanes where they navigate;
- Smaller crafts (e.g. recreational, fishing and whale watch vessels) make an important contribution in sub-regions such as Haro Strait and the San Juan Islands, especially in summer. Their localized noise contribution may be particularly important in areas where their presence overlaps with high-use areas for SRKW;
- The study likely underestimated the noise contribution of small crafts due to limited vessel tracking (AIS) information available for these vessels.

The commercial vessel sector (commercial deep-sea vessels, ferries, tugs etc.) is the main contributor of underwater noise in the region.

How are the results being used to help reduce underwater noise and its effects on at-risk whales?

The results of this study furthered the ECHO Program's understanding of how different vessel sectors (commercial shipping and transportation, recreational boating, whale watching and fishing) and vessel categories (e.g., tugs, bulk carriers, container ships, cruise ships, ferries, whale watching boats etc.) are contributing to existing underwater noise levels. The ECHO Program is using this knowledge to help focus management efforts and inform the development of vessel noise reduction solutions that are appropriate for the vessel sectors (or categories) and sub-regions.

Regional Ocean Noise Contributors Analysis

Enhancing Cetacean Habitat and Observation Program

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The results presented herein are relevant within the specific context described in this report. They could be misinterpreted if not considered in the light of this report's entire information. The results may also not be representative of different acoustic sources, receivers, fauna, and physical environments. Accordingly, if information from this report is used in documents released to the public or to regulatory bodies, such documents must include a clear citation of the original report and the latter shall be made readily available to the recipients in integral and unedited form.

JASCO provides modelling and analysis for determining noise emissions based on assumptions regarding types of noise-generating equipment and their emission levels, locations of their operations and environmental conditions ("Noise Emissions") and relies on third party data and information. The Client is solely responsibility for determining whether or not such assumptions and third party data and information are appropriate for the commercial purposes in which Client intends to use such Noise Emissions. JASCO disclaims any and all warranties and representations that any Noise Emissions used by Client based on such assumptions and third party data and information will be error free or be appropriate for Client's actual operation and Client acknowledges and agrees that it is solely liable and responsible for its reliance on such assumptions and third party data and information in any and all circumstances.

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1. Introduction

Commercial shipping routes in the Salish Sea pass through important marine mammal habitat, including areas often used by an endangered population of Southern Resident Killer Whales (SRKW) (Fisheries and Oceans Canada 2011). Cumulative noise from vessels can negatively affect marine wildlife: elevated background noise reduces their effective communication and available foraging space, and chronic exposure to manmade noise could make whales avoid an area or otherwise change their normal behaviours (Tyack 2008). Managing the potential effects of commercial shipping noise requires an understanding of how different sources contribute to the underwater soundscape in the region. Model-based noise mapping provides an effective tool for assessing noise originating from large numbers of vessels at a regional scale (Erbe et al. 2012).

The Vancouver Fraser Port Authority (VFPA) has initiated the Enhancing Cetacean Habitat and Observation (ECHO) program which is "aimed at better understanding and managing the impact of cumulative shipping activities on at-risk whales throughout the southern coast of British Columbia" (Port of Vancouver 2016). To this end, the ECHO Advisory Working Group identified the following information requirements:

1. How much does the commercial vessel sector (e.g. commercial deep-sea vessels, passenger ferries, tugs) contribute to the underwater noise baseline in southern resident killer whale (SRKW) critical habitat?
2. Of the commercial vessel sector noise contribution, to what extent are the different vessel categories (ie. tugs vs. ferries) contributing to the underwater noise budget, and how does this differ by geographical sub-region?
3. How much do other different categories of vessel fleets (e.g. whale watch vessels, fishing boats, recreational vessels) respectively contribute to the underwater noise baseline in SRKW critical habitat?

To help answer these questions, JASCO has developed regional ocean noise contributors model, based on vessel tracking data from the Automated Identification System (AIS), to create cumulative noise maps for the Salish Sea. This model framework was used for the Roberts Bank Terminal 2 (RBT2) project Environmental Impact Statement (MacGillivray et al. 2014), but it has since been updated with expanded vessel categories and more recent vessel tracking data for 2015 to address the specific requirements of the ECHO program. The noise maps produced by the model have been broken down by vessel category (11 total) and by geographic sub-region (6 total) to estimate the contributions of different vessel categories to the underwater noise budget in the vessel noise contributors study area (Figure 1).

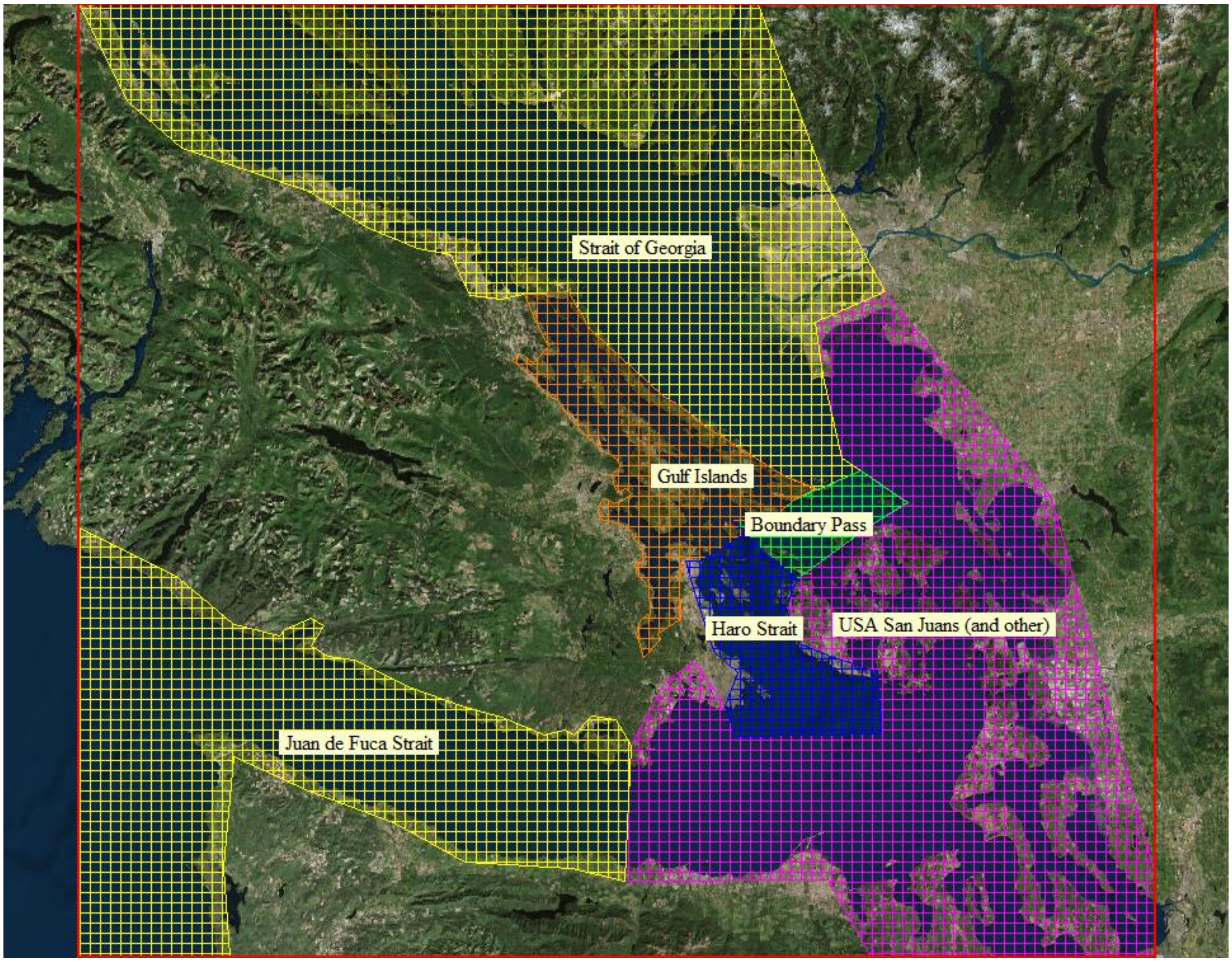

Figure 1. Vessel noise contributors study area (red box) and the six geographic sub-regions (hatched areas).

2. Model Description

The cumulative vessel noise model was developed by JASCO to map time-averaged noise levels generated by large numbers of vessels on a regional scale. The model synthesizes a number of data sources—including vessel tracking data, noise emission data, and environmental data—to produce noise maps for the study area (Figure 2).

The steps in the model calculation are as follows:

1. The model represents the region of interest on a computational grid (easting and northing) where the vessel density and speed is specified in each grid cell (Section 3.1).
2. For each category, the total vessel noise emitted in each grid cell is calculated according to the characteristic noise emissions, the total vessel time in each grid cell, and the mean vessel transit speed in each grid cell (Section 3.2).
3. The propagation of vessel noise to surrounding grid cells is calculated according to sound transmission curves, which are based on water depth, water column properties, and the seabed composition (Section 3.3).
4. The noise contributions from all vessel categories are summed together to calculate the cumulative noise in each grid cell.
5. The model generates maps of monthly-average sound levels (L_{eq}) for the study area, in decibels, broken down according to vessel category.

All model calculations are frequency-dependent, where the frequency range covers the hearing range of most marine mammals present in the study area (from 10 Hz to 64 000 Hz). This means the model outputs can be analyzed in terms of animal-specific hearing sensitivity (i.e., using audiogram weighting), however, for this study, the total broadband noise has not been weighted according to a specific marine mammal. More details about the development of the cumulative vessel noise model are provided in Section 2.1 of MacGillivray et al. (2014).

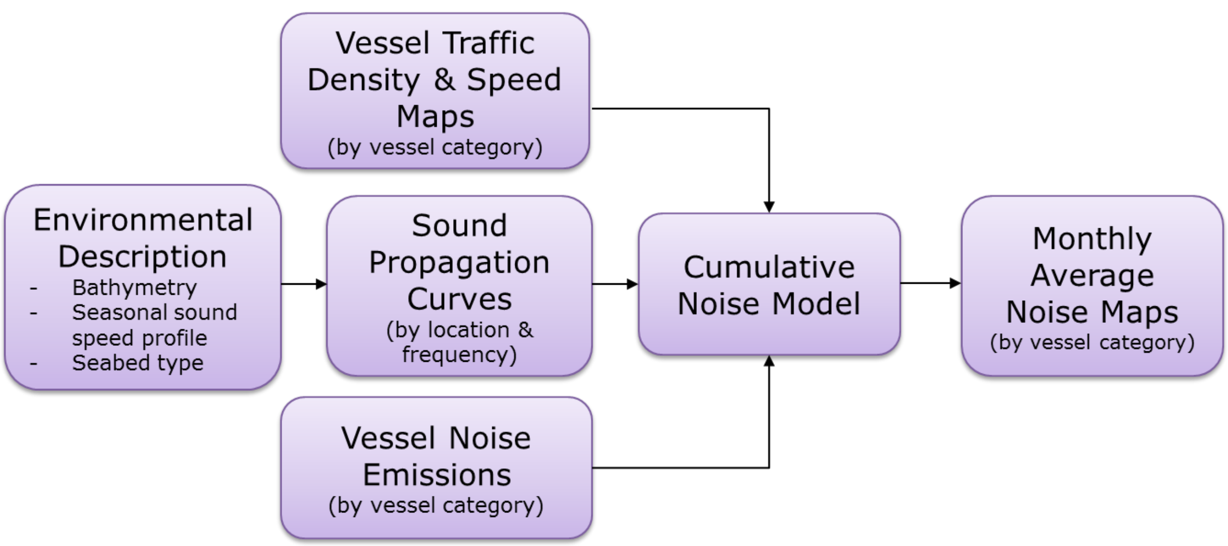

Figure 2. High-level flow chart of the regional vessel noise model.

3. Data Sources

3.1. Vessel Traffic

Historical vessel tracking data for the study area, for January and July of 2015, were obtained from the Marine Traffic AIS network (MarineTraffic.com). The raw data consisted of time-stamped position reports as well as other relevant vessel information (Table 1). The AIS dataset only included those vessels carrying AIS transceivers, and only moving vessels were included in the study. In Canada, federal regulations require every vessel of 500 deadweight tons or more to carry AIS, except fishing vessels. In practice, many smaller craft and fishing vessels also carry AIS for safety reasons. As such, the AIS dataset contained approximately 3 million position reports for the two months covered by this study (1.2 million for January and 1.8 million for July).

Table 1. Data fields included in the AIS dataset.

Field	Description
MMSI	A unique 9-digit vessel identifier
STATUS	Vessel status (under way, at anchor, moored, etc.)
SPEED	Speed over ground in knots
LON	Vessel longitude in degrees
LAT	Vessel latitude in degrees
COURSE	Vessel course in degrees
HEADING	Vessel heading in degrees
TIMESTAMP	Time of position report (UTC)
VESSEL_ TYPE	See Appendix A
NEXT_PORT	Destination of vessel
DRAUGHT	Vessel draught in metres
LENGTH	Vessel length in metres
DWT	Vessel tonnage in DWT

To generate the monthly traffic density and speed maps used in the model, individual vessels in the AIS dataset were divided into different categories according to their vessel type code (Appendix A). For each of these categories (except whale watch vessels), density and speed maps were calculated according to the following procedure:

1. Individual position reports were joined into contiguous tracks (i.e., sequences of consecutive position reports corresponding to vessel trips).
2. The tracks were overlaid onto an easting/northing grid (BC Albers projection) covering the study area. The dimensions of the grid were 208 km × 184 km and the individual grid cells were 800 m × 800 m.
3. A computational geometry algorithm was used to calculate the overlap between the vessel tracks and the grid cells.
4. Based on the overlap, the total vessel time and average vessel speed were calculated in each grid cell for each vessel category.

Traffic density and speed maps for the study area (Appendix B) were the primary inputs to the cumulative vessel noise model. The density maps for the individual vessel categories were summed to create maps of total AIS vessel traffic density for the study area in January and July (Figure 3).

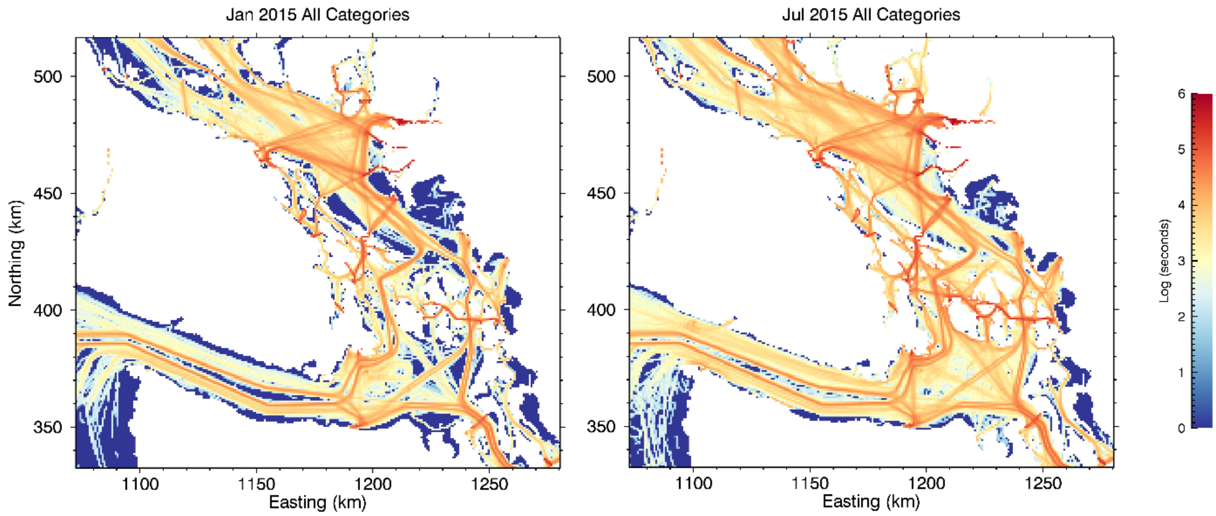

Figure 3. Total AIS vessel density (all categories except whale watch vessels) in the study area for January (left) and July (right). Maps show total vessel duration (seconds, log scale) per 800 m × 800 m grid cell on a logarithmic scale (BC Albers projection).

Traffic density and speeds for whale watch fleet in the Salish Sea were treated separately from other vessel categories because these predominantly small craft do not typically carry AIS transceivers, and were therefore assumed not to be represented in the AIS data. SMRU Consulting simulated traffic density for the Salish Sea whale watch fleet based on data from the Whale Museum's Soundwatch program (The Whale Museum 2016). The simulated whale watch traffic density was based on the number of vessels in the fleet, the average duration of their trips, the total number of trips per day, and the distribution of whales in the study area. Furthermore, it was assumed that whale watch vessels spend two thirds of their time transiting (at high speed) and one third of their time observing whales (at low speed). Appendix C provides further details about the methods used to simulate whale watch traffic density. Simulated traffic density maps were used to calculate the noise contribution of whale watch vessels in the model.

3.2. Vessel Noise Emissions

Different types of vessels have characteristic noise emissions because of their specific design and operating conditions. Propeller cavitation and hull-borne machine vibration are the predominant sources of underwater noise from vessels (Ross 1976). Vessels in this study were divided into fifteen source types, based on their class and size. Each source type was assigned a frequency-dependent source level curve that represented its characteristic noise emissions (Figure 4), which were used in the cumulative vessel noise model. These fifteen source level types were assigned to eleven different vessel categories (Table 2), where each category represented one sector's contribution to the regional noise budget[1].

[1] These eleven category names appear capitalized (e.g., Tugs, Ferries, Container Ships, etc.) when referring to to the specific vessel category definitions used in the model (see Appendix A).

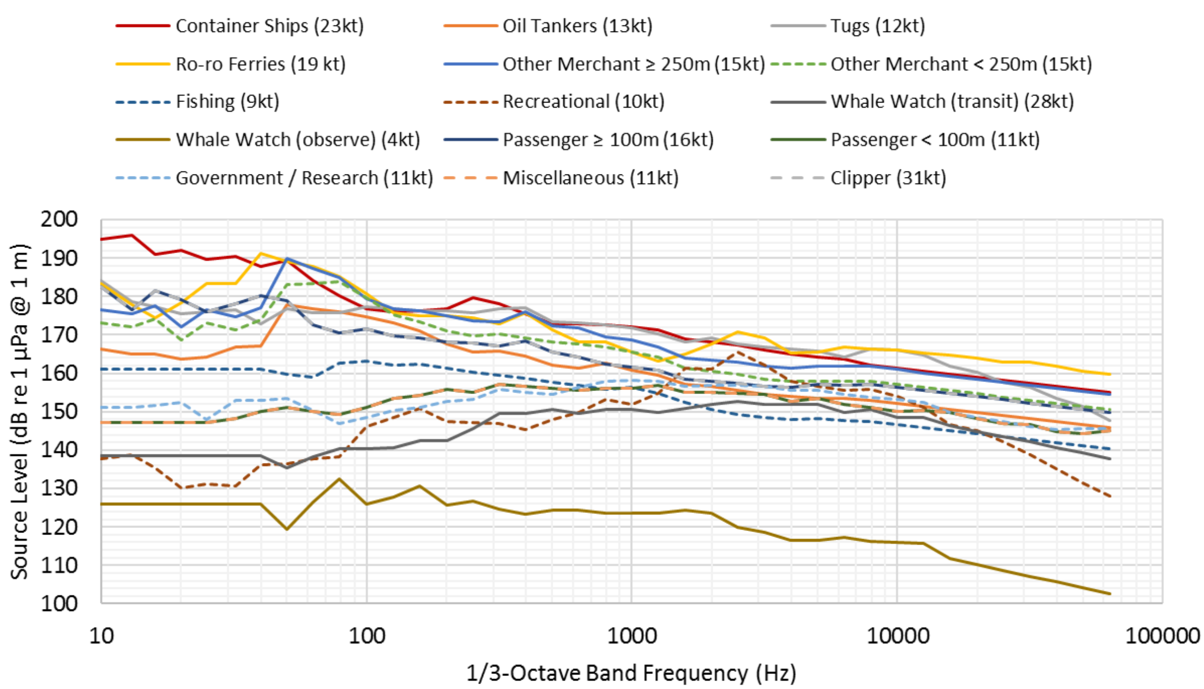

Figure 4. Frequency-dependent source levels (characteristic noise emissions) by vessel type in 1/3-octave bands. The reference speed (average transit speed) for each vessel type is indicated in the plot legend.

Table 2. Vessel categoriy definitions used for the noise contributors study. Some categories include source level subtypes, for vessels with distinct size, class, or operating conditions.

Vessel Category	Source Level Subtypes
Container Ships	n/a
Ferries	Ro-ro Ferries Clipper
Fishing	n/a
Government, Navy, and Research	n/a
Other Merchant Vessels	Other Merchant < 250 m Other Merchant ≥ 250 m
Passenger	Passenger < 100 m Passenger ≥ 100 m
Recreational	n/a
Oil Tankers	n/a
Tugs	n/a
Whale Watch	Transiting Observing
Miscellaneous	n/a

Source levels for most vessel types were based on measurements of representative vessels obtained in the study area. The majority of source level data were obtained from a collection of thousands of measurements collected by The Whale Museum and Beam Reach at their Lime Kiln hydrophone station, which is situated adjacent to the northbound international shipping lane in Haro Strait (Hemmera Envirochem Inc. et al. 2014). Gaps in the Lime Kiln data at very low frequencies (50 Hz and below) and very high frequencies (above 8000 Hz) were supplemented using data from past JASCO measurements and measurements from the published literature (see Table 2-2 in MacGillivray et al. (2014)). Source levels for two vessel types, roll-on/roll-off (ro-ro) passenger ferries and whale watch boats, were not represented in the Lime Kiln dataset, and so their characteristic noise emissions had to be obtained from other sources.

The Ferries category encompassed vessels from the following fleets: BC Ferries, Washington State Ferries, Blackball Line, Alaska Marine Highway Service, Clipper Line, and SeaSpan Ferries[2]. Source levels for ro-ro ferries were derived from dedicated source level measurements performed by JASCO at Roberts Bank near the Tsawassen Ferry terminal[3]. In addition, a special source level type was used for the Clipper Line, a passenger ferry service that travels between Victoria and Seattle. The high-speed jet catamarans in the Clipper fleet cannot be represented using ro-ro passenger ferry source levels. Instead, they were represented using passenger vessel (≥ 100 m) source levels from the Lime Kiln dataset[4], though they were classified under Ferries for the purpose of this study.

Source levels for the Whale Watch category were provided by Christine Erbe (Curtin University CMST) from a large collection of measurements of planing-hull vessels, which were collected in Haro Strait and Juan de Fuca Strait (Erbe 2002). Whale watch boats are unique, in that they operate in two very distinct speed regimes: travelling at high speed while transiting, and travelling at low speed while observing whales. Vessels in the Whale Watch category were therefore represented using separate source levels for these two operational regimes.

3.3. Noise Propagation

JASCO's Marine Operations Noise Model (MONM) was used to simulate frequency-dependent sound transmission curves (i.e., transmission loss) for the study area. This model was previously validated via field tests using a controlled sound source at several different locations within the study area (Warner et al. 2014). The propagation model accounts for the different environmental factors that influence underwater sound propagation, which includes the temperature and salinity of the water, the water depth, and the seabed sediment type.

The sound transmission curves were based on a detailed description of the study environment. Different sound speed profiles were used for January and July, based on a collection of 130 temperaure and salinity profiles collected by Fisheries and Oceans Canada over the period 2006-2010 (Figure 5). Water depths in the study area were based on a high-resolution bathymetry map for the Salish Sea (Figure 6). Seabed sediment properties were defined for four different zones inside the study area (Figure 7). These environmental parameters were used to calculate a set of 80 frequency-and-range-dependent sound transmission curves, which represented noise propagation in different parts of the study area (Figure 8). These transmission curves were used to predict how vessel noise propagates in the cumulative vessel noise model[5].

[2] Only ro-ro vessels from the SeaSpan fleet were included under Ferries. Articulated tug and barge vessels from the SeaSpan fleet were assigned to the Tug category.
[3] Ferry source levels were based on the average of 9 independent measurements of two different ro-ro passenger ferries (140 m and 160 m length) transiting along the Tsawassen-Duke Point route (Mouy et al. 2012, Appendix B).
[4] This assignment was based on the magnitude of measured Clipper source levels, as reported in Bassett et al. (2012) and Veirs et al. (2016), rather than vessel size.
[5] Range-dependent propagation between locations with different transmission loss curves was calculated according to the method described in Section 2.1.9 of MacGillivray et al. (2014).

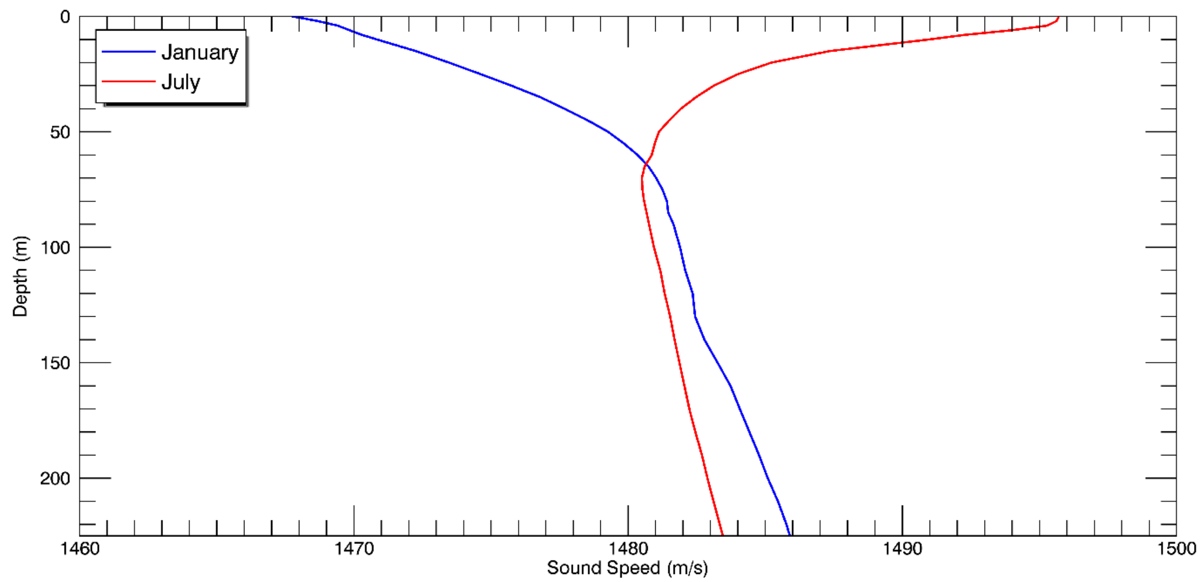

Figure 5. Mean sound speed profiles for the study area, based on historical ocean temperature and salinity profiles for January and July from Fisheries and Oceans Canada (DFO).

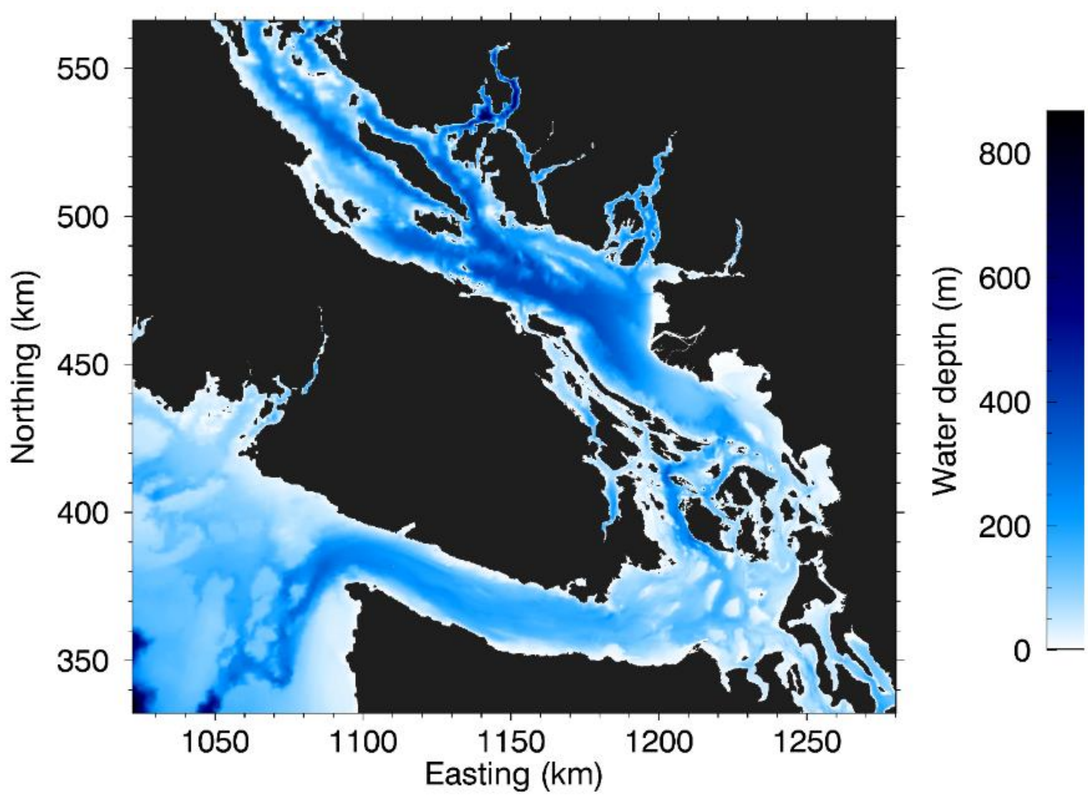

Figure 6. Map of water depths for the study area (BC Albers projection).

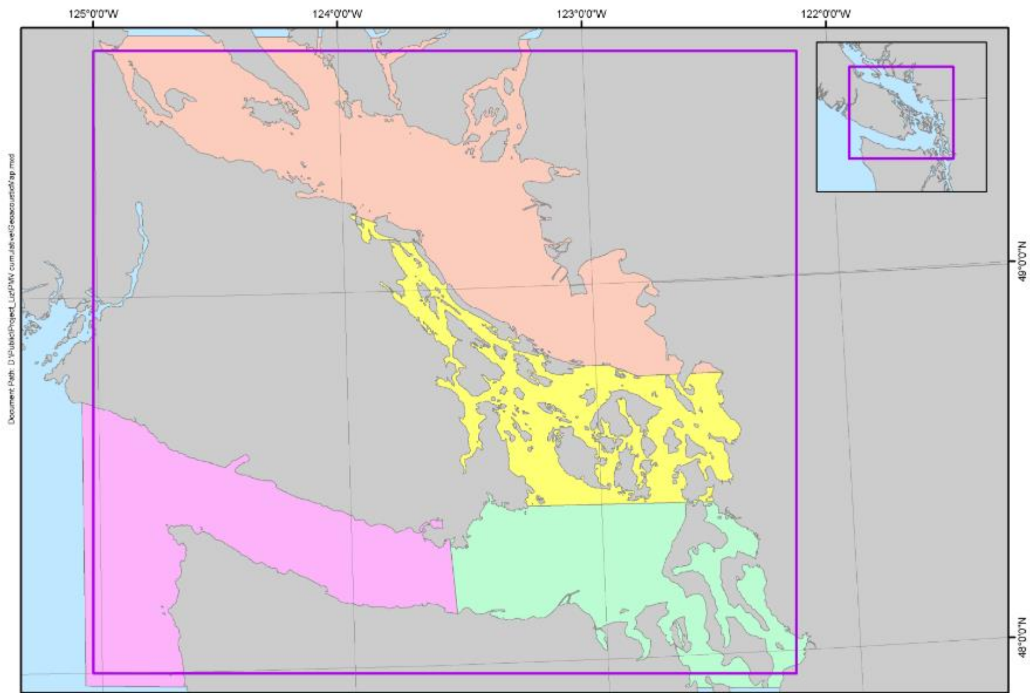

Figure 7. Map showing the four zones with different seabed sediment types used for defining sound propagation in the model. Clockwise from the top, they are as follows: Georgia Strait, Gulf & San Juan Islands, East Juan de Fuca Strait, and West Juan de Fuca Strait. For more details on seabed sediment types see Section 2.1.5 in MacGillivray et al. (2014).

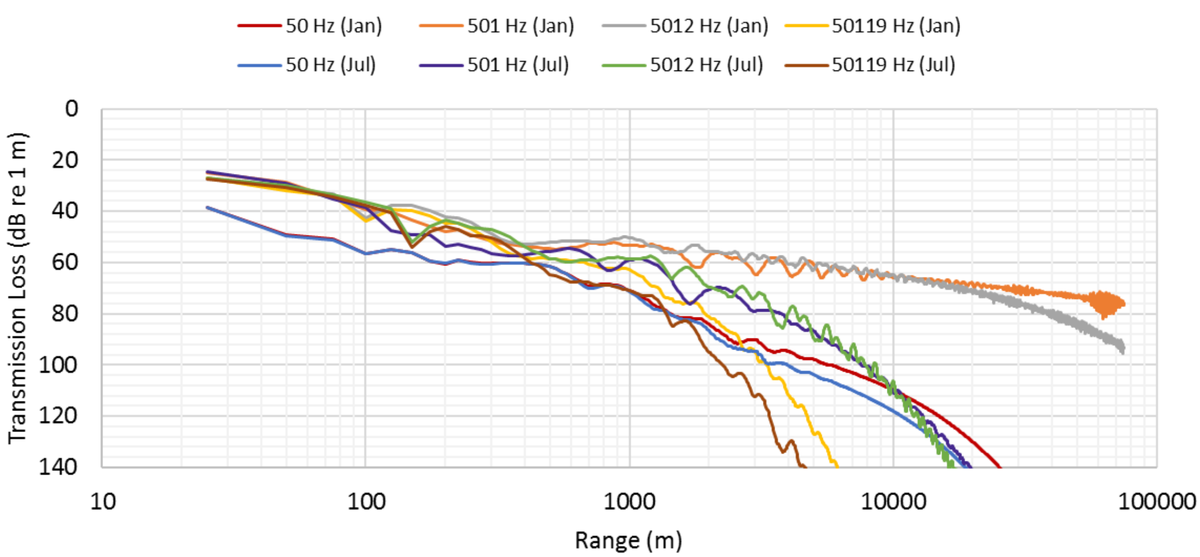

Figure 8. Examples of frequency-dependent sound transmission curves in Georgia Strait for January and July, as calculated by JASCO's Marine Operations Noise Model (MONM). The modelled receiver depth is 10 m, which is near the sea surface, since marine mammals spend most of their time in this zone. Differences between long-range sound propagation in January and July are due to seasonal differences in the sound speed profile (see Figure 5).

4. Noise Contributors Analysis

The objective of the noise contributors analysis was to break down the regional vessel noise model into a budget that shows the relative contribution of each vessel category to the total noise in the study area. The preferred “currency” for calculating a noise budget is the average sound intensity (NRC 2003) which, for long-term time averages, is proportional to the mean squared sound pressure (Miller et al. 2008). For large numbers of distributed sound sources, mean squared sound pressure is strictly an additive quantity and is therefore suitable for calculating a noise budget. Following this convention, the noise budget for the current study has been broken down in terms of the mean squared sound pressure contributed by each vessel category[6]. The resulting noise budgets are presented as pie charts, which show how each category contributed over the study area as a whole and within six geographic sub-regions (Section 5).

The noise budgets calculated in the present study only include contributions from vessels. Other sources of ocean noise, such as wind and waves, precipitation, and biological sources, are not included in the noise budget. Past measurements suggest that vessels are the overwhelming (> 99%) source of underwater noise in the Salish Sea (Bassett et al. 2012). This study presents total vessel noise in terms of unweighted broadband SPLs, which are a direct measure of physical sound pressure. They can be understood as the raw sound levels that would be measured by a calibrated acoustic sensor. By definition, they have not been weighted according to the hearing sensitivity of any marine animal.

[6] Note that sound pressure level, in decibels, represents mean squared sound pressure on a logarithmic scale, so the two quantities are directly related. See glossary for details.

5. Model Results

The cumulative vessel noise model was used to create maps of mean noise levels in the study area for January and July (Figure 9), based on the combined 2015 Marine Traffic AIS dataset (Appendix B) and the Soundwatch whale watch traffic dataset (Appendix C). These maps represent the total time-averaged noise levels in the study area from all vessel categories captured by the model in a single month. Ferry routes and international shipping lanes appear as areas with higher sound levels on the noise maps. Outside the main traffic routes, differences between the January and July noise maps are mostly due to seasonal differences in the sound transmission curves rather than seasonal differences in the vessel traffic density (see Section 3.3).

For the noise budget calculation, the maps were broken down into individual vessel layers containing each vessel category's unique noise contribution to the total. The noise contributions from the different vessel categories were compared in terms of their total average sound pressure level for each month (Figure 10). Sound pressure levels provide a useful method to compare the categories since the logarithmic (decibel) scale is a standard quantity for reporting acoustic measurements, and is related to hearing perception. Nonetheless, it is for this same reason that sound pressure levels are not well suited to breaking down a noise budget: decibels are not strictly an additive quantity (see Section 4). Therefore, the relative noise contribution of each category, as a percentage of the total, was computed from the individual layers according to their mean squared sound pressure contributions over each of the six sub-regions (Table 3 and Table 4). Noise pie charts were also created for the six sub-regions: these were rendered as maps (Figure 11 and Figure 12) and as individual charts (Appendix D).

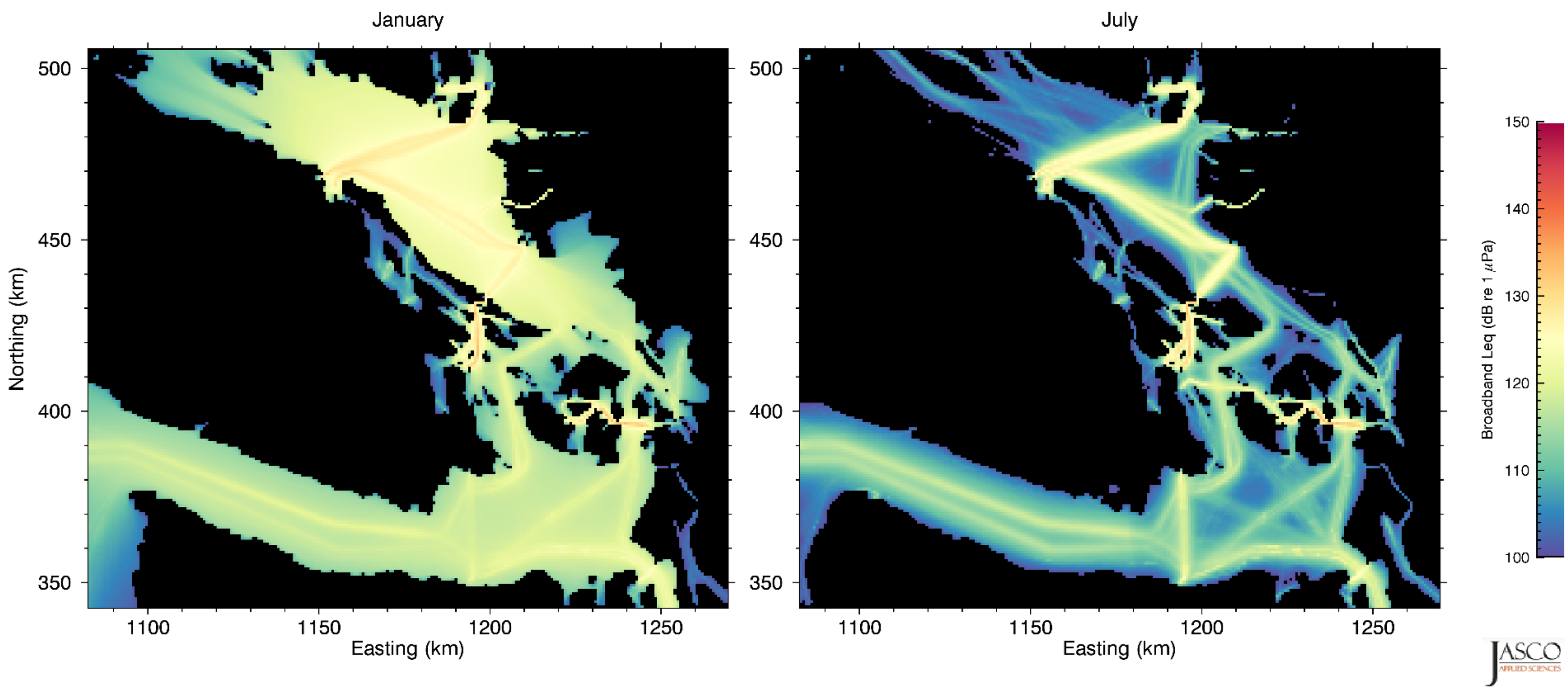

Figure 9. Monthly average sound pressure level (L_{eq}) for January (left) and July (right) as calculated by the cumulative vessel noise model (BC Albers projection). The L_{eq} is proportional to total number of vessels, the amount of time they spend in the region, and their source level.

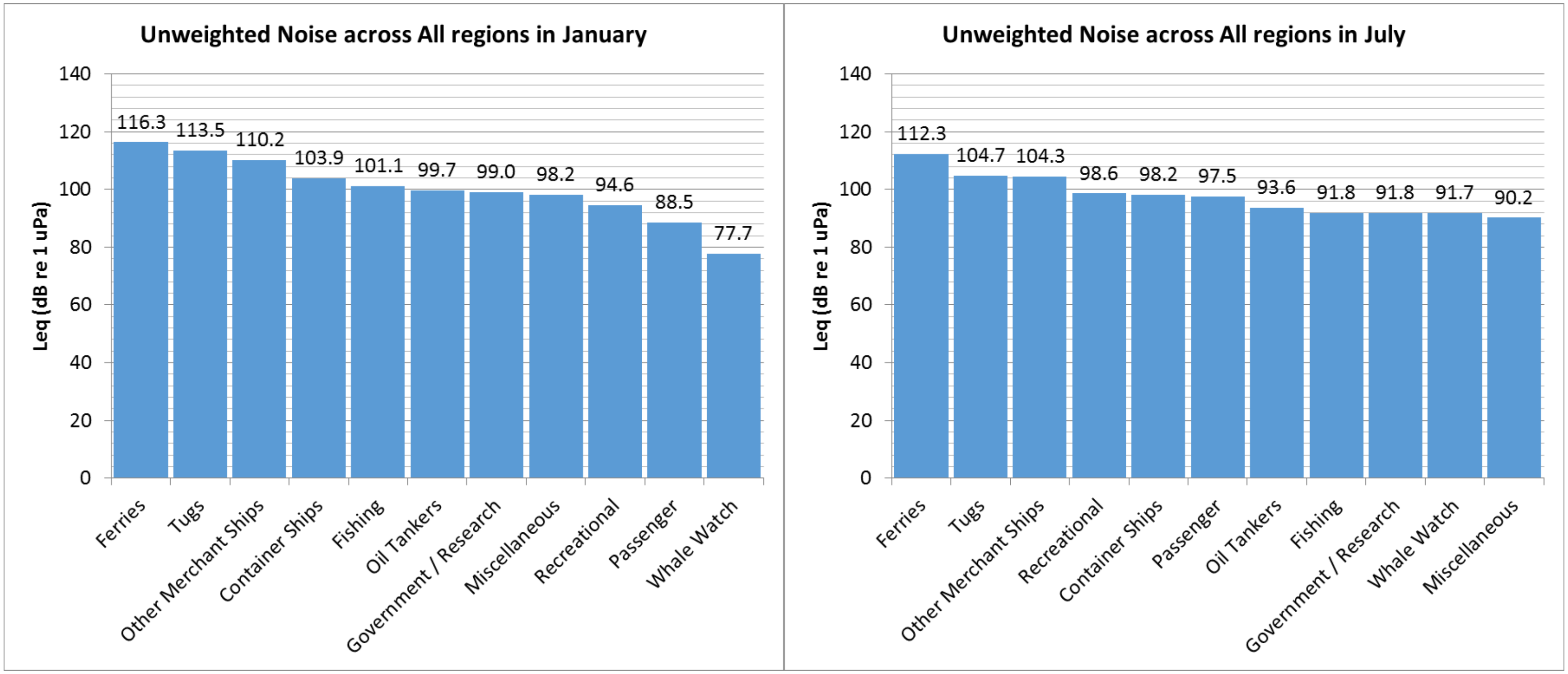

Figure 10. Bar charts showing the mean sound pressure level from each vessel category across all regions for January (left) and July (right) Each bar represents the average sound pressure level (linear mean) across the entire study area from all vessels in a particular category. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.

Table 3. Relative noise contribution, by vessel category, sub-region and region, for January. Percentages are the proportion of the total mean squared sound pressure attributed to all vessels in each category over the specified region. The total mean squared sound pressure is also listed for each sub-region, as well as the region as a whole. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.

January	Regional Average	Sub-regions					
		Haro Strait	Boundary Pass	Gulf Islands	Strait of Georgia	San Juans and Other	Strait of Juan de Fuca
Average total mean squared sound pressure (kPa^2)	**0.82**	**0.54**	**0.47**	**0.80**	**1.48**	**0.59**	**0.33**
Container Ships	3.0%	10.7%	10.8%	0.3%	0.8%	6.3%	7.4%
Ferries	52.3%	5.3%	15.4%	88.4%	70.6%	27.5%	0.3%
Fishing	1.6%	1.8%	0.6%	0.2%	0.7%	2.6%	5.2%
Government / Research	1.0%	3.5%	1.8%	0.9%	0.6%	1.5%	1.2%
Other Merchant Ships	12.6%	41.0%	45.9%	1.9%	4.3%	16.1%	46.4%
Miscellaneous	0.8%	1.5%	0.4%	0.3%	0.2%	2.1%	1.4%
Passenger	0.1%	0.1%	0.0%	0.0%	0.1%	0.1%	0.0%
Recreational	0.4%	1.5%	0.9%	0.2%	0.2%	0.7%	0.4%
Oil Tankers	1.2%	2.1%	1.6%	0.0%	0.2%	1.5%	6.2%
Tugs	27.1%	32.4%	22.5%	8.0%	22.4%	41.5%	31.5%
Whale Watch	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4. Relative noise contribution, by vessel category, sub-region and region, for July. Percentages are the proportion of the total mean squared sound pressure attributed to all vessels in each category over the specified region. The total mean squared sound pressure is also listed for each sub-region, as well as the region as a whole. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.

July	**Regional Average**	**Sub-regions**					
		Haro Strait	**Boundary Pass**	**Gulf Islands**	**Strait of Georgia**	**San Juans and Other**	**Strait of Juan de Fuca**
Average total mean squared sound pressure (kPa^2)	**0.25**	**0.20**	**0.14**	**0.73**	**0.32**	**0.24**	**0.12**
Container Ships	2.6%	7.9%	13.2%	0.1%	0.4%	3.5%	8.6%
Ferries	66.9%	27.8%	8.2%	94.7%	88.6%	57.9%	0.0%
Fishing	0.6%	1.4%	0.6%	0.2%	0.1%	0.4%	2.7%
Government / Research	0.6%	1.6%	1.3%	0.4%	0.3%	0.9%	0.7%
Other Merchant Ships	10.6%	34.2%	53.8%	0.3%	1.8%	7.9%	48.0%
Miscellaneous	0.4%	0.5%	1.6%	0.1%	0.1%	1.0%	0.3%
Passenger	2.2%	1.5%	1.0%	0.0%	0.3%	2.3%	11.0%
Recreational	2.8%	10.0%	8.5%	1.6%	1.2%	5.2%	1.8%
Oil Tankers	0.9%	1.0%	1.4%	0.0%	0.0%	0.7%	5.3%
Tugs	11.7%	9.5%	8.1%	2.5%	7.2%	19.2%	21.0%
Whale Watch	0.6%	4.6%	2.4%	0.2%	0.1%	1.0%	0.5%

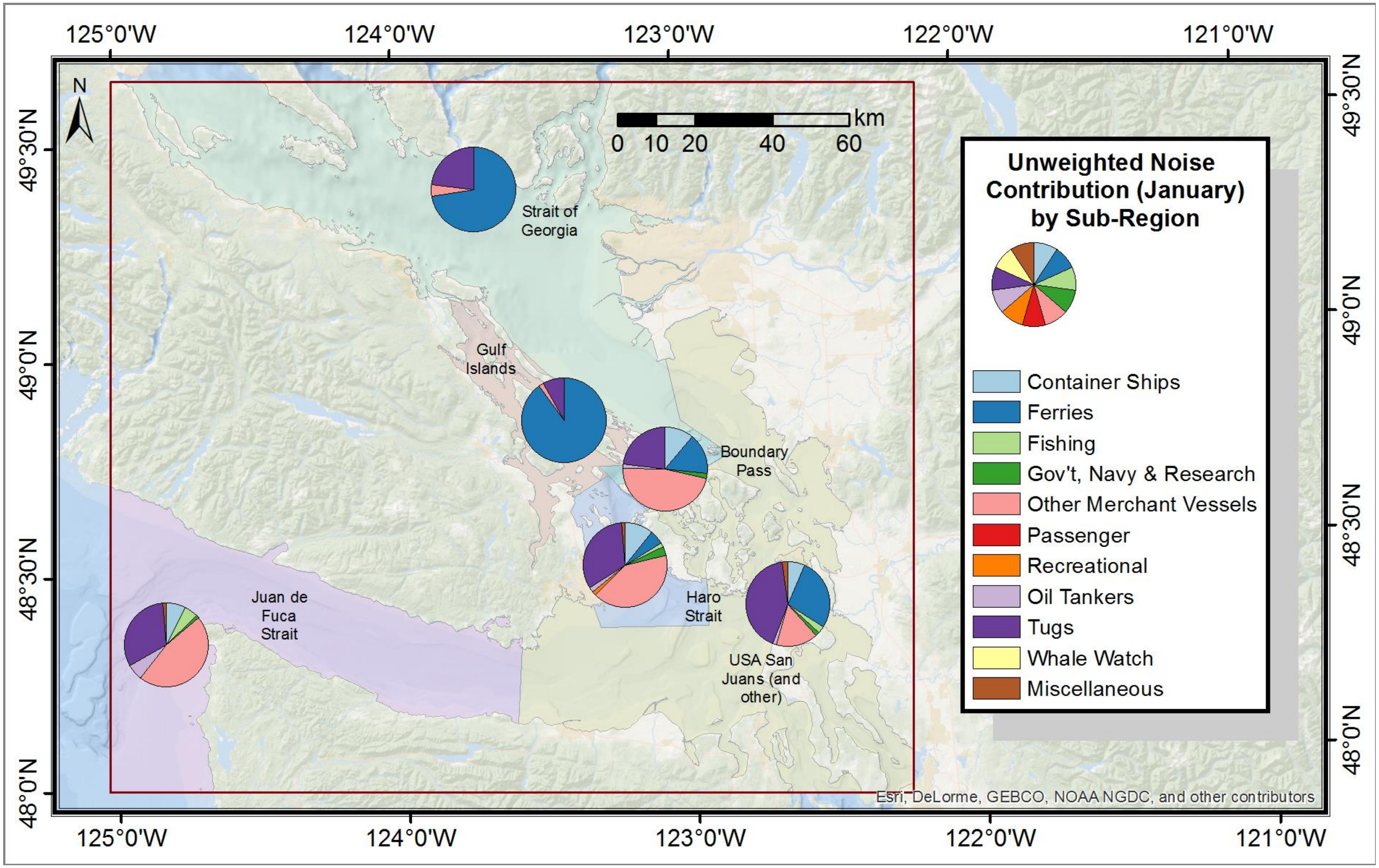

Figure 11. Map showing the relative noise contribution of all vessels in each category, broken down by sub-region, for January. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.

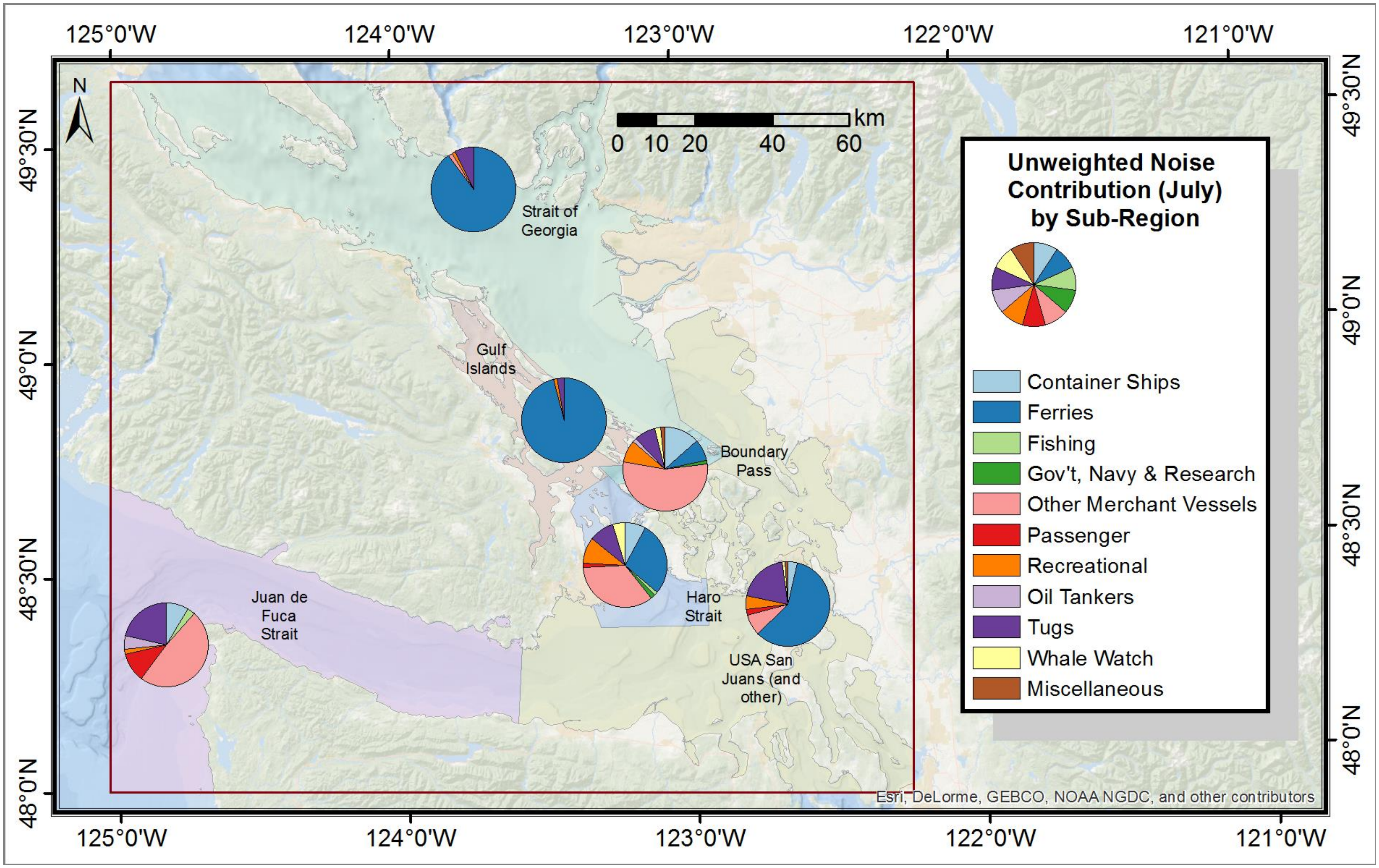

Figure 12. Map showing the relative noise contribution of all vessels in each category, broken down by sub-region, for July. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.

6. Discussion

6.1. Vessel Noise Contributors

The model results show that, while many different vessel sectors contribute to ocean noise in the study area, the commercial vessel sector is the dominant source throughout the region. Nonetheless, categories for smaller craft (Recreational, Fishing, Whale Watch) make an important contribution in certain sub-regions, such as Haro Strait and the San Juan Islands, where these vessels congregate in greater numbers. Ultimately, because large commercial vessels have much higher noise emissions than smaller craft, their total contribution is greater.

Ferries make a relatively large contribution to regional ocean noise because they make frequent trips and their routes are widely distributed throughout the study area. As expected, their greatest contributions are in those sub-regions containing the most frequently-travelled inter-island routes (Georgia Strait, Gulf Islands, and San Juan Island). Similarly, Tugs make a relatively large contribution to regional ocean noise due to the substantial volume of tug traffic in the study area. This category has the greatest total number of vessel hours of all the vessel categories in the AIS dataset (Figure 13). The noise contribution of Tugs is widely distributed across all sub-regions in the study area, over both seasons. The merchant vessel categories (Container Ships, Oil Tankers, Other Merchant Ships) make a relatively large contribution, but it is focused in those sub-regions intersecting the international shipping routes.

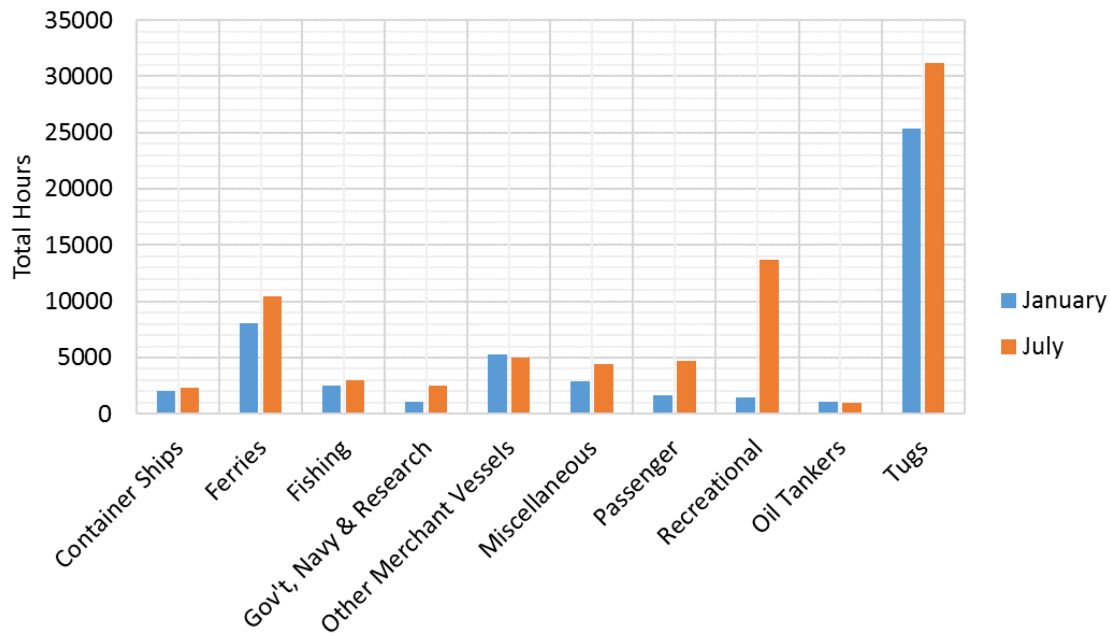

Figure 13. Total AIS vessel hours in the study area, by category, for January and July. Whale watch vessels are not shown, as they were not part of the AIS dataset (see Appendix C).

Most of the vessel categories captured by the model exhibit a seasonal component, with more traffic present in summer than in winter. The most significant seasonal variations are in the Recreational, Whale Watch, and Passenger categories, which have substantially more activity in July than in January. Ferry traffic volume is also seasonal to a smaller extent, which is why the Ferries contribution is greater in July than January. In contrast, traffic volumes in the Merchant, Container, and Tanker vessel categories do not increase substantially in summer, which is why their relative noise contributions appear to decrease in July. Nonetheless, overall noise levels in the region are higher in January, despite the lower traffic density, due to oceanographic conditions that favour long-range sound propagation in winter (see Figure 8).

6.2. Sources of Uncertainty

While the cumulative vessel noise model applied in this study is based on the best available data at the time of writing, some data gaps must be acknowledged when interpreting the results.

The most important data gap is regarding the proportion of vessels in the Recreational and Fishing categories that are represented in the AIS dataset. Despite the fact they are not required to do so, a large number of vessels in both these categories did in fact transmit on AIS (Figure 14) and were thus captured in the Marine Traffic database. In particular, the Recreational category contained the largest number of unique vessels, even though most vessels in this category were under 30 m in length. Adjusting the contribution of the Recreational and Fishing categories to correct for the proportion of these fleet that are not sampled by AIS would require an independent (non-AIS) count of absolute number of vessel trips per month in these categories. At the time of writing, however, no known data source could be identified that provides this information for study area.

While two previous (non-AIS) studies of recreational boating traffic volumes have been conducted in the Salish Sea, neither was suitable for independently estimating the overall size of the recreational fleet in the study area. In one study, vessel track data was gathered via face-to-face surveys with recreational boaters between June and September 2007, at six sampling sites throughout the Gulf Islands, with each site being sampled for eight days (Gray et al. 2011). In the other study, boat positions in the San Juan Islands were recorded via aerial surveys, two times per day, over 19 days between June and September 2010 (Dismukes et al. 2010). In both cases, the sampling was too limited to be able to infer from the results the overall quantity of the recreational boating fleet traffic in the focus areas. For fishing vessels, no publicly available data were found detailing the size of the Salish Sea fleet. It is possible that the size of the combined U.S. and Canadian fishing fleets could be estimated from fisheries licensing and landing statistics for the study area (e.g., from Fisheries and Oceans Canada and NOAA Fisheries), but this is a data mining exercise that is well outside the scope of the current study. Thus, it is likely that the present study underestimates the overall contribution of the Recreational and Fisheries categories. It is nonetheless highly unlikely their ocean noise contribution would exceed that of larger commercial vessels in the study area as a whole because these categories consist mainly of small vessels which have much lower noise emissions.

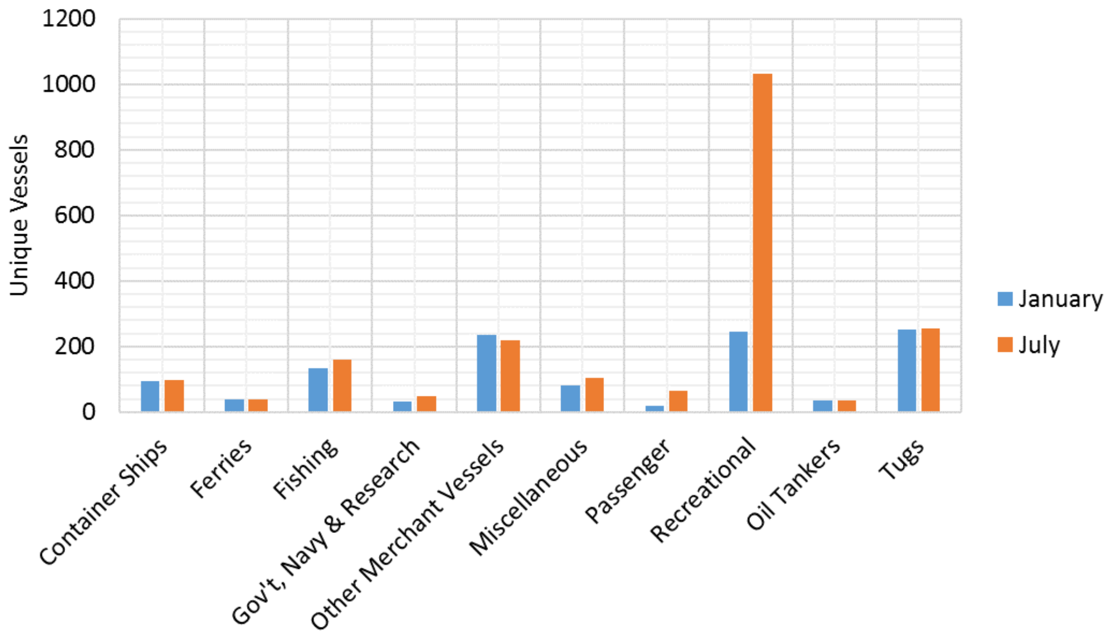

Figure 14. The number of unique AIS vessels in each category, for January and July. Whale watch vessels are not shown, as they were not part of the AIS dataset (see Appendix C).

Another source of uncertainty is related to gaps in the vessel noise emissions data collected at Lime Kiln. Ferries were not present in the Lime Kiln dataset, due to the fixed location of the hydrophone near the international shipping lanes. Instead, noise emissions for ferries were based on long-term hydrophone data collected from regular passes of two large roll-on/roll-off ferries on the Tsawassen-Duke Point ferry route. It is not known whether source levels of ferries along this route are representative of the broader regional ferries fleet. Nonetheless, ferries undoubtedly contribute a large amount of noise in the study area, due both to their size (average length 109 m) and the large number of monthly ferry trips, so the magnitude of their contribution in the model is likely correct. In addition, some vessel categories (for example Miscellaneous, and Government, Naval & Research) contained a mixture of vessel sizes and types, ranging from the very small (under 10 m) to the very large (over 200 m), which are not likely to be well represented using an average source level. Nonetheless, the total amount of traffic in these categories is small so the resulting error is likely also small. A final limitation of the Lime Kiln data is related to gaps in the measurements at low (50 Hz and below) and high (10 000 Hz and above) frequencies, caused by the distance (2.5 km) of the Lime Kiln hydrophone from the northbound shipping lanes. Future measurements collected at shorter range on the ECHO project's underwater listening station in Georgia Strait could be used to fill in data gaps related to vessel source levels in the study area.

7. Conclusion

In summary, this study has developed a noise budget for the Salish Sea based on a model of cumulative vessel noise for the region. The model applied in this study takes regional, AIS-based vessel traffic data and whale watch vessel traffic data and propagates their noise emissions through the ocean environment to map the long-term cumulative distribution of vessel noise throughout the study area. The cumulative vessel noise maps were split into 11 categories to produce relative noise budgets for the entire region and also across six different sub-regions covering areas of critical Southern Resident Killer Whale (SRKW) habitat.

The results of this study indicate that vessels from the commercial sector (ferries, tugs, commercial deep-sea vessels) contribute the most underwater noise in the region. The noise contributions of other sectors (fishing, whale watching, recreational craft) are smaller, tend to be focused in specific sub-regions and have a strong seasonal component. Nonetheless, the localized noise contribution from smaller vessels may be important in critical habitat areas where their presence overlaps high-use areas for SRKW. Results from this study could be used to inform potential future noise mitigation efforts for different vessel sectors that operate in the region.

8. Acknowledgements

Editorial review of this report was provided by Katherine Williams (JASCO). Whale watch traffic density data for the study area was provided by Jason Wood (SMRU Consulting). The category assignments for vessels in the AIS dataset were developed in consultation with Jeffrey Pelton (Vancouver Fraser Port Authority, Operations). Orla Robinson (Vancouver Fraser Port Authority, ECHO Program) and Krista Trounce (Vancouver Fraser Port Authority, ECHO Program) provided many helpful comments and suggestions that were incorporated into this work.

Glossary

1/3-octave-band
Standard, non-overlapping frequency bands approximately one-third of an octave wide (see octave). Standard 1/3-octave band centre frequencies (f_c) are given by the formula $f_c = 10^{n/10}$ where n is an integer. Measured in the unit Hz.

automated identification system (AIS)
A radio-based tracking system whereby vessels regularly broadcast their identity, location, speed, heading, dimensions, class, and other information to nearby receivers.

broadband sound level
The total sound pressure level over the entire modelled or measured frequency range.

BC Albers
A standard map projection that is used by the province of British Columbia for representing spatial information with minimal distortion.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 R2004).

frequency
The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

hearing threshold
The sound pressure level that is barely audible for a given individual in the absence of significant background noise during a specific percentage of experimental trials.

hertz (Hz)
A unit of frequency defined as one cycle per second.

hydrophone
An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: p.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound intensity
Sound energy flowing through a unit area perpendicular to the direction of propagation per unit time.

sound pressure level (SPL)
The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 R2004).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 µPa) and the unit for SPL is dB re 1 µPa:

$$\mathrm{SPL} = 10\log_{10}\left(p^2/p_0^2\right) = 20\log_{10}\left(p/p_0\right)$$

Unless otherwise stated, SPL refers to the root-mean-square sound pressure level (rms SPL).

sound speed profile
The speed of sound in the water column as a function of depth below the water surface.

source level (SL)
The sound pressure level at 1 meter distance from a theoretical point source that radiates the same total sound power as the actual source. Unit: dB re 1 µPa @ 1 m.

time-averaged sound level (Leq)
The decibel level of the mean square sound pressure over a specified time period.

transmission loss (TL)
The decibel reduction in sound level between a source and a receiver that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also called propagation loss. Measured in units dB re 1 m.

unweighted
Refers to a sound pressure level that has not been weighted according to the hearing sensitivity of any organism (i.e., raw SPL).

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Appendix A. AIS Vessel Category Assignments

The following table shows how vessel type codes from the Marine Traffic AIS dataset (left) were assigned to the vessel categories in the regional noise contributors model (right). Note that Clipper Line vessels travelling the Victoria-Seattle route, and roll-on/roll-off vessels in the Seaspan Ferries fleet were manually assigned to the Ferry category. Sailing vessels were excluded from the Recreational vessel category and were not included in the model (i.e., they were assumed not to be under power).

VESSEL_TYPE	Model Category
Cargo/Containership	Container
Container Ship	Container
Ro-Ro/Passenger Ship	Ferry
Factory Trawler	Fishing
Fish Carrier	Fishing
Fish Factory	Fishing
Fishing	Fishing
Fishing Vessel	Fishing
Trawler	Fishing
Buoy-Laying Vessel	Government
Fishery Patrol Vessel	Government
Fishery Research Vessel	Government
Law Enforce	Government
Logistics Naval Vessel	Government
Military Ops	Government
Patrol Vessel	Government
Replenishment Vessel	Government
Research/Survey Vessel	Government
Bulk Carrier	Merchant
Cargo	Merchant
Cargo - Hazard A (Major)	Merchant
Chemical Tanker	Merchant
General Cargo	Merchant
LPG Tanker	Merchant
Rail/Vehicles Carrier	Merchant
Reefer	Merchant
Ro-Ro Cargo	Merchant
Ro-Ro/Container Carrier	Merchant
Self Discharging Bulk Carrier	Merchant
Timber Carrier	Merchant
Vehicles Carrier	Merchant
Wood Chips Carrier	Merchant
Anti-Pollution	Miscellaneous

VESSEL_TYPE	Model Category
Cable Layer	Miscellaneous
Dive Vessel	Miscellaneous
Drill Ship	Miscellaneous
Heavy Lift Vessel	Miscellaneous
High Speed Craft	Miscellaneous
Hopper Dredger	Miscellaneous
Local Vessel	Miscellaneous
Other	Miscellaneous
Pilot Vessel	Miscellaneous
Port Tender	Miscellaneous
Reserved	Miscellaneous
SAR	Miscellaneous
Tender	Miscellaneous
Unspecified	Miscellaneous
Wing In Grnd	Miscellaneous
Passenger	Passenger
Passengers Ship	Passenger
Pleasure Craft	Recreational
Yacht	Recreational
Crude Oil Tanker	Tanker
Oil Products Tanker	Tanker
Oil/Chemical Tanker	Tanker
Tanker	Tanker
Anchor Handling Vessel	Tug
Fire Fighting Vessel	Tug
Multi Purpose Offshore Vessel	Tug
Offshore Supply Ship	Tug
Pollution Control Vessel	Tug
Pusher Tug	Tug
Towing Vessel	Tug
Tug	Tug

Appendix B. AIS Shipping Traffic Layers

The following figures show maps of shipping density (total seconds, log scale in the left hand images) and mean transit speed (in the right hand images) in January and July for the study area for all vessel categories, as calculated from the Marine Traffic AIS dataset. Density and speed values are given per 800 m × 800 m grid cell. The month and category (or sub-category) for each map is indicated in the plot title. Maps for January are presented first, followed by maps for July.

Vessels in the Seaspan fleet were captured in separate density and speed maps (SeaspanRoro and SeaspanTugs) because their categories designations had to be manually assigned based on MMSI rather than AIS vessel type code. Their noise contribution was included in the Ferries and Tug categories, respectively. The Whale Watch category was not included in the AIS dataset—density maps for this category are shown in Appendix C.

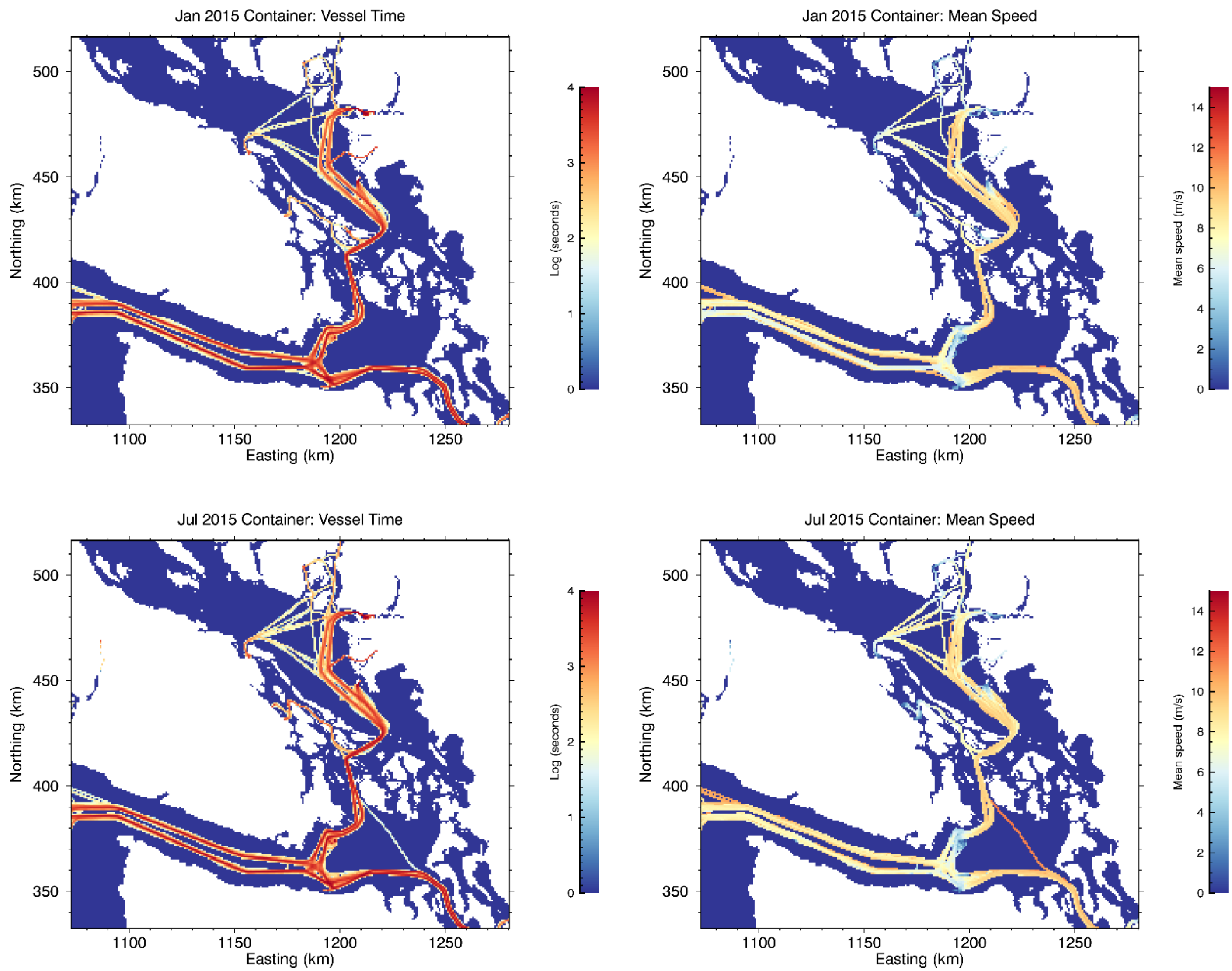

Figure B-1. Container category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

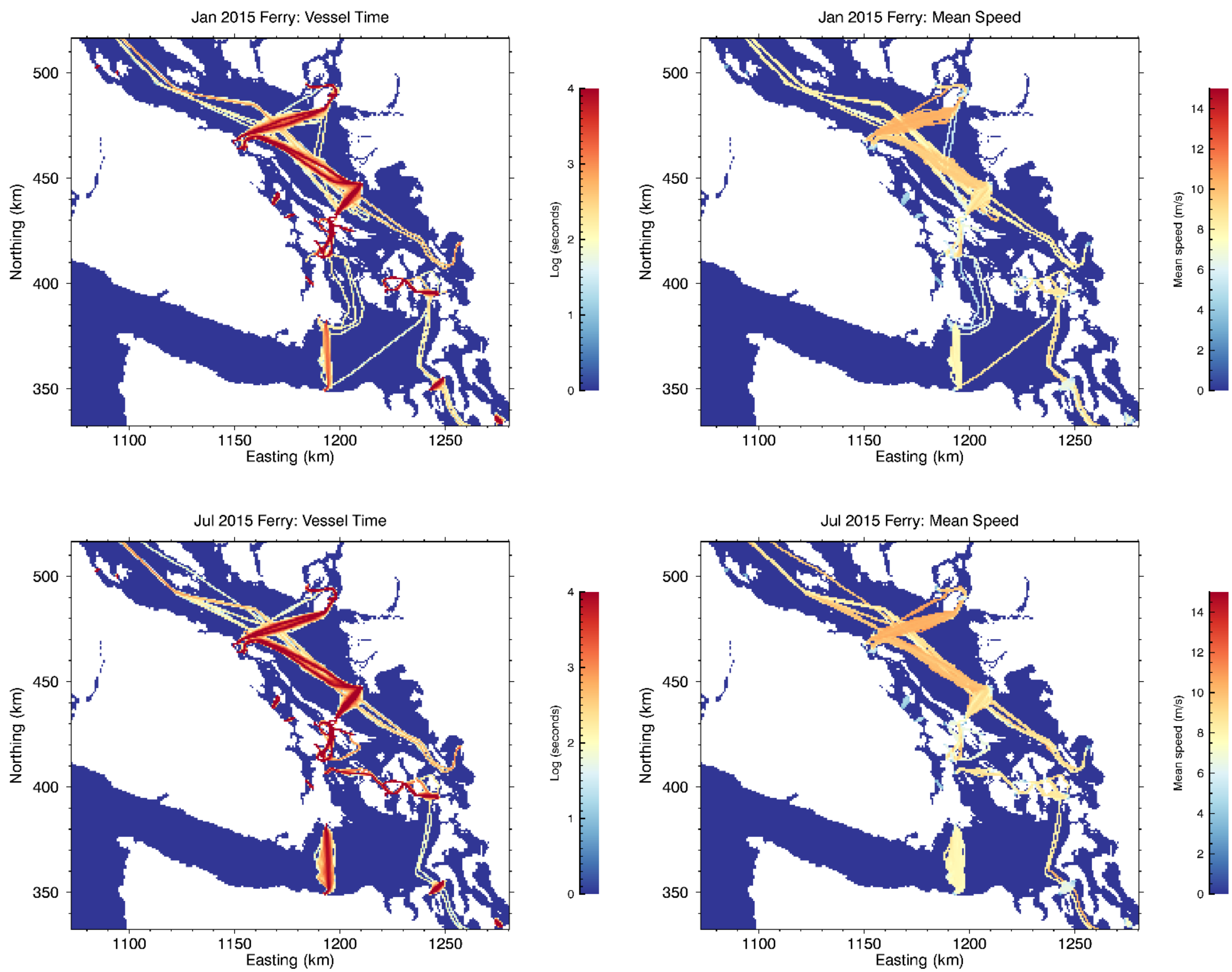

Figure B-2. Ferry category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

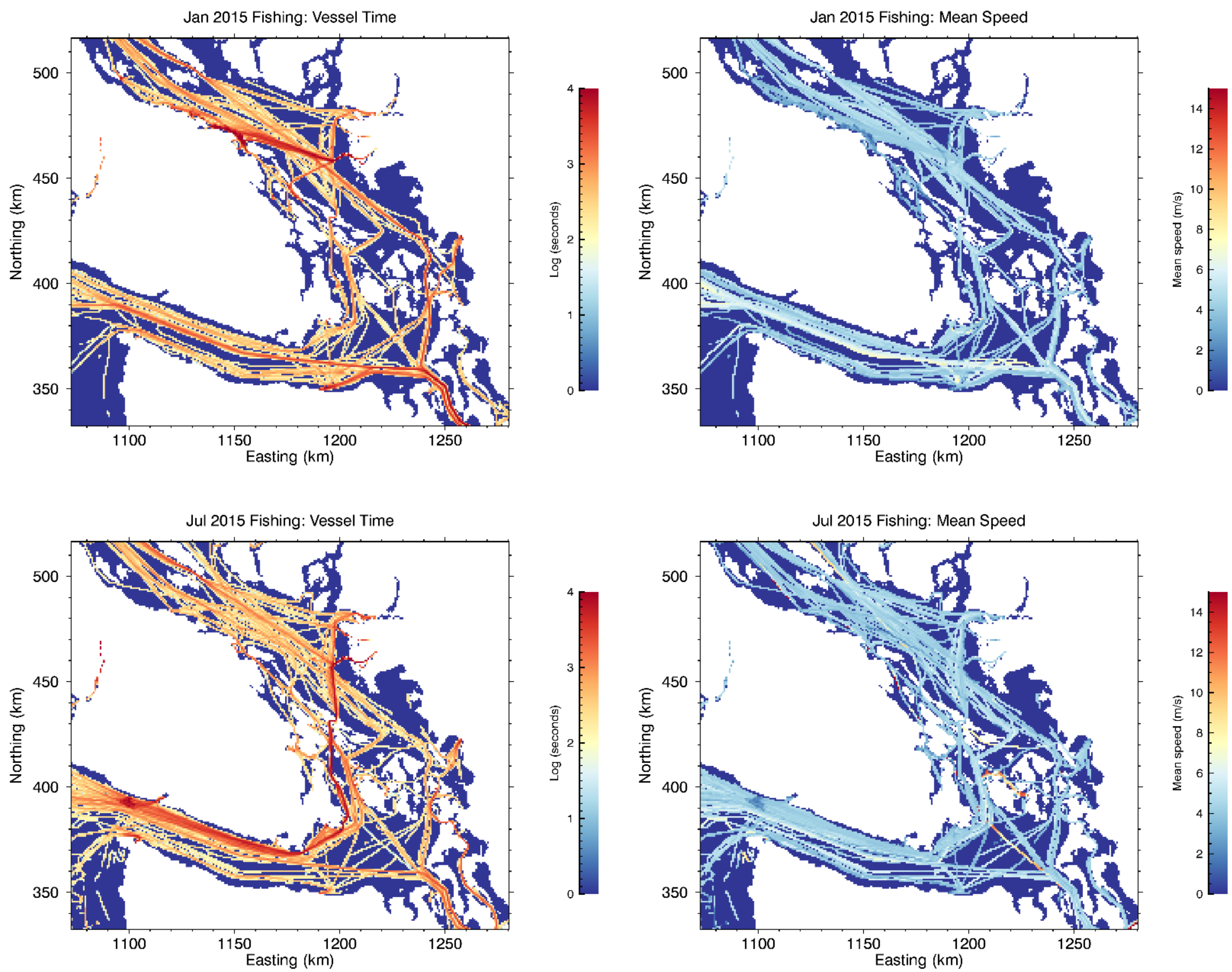

Figure B-3. Fishing category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

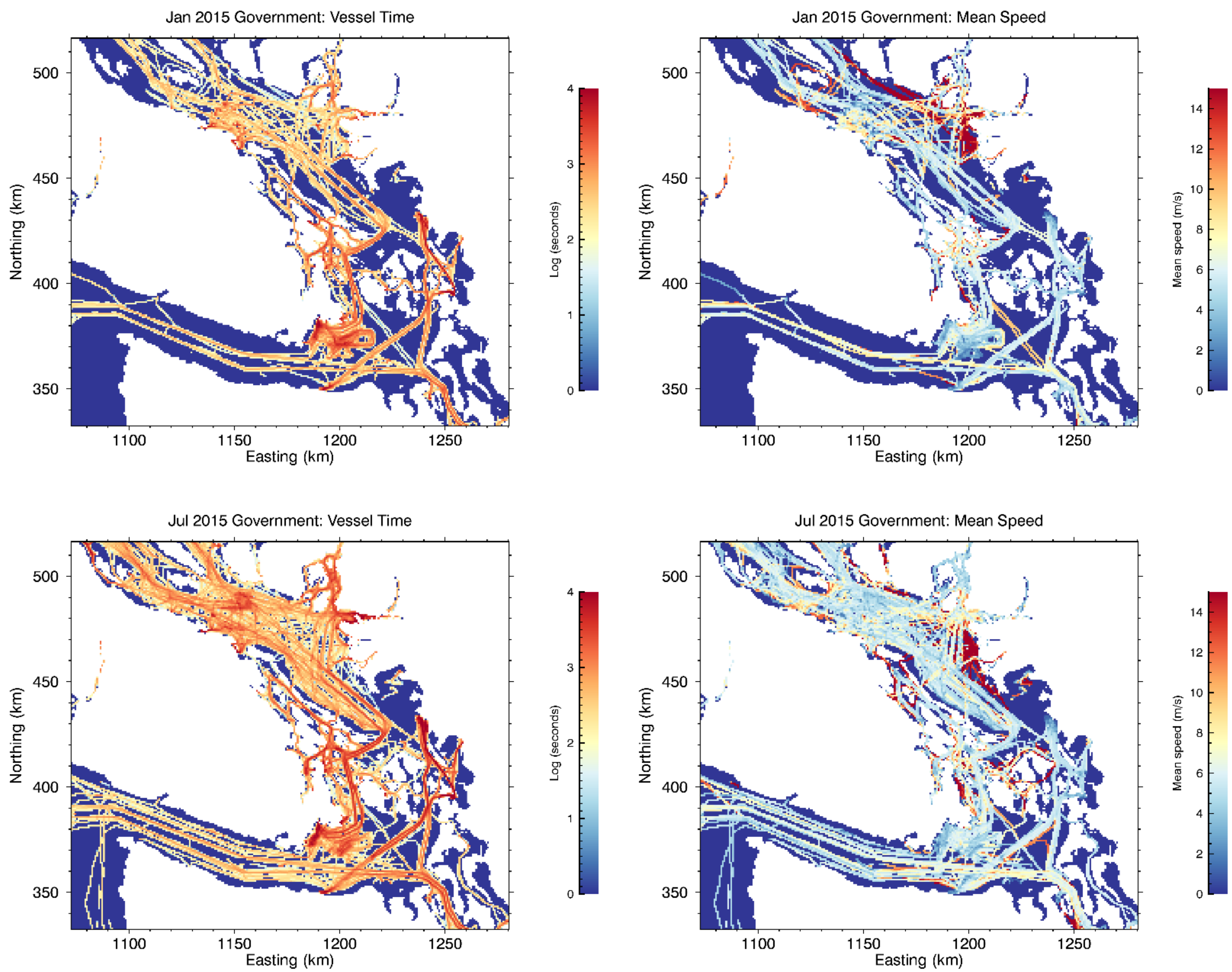

Figure B-4. Government category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

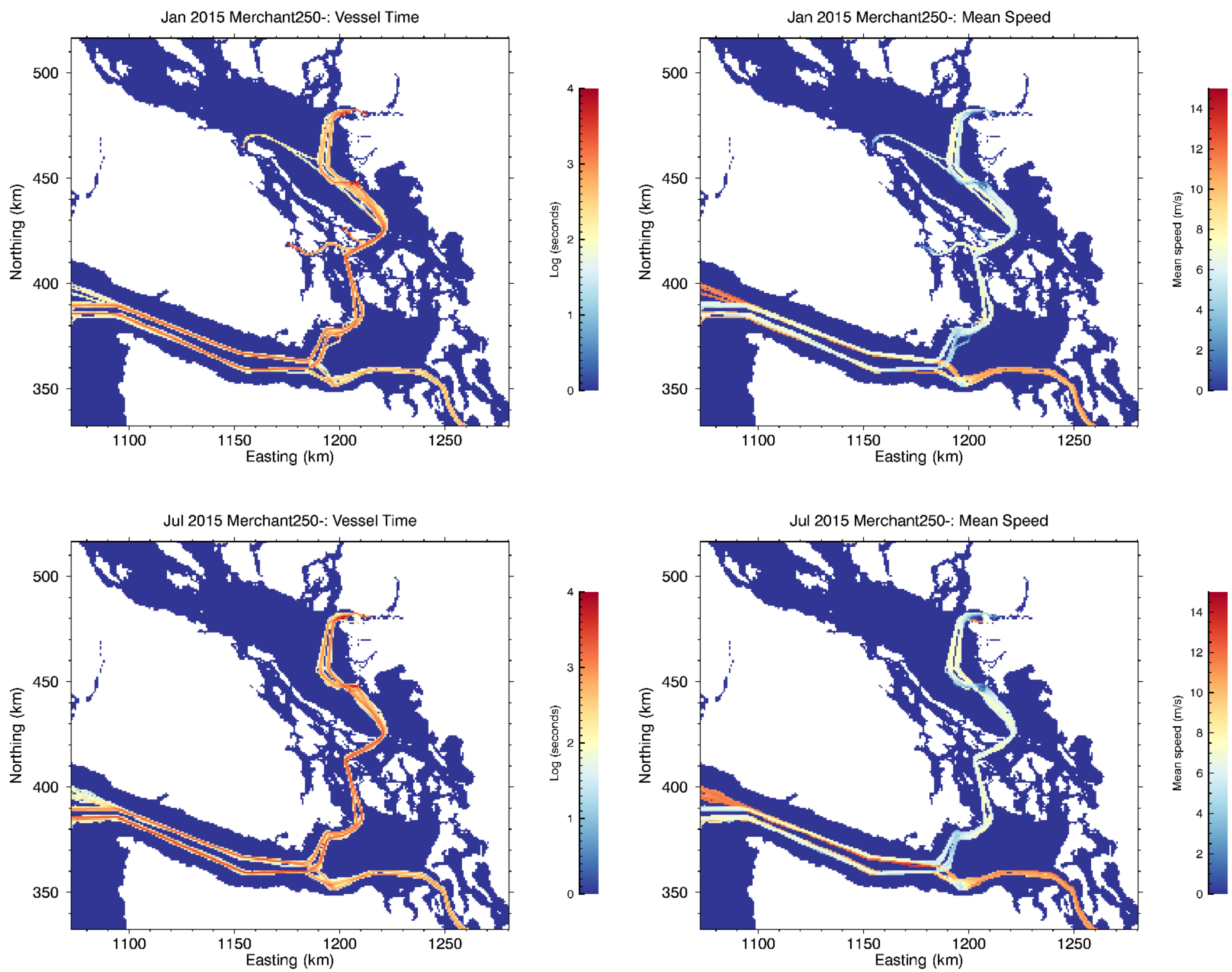

Figure B-5. Merchant (< 250 m) category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

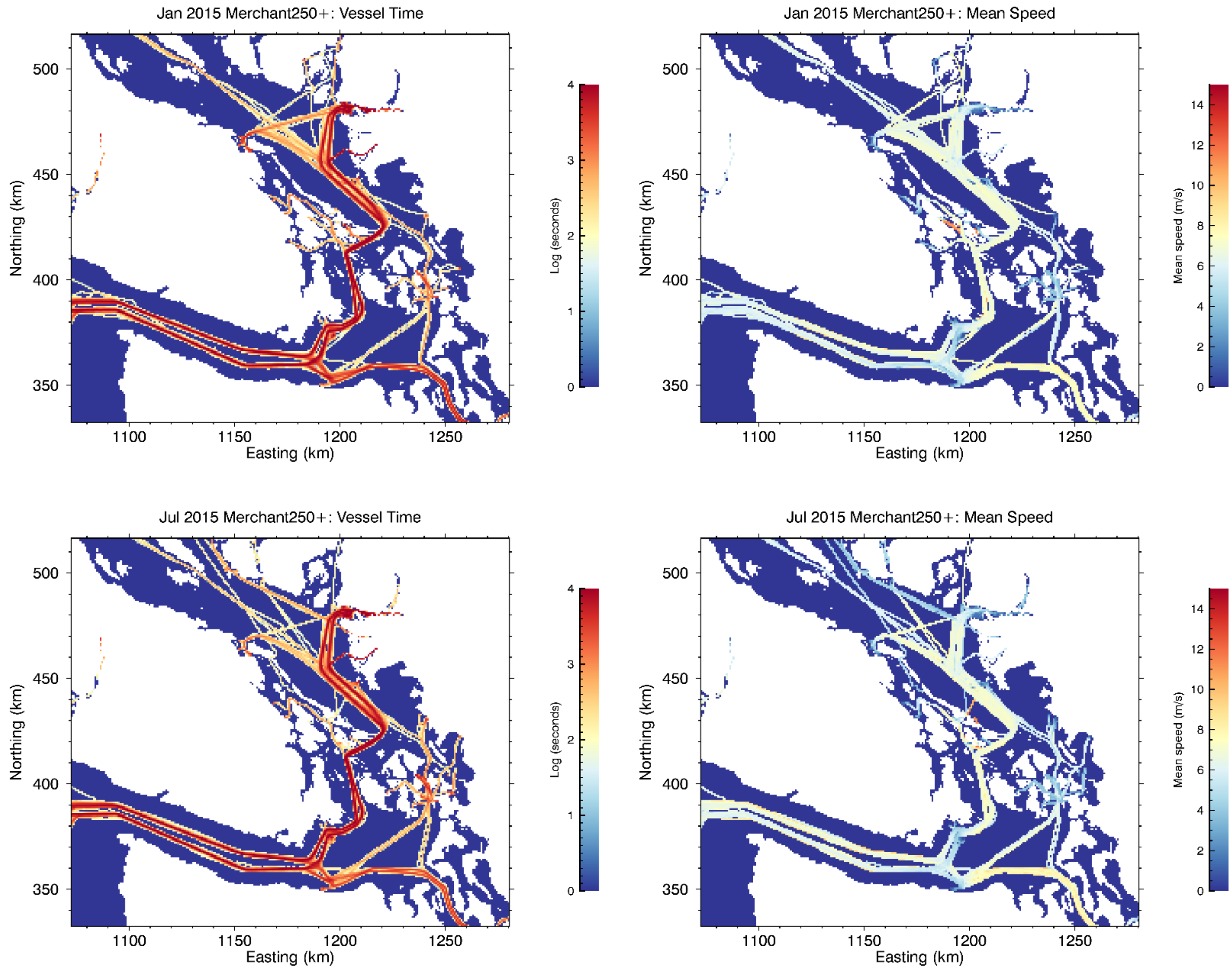

Figure B-6. Merchant (≥ 250 m) category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

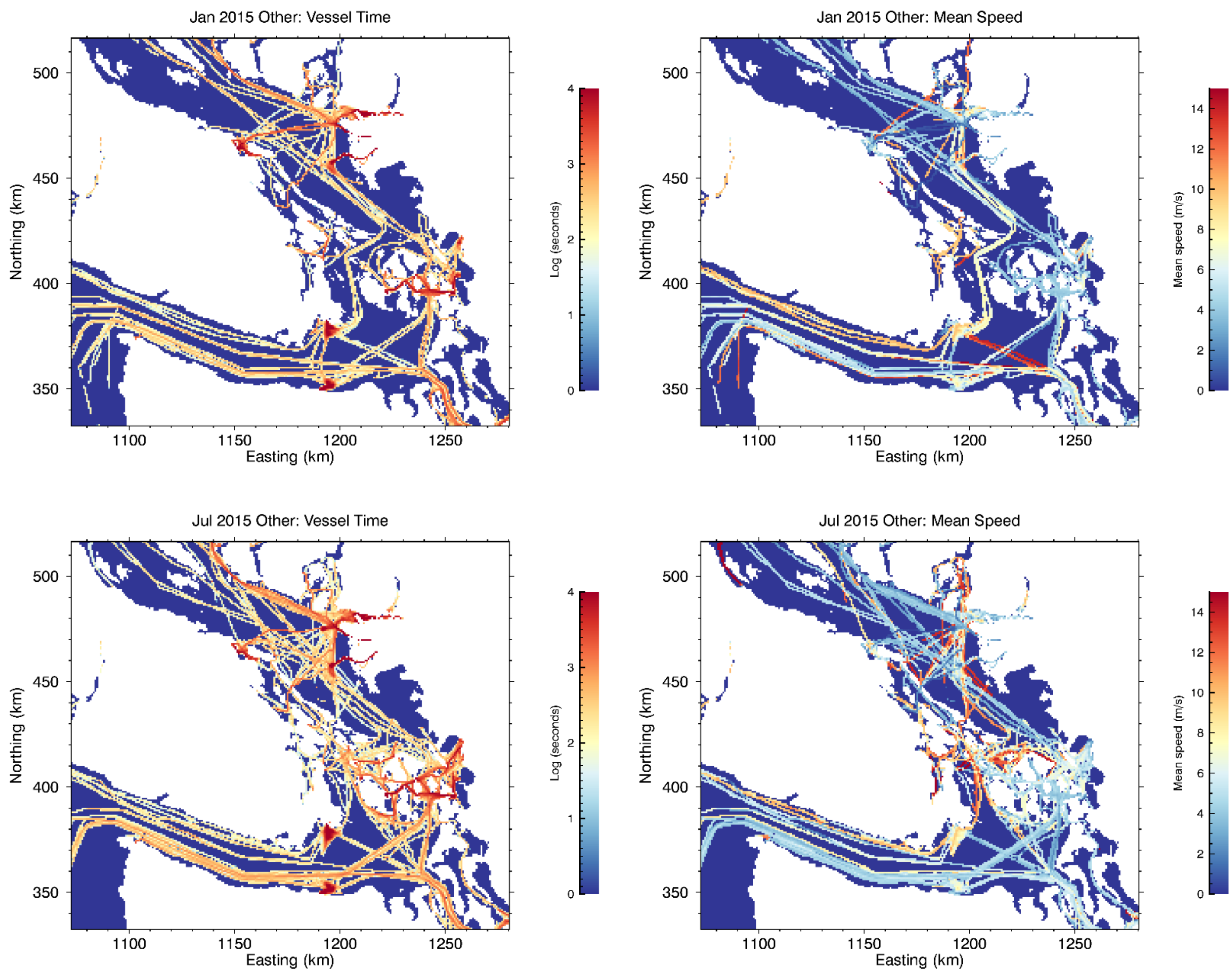

Figure B-7. Miscellaneous category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

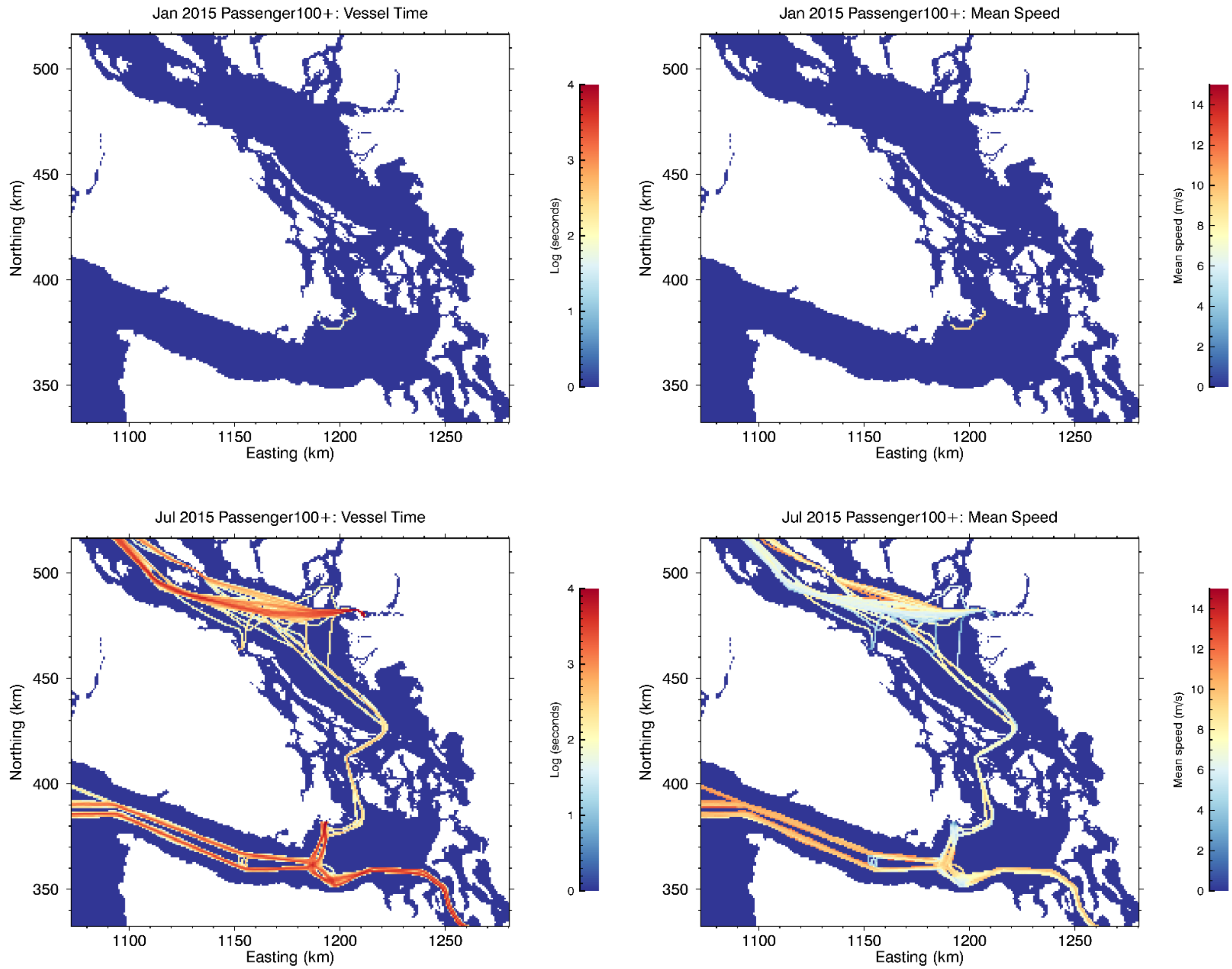

Figure B-8. Passenger (≥ 100 m) category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

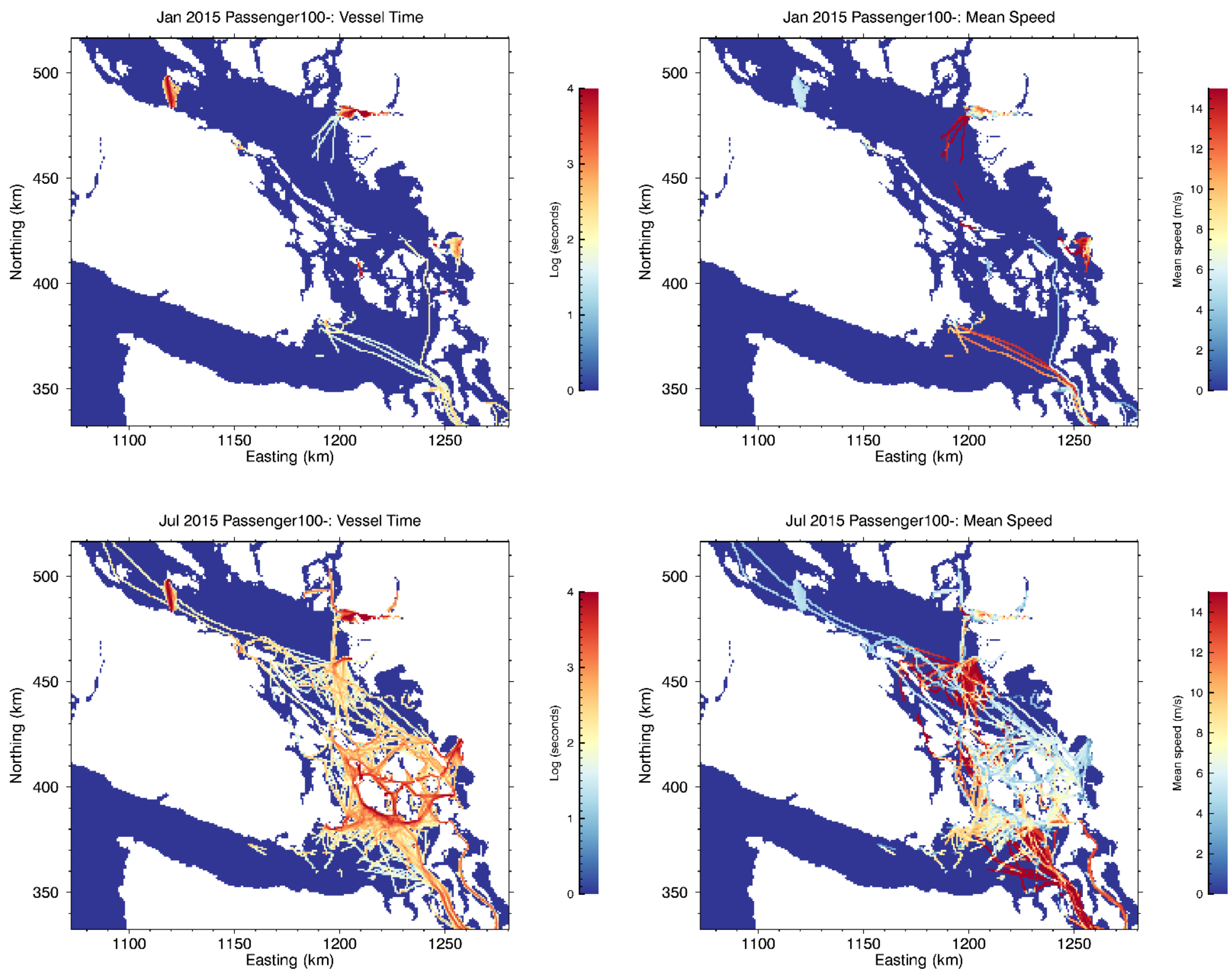

Figure B-9. Passenger (< 100 m) category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

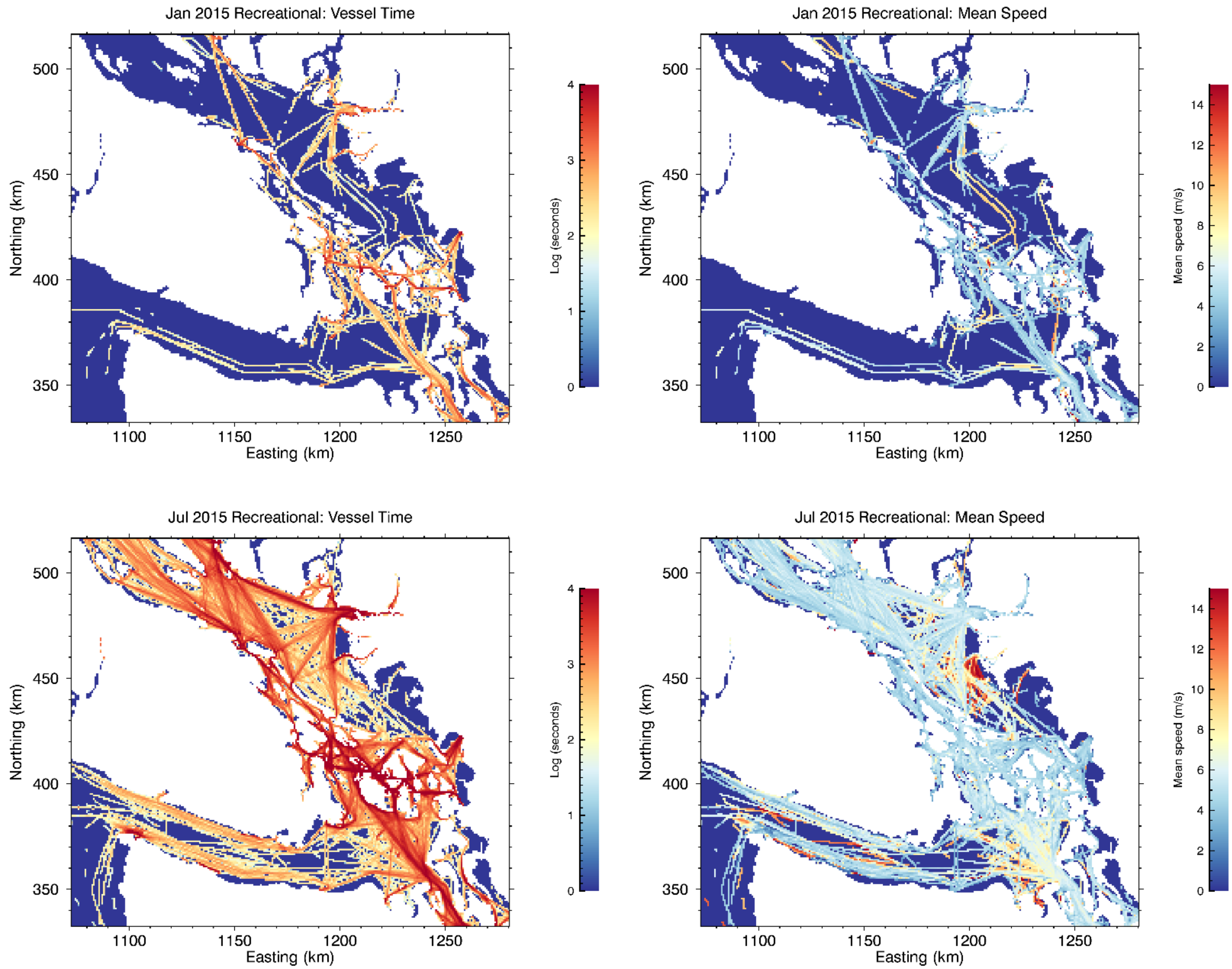

Figure B-10. Recreational category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

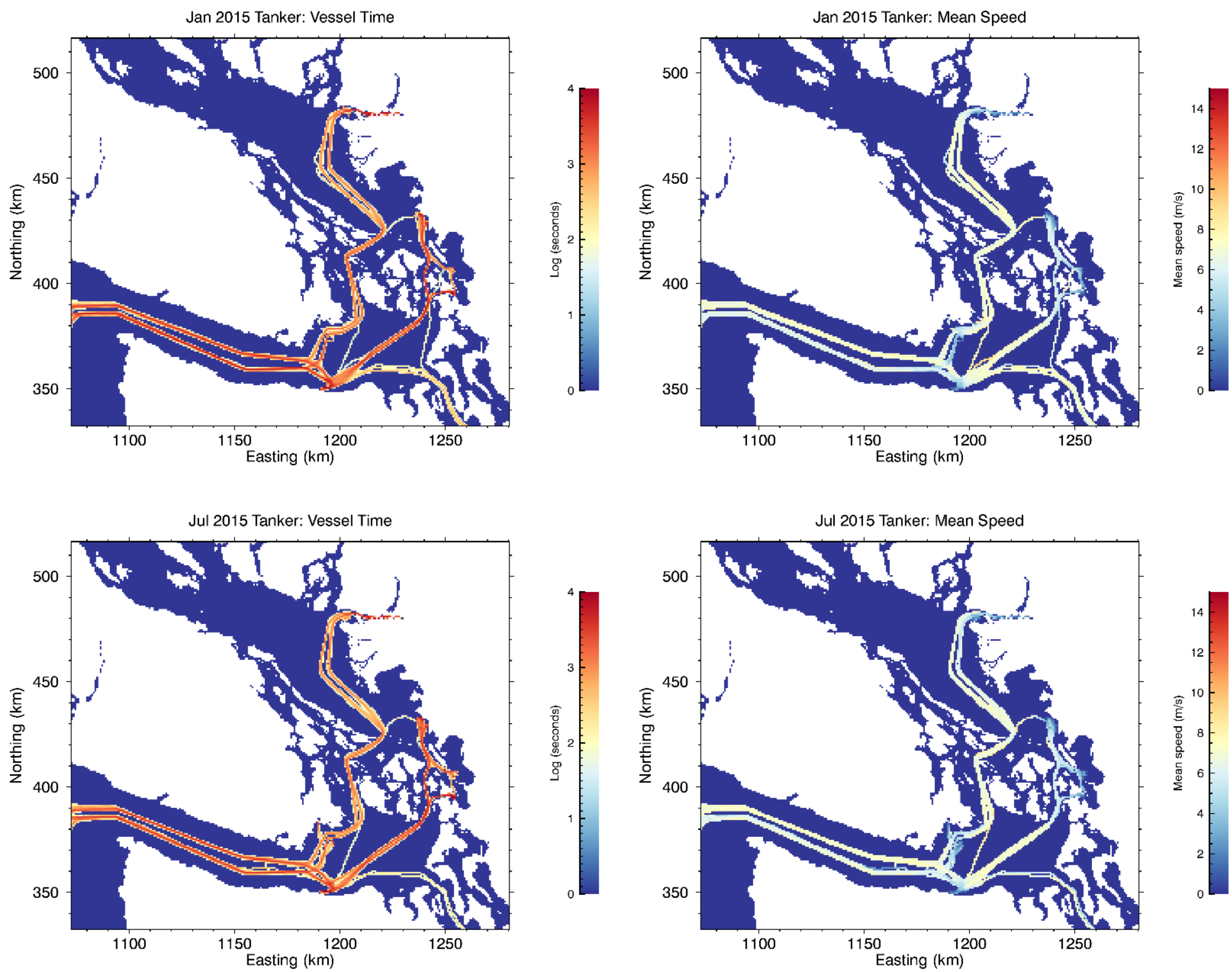

Figure B-11. Tanker category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

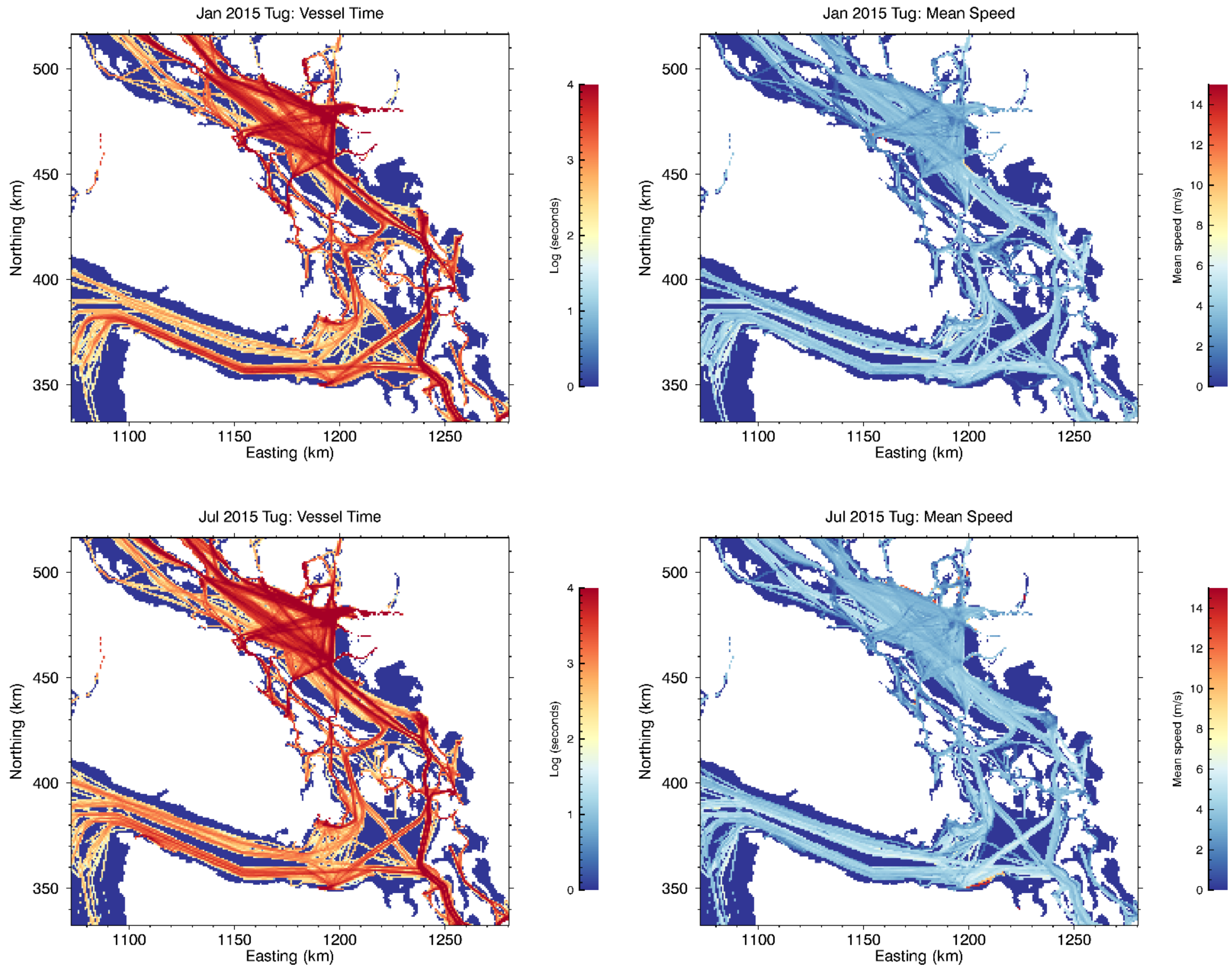

Figure B-12. Tug category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

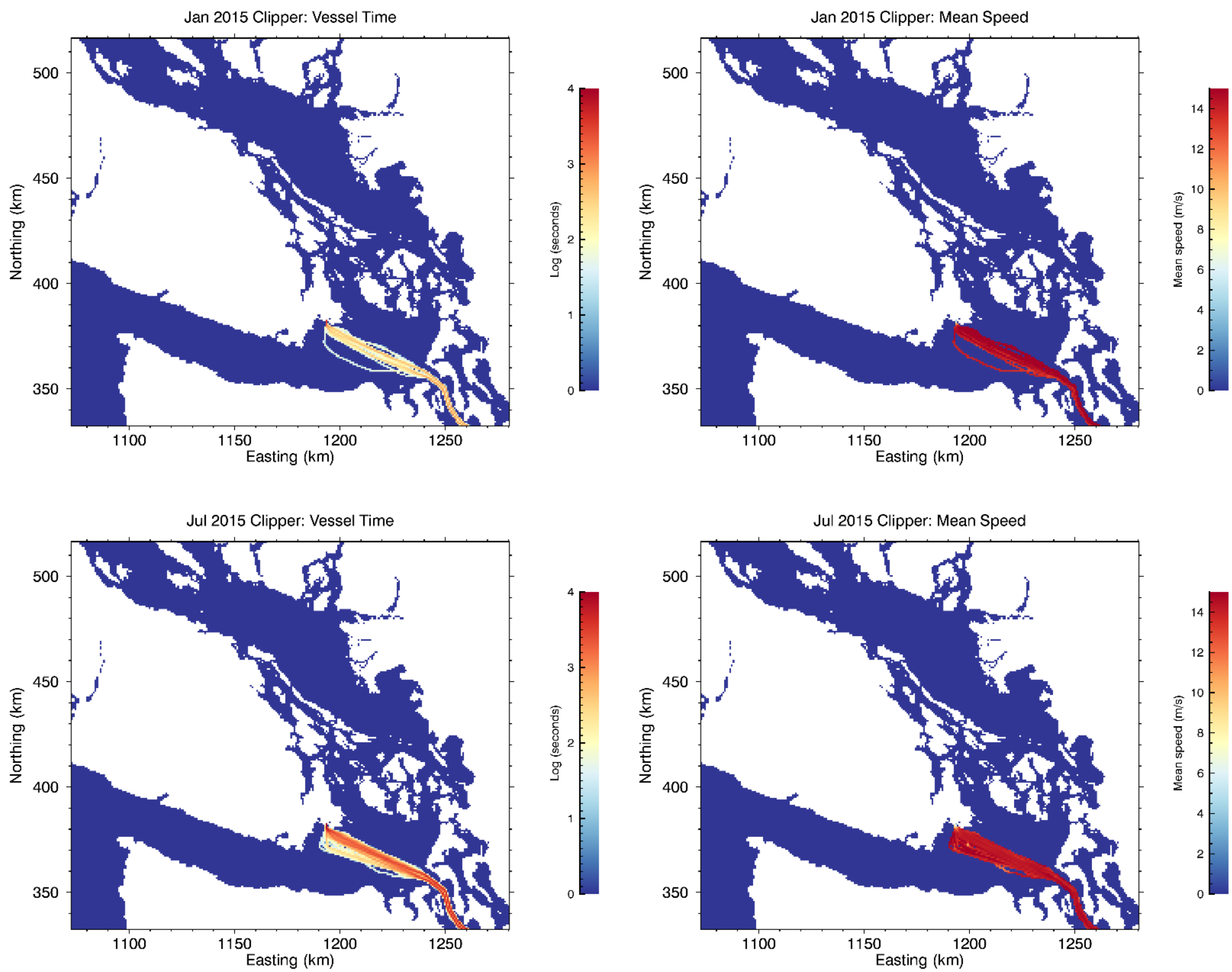

Figure B-13. Clipper category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

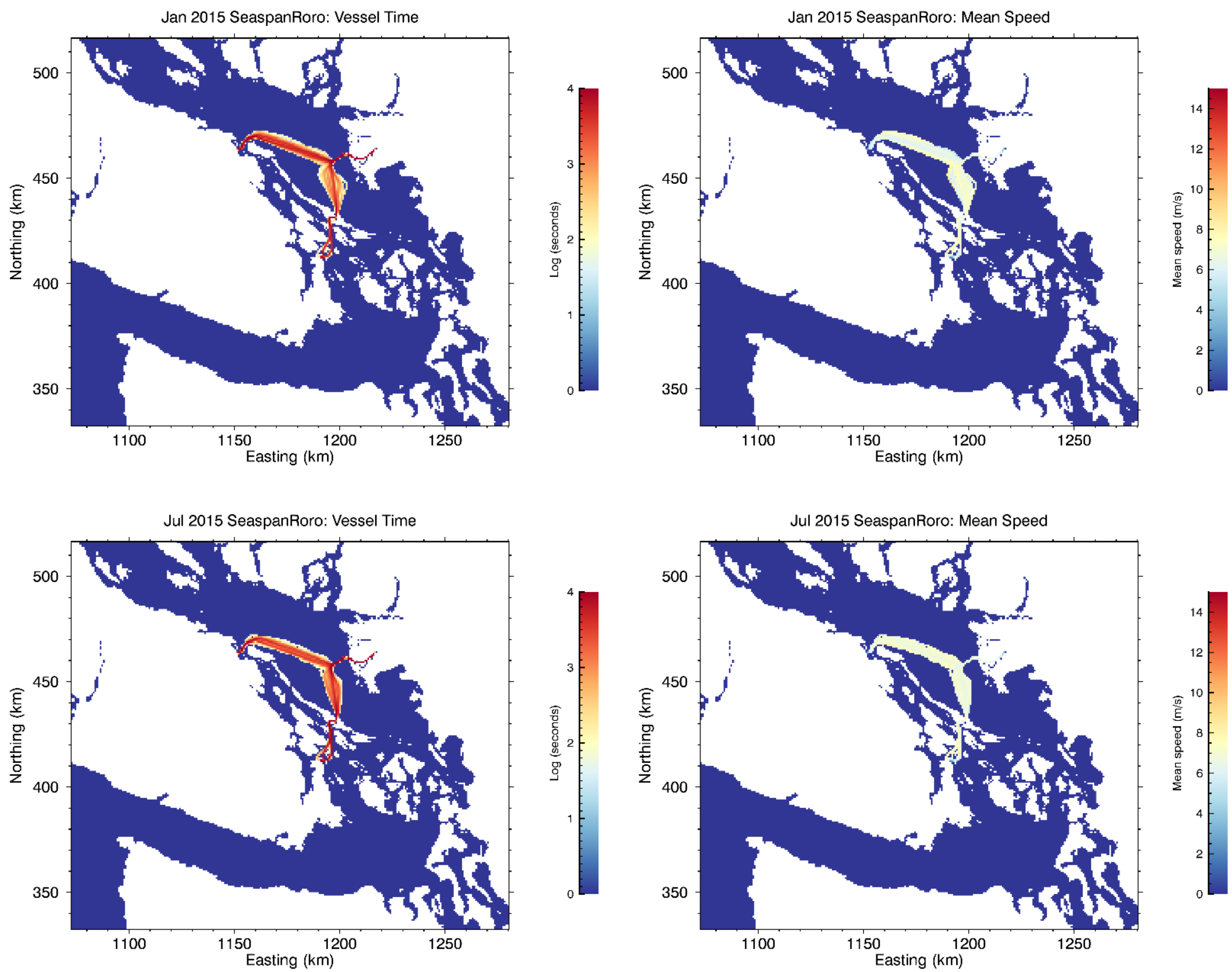

Figure B-14. Seaspan Ro-ro category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

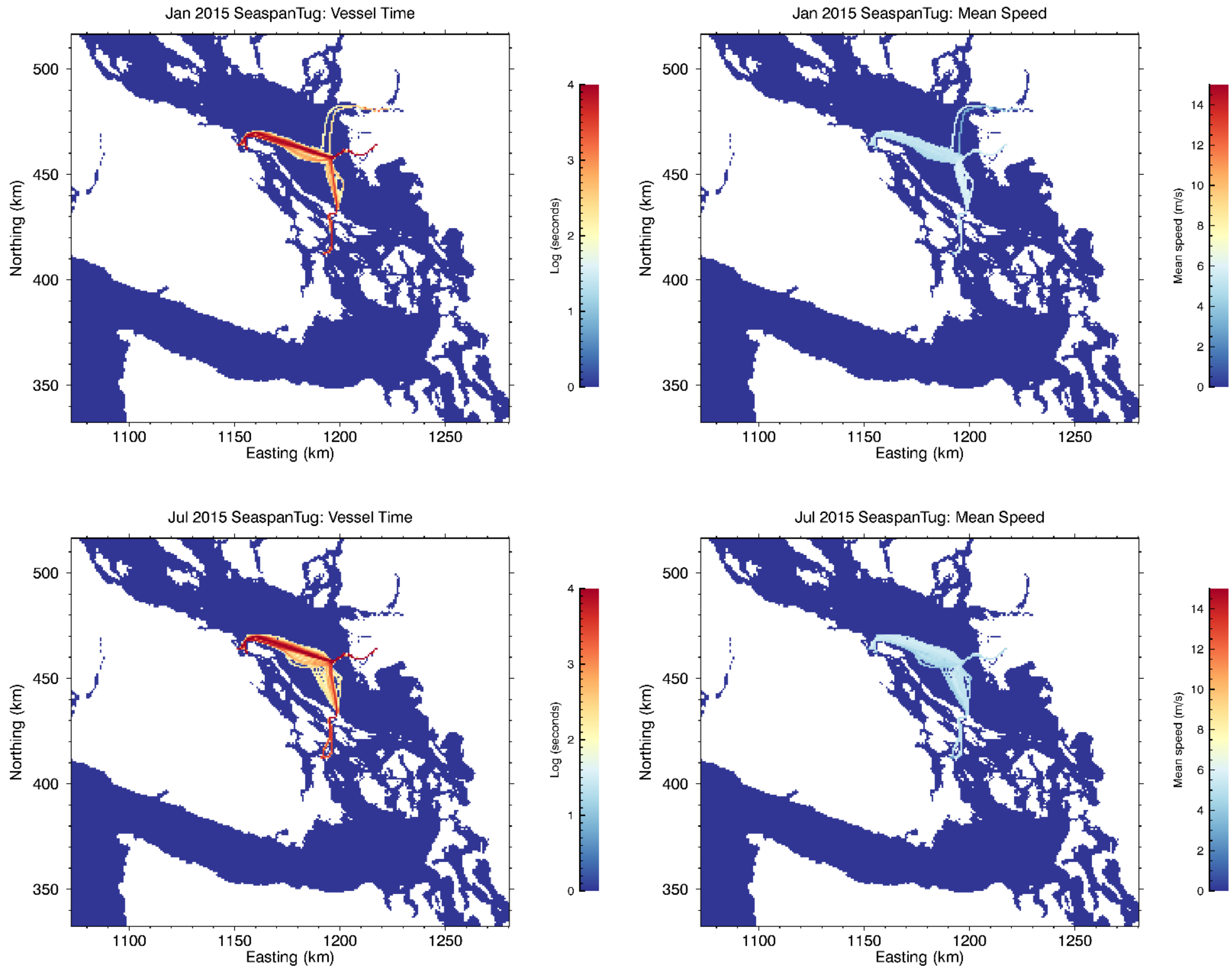

Figure B-15. Seaspan Tug category, total vessel time (left) and mean transit speed (right) in January (top) and July (bottom) 2015.

Appendix C. Whale Watch Vessel Traffic Analysis[1]

SMRU Consulting simulated whale watch boat traffic density for the month of July based on whale watch trip data from the Whale Museum's Soundwatch program. The simulated traffic density map was based on the total estimated effort for the Salish Sea whale watch fleet and the relative distribution of SRKW in the study area. The total whale watch effort for July was calculated according to the following assumptions:

1. Each whale watch trip lasts three hours.
2. There are 146 trips per day in the combined fleet (based on Soundwatch data) and 31 days in July.
3. Two hours of each trip is spent travelling (9052 hours total) and one hour is spent observing (4526 hours total).

A cost-distance analysis was conducted based on Soundwatch data on the home port of each whale watch vessel in the fleet and on assumptions on the typical range these boats venture from their home port during a whale watch trip (informed by discussions with members of the whale watch fleet). This resulted in a relative density of the combined fleet that has higher densities near home ports and successively lower densities the further one is from these home ports. This relative density was then scaled by the number of hours the boats were assumed to be on the water.

For the month of January, it was estimated that the whale watch fleet during the winter was 0.5% of their effort in the summer. This multiplier was then applied to the July Soundwatch data

SRKW relative density was generated from opportunistic sightings recorded by the BC Cetacean Sightings Network (from the Vancouver Aquarium) and the OrcaMaster dataset (from the Whale Museum). Based on the type of reporting party (e.g. whale watcher, coastal worker, population centers, etc.), the data were effort corrected to account for either the distance travelled or the amount of time spent on the water (Koshure and Wood 2014). This resulted in estimates of whale density per unit effort which were then scaled to a relative density from 0 to 1.

Transit speeds for whale watch vessels vary depending on hull design. It was estimated that 85% of the whale watch fleet (according to 2012 Soundwatch data) was of a faster planing-hull design, as opposed to a slower displacement-hull design. Since displacement-hull vessels only account for a small proportion of the fleet, and available source levels are for planing-hull vessels only, it was assumed for the purpose of this study that whale watch traffic consisted entirely of planing-hull vessels. Past measurements of whale watch boats in the study area suggest a typical transit speed for planing-hull vessels of 25 knots (Erbe 2002, Hunt 2007).

Observation speeds were estimated based on the average travelling speeds of the whales themselves since, to observe them, the boats will have to travel that speed as well. In the past, mean speeds of travelling whales have been estimated at 3.1 knots (Williams and Noren 2009), 5.8 knots (Ford 1989), and 4.3 knots (Vergara and Miller). For this study, the observing speed of whale watch boats was taken to be the average of these three estimates (4.4 knots).

The maps below show total whale watch traffic density (total seconds, log scale) in the study area for January (left) and July (right) while observing (top) and transiting (bottom). Density values are given per 800 m × 800 m grid cell.

[1] Author: Jason Wood, SMRU Consulting.

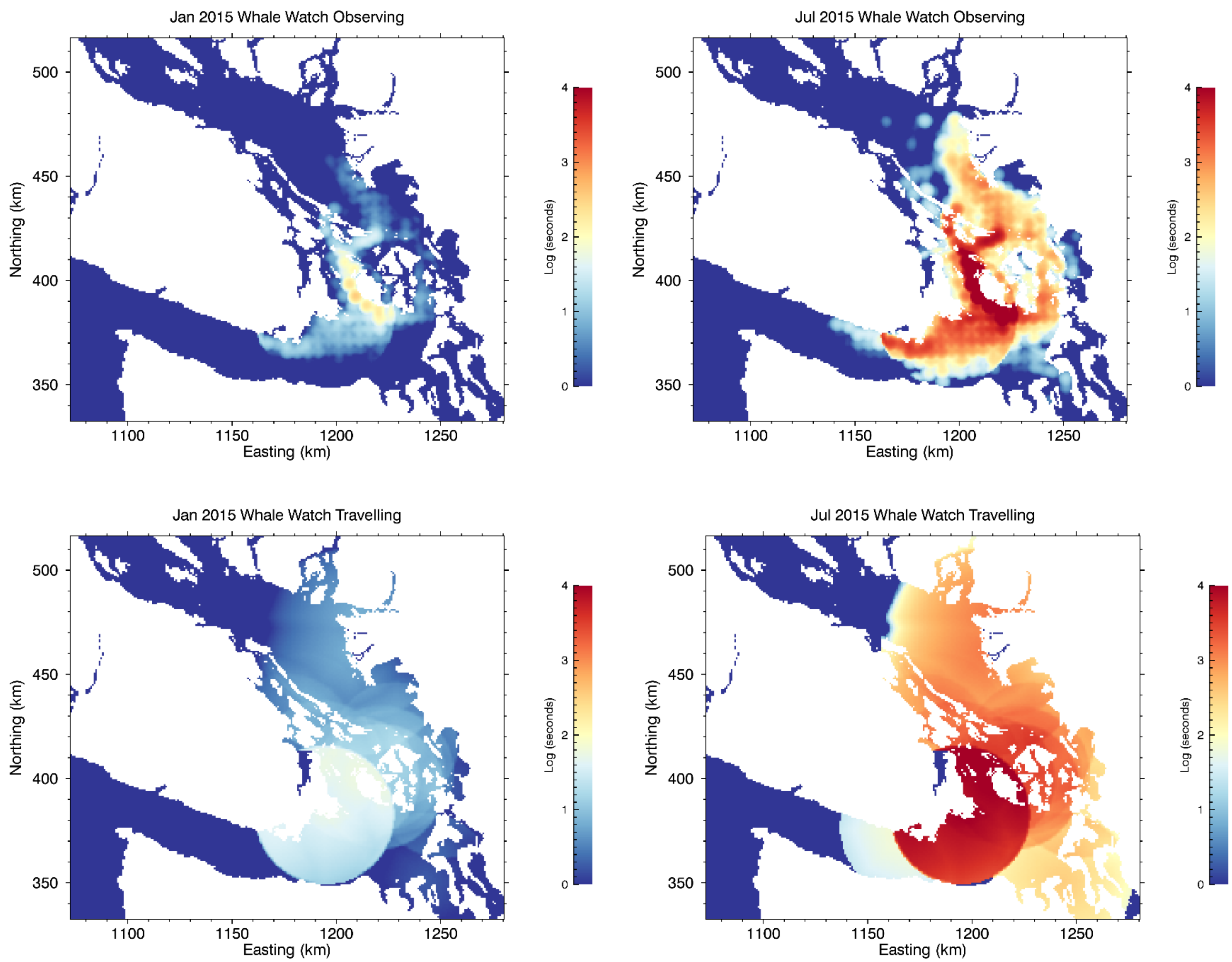

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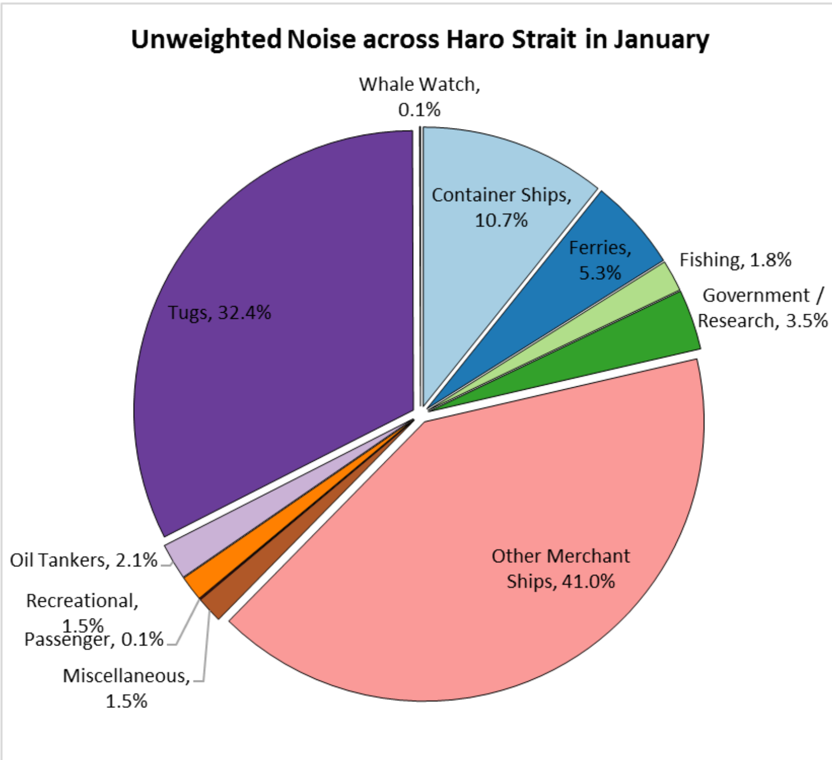
Figure C-1. Total vessel time for whale watch category under observing (top) and travelling (bottom) conditions in January (top) and July (bottom).

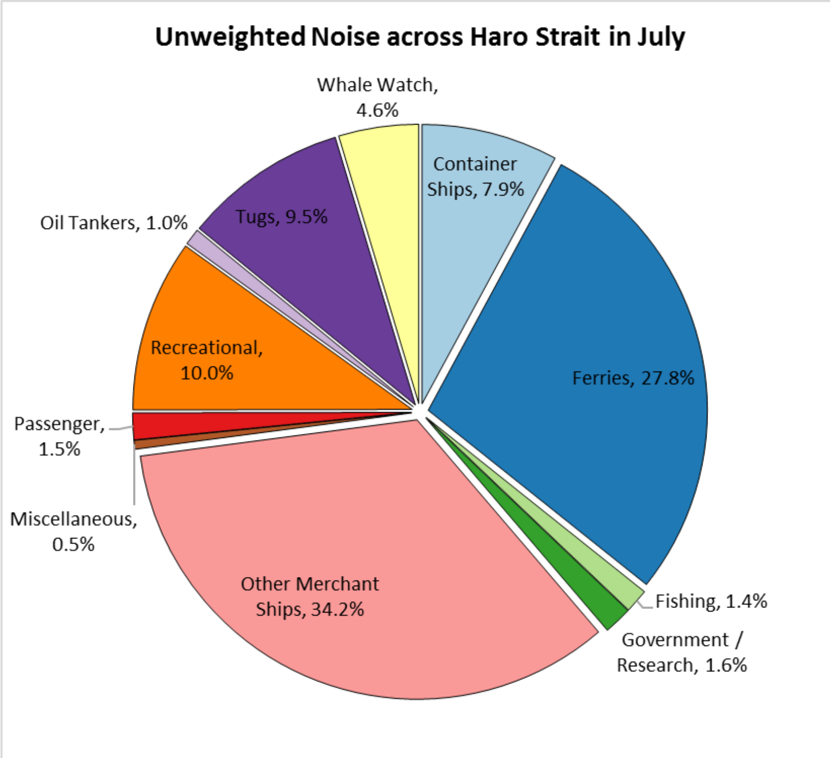
Appendix D. Noise Pie Charts by Sub-region

The following charts show noise budget pie charts for the six sub-region for January and July, in terms of mean square sound pressure. Tabular listings of the data shown in the pie charts are available in Table 3 and Table 4 (see Section 5).



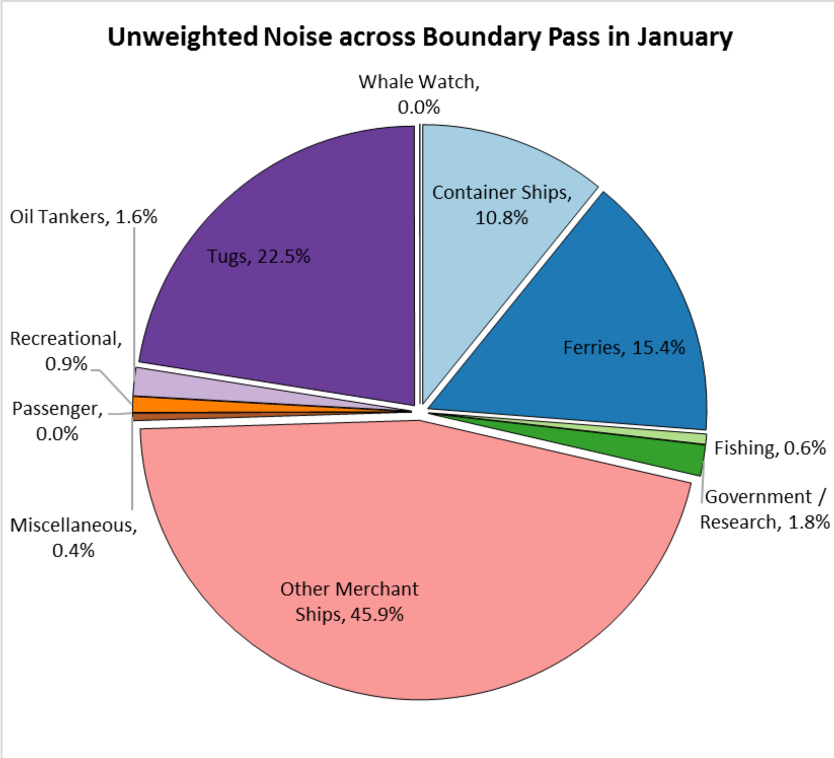
Vessel category	Total mean squared sound pressure (kPa^2)	Percent contribution
Container Ships	0.05792	10.7%
Ferries	0.02874	5.3%
Fishing	0.00981	1.8%
Government / Research	0.01878	3.5%
Other Merchant Ships	0.22086	41.0%
Miscellaneous	0.00819	1.5%
Passenger	0.00034	0.1%
Recreational	0.00785	1.5%
Oil Tankers	0.01132	2.1%
Tugs	0.17486	32.4%
Whale Watch	0.00028	0.1%
All Categories	**0.53895**	**100.0%**

Figure D-1. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in Haro Strait sub-region, for January. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



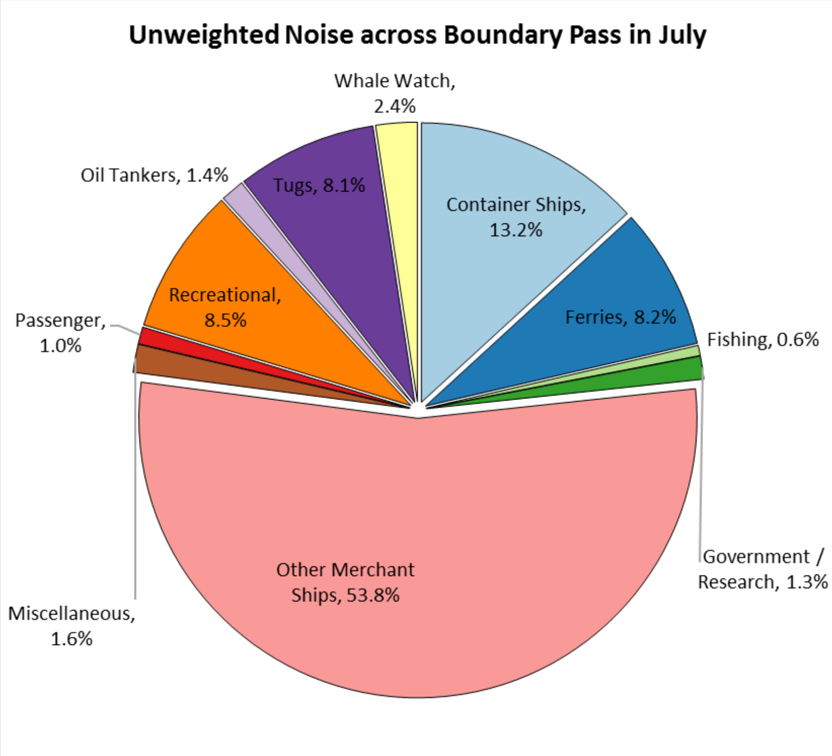
Vessel category	Total mean squared sound pressure (kPa^2)	Percent contribution
Container Ships	0.01589	7.9%
Ferries	0.05590	27.8%
Fishing	0.00278	1.4%
Government / Research	0.00327	1.6%
Other Merchant Ships	0.06873	34.2%
Miscellaneous	0.00102	0.5%
Passenger	0.00309	1.5%
Recreational	0.02004	10.0%
Oil Tankers	0.00192	1.0%
Tugs	0.01904	9.5%
Whale Watch	0.00932	4.6%
All Categories	**0.20101**	**100.0%**

Figure D-2. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in Haro Strait sub-region, for July. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



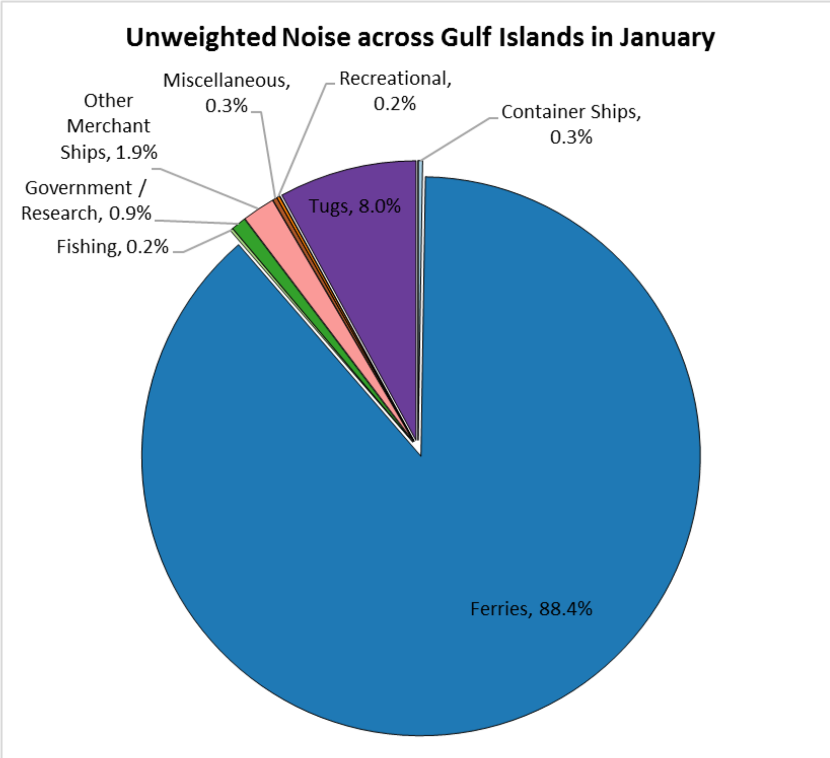
Vessel category	Total mean squared sound pressure (kPa^2)	Percent contribution
Container Ships	0.05055	10.8%
Ferries	0.07176	15.4%
Fishing	0.00277	0.6%
Government / Research	0.00838	1.8%
Other Merchant Ships	0.21419	45.9%
Miscellaneous	0.00206	0.4%
Passenger	0.00003	0.0%
Recreational	0.00426	0.9%
Oil Tankers	0.00761	1.6%
Tugs	0.10486	22.5%
Whale Watch	0.00010	0.0%
All Categories	**0.46658**	**100.0%**

Figure D-3. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in Boundary Pass sub-region, for January. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



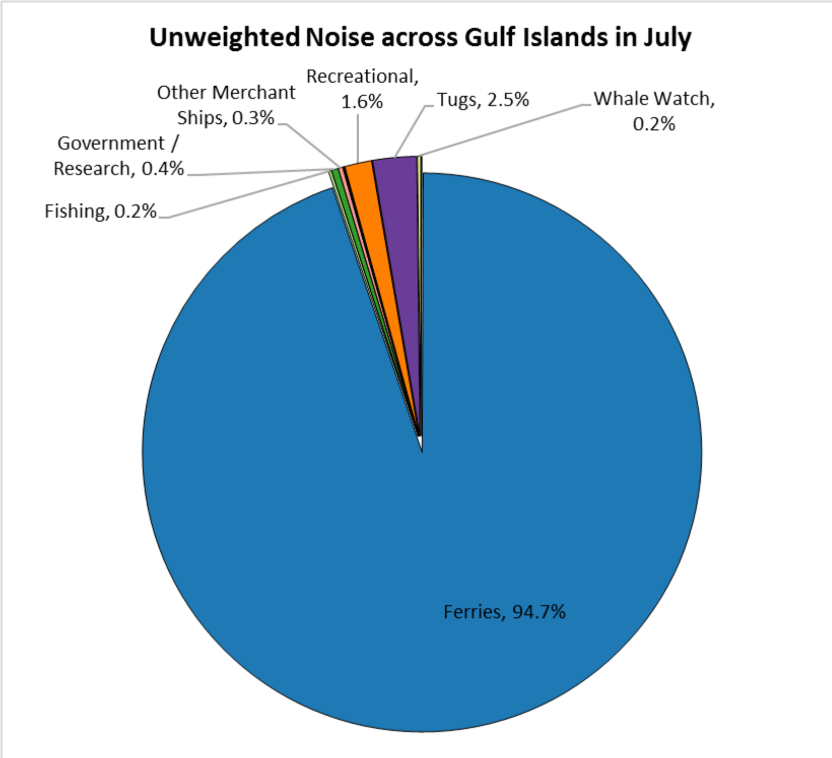
Vessel category	Total mean squared sound pressure (kPa^2)	Percent contribution
Container Ships	0.01905	13.2%
Ferries	0.01182	8.2%
Fishing	0.00085	0.6%
Government / Research	0.00193	1.3%
Other Merchant Ships	0.07759	53.8%
Miscellaneous	0.00234	1.6%
Passenger	0.00140	1.0%
Recreational	0.01222	8.5%
Oil Tankers	0.00198	1.4%
Tugs	0.01169	8.1%
Whale Watch	0.00346	2.4%
All Categories	**0.14433**	**100.0%**

Figure D-4. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in Boundary Pass sub-region, for July. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



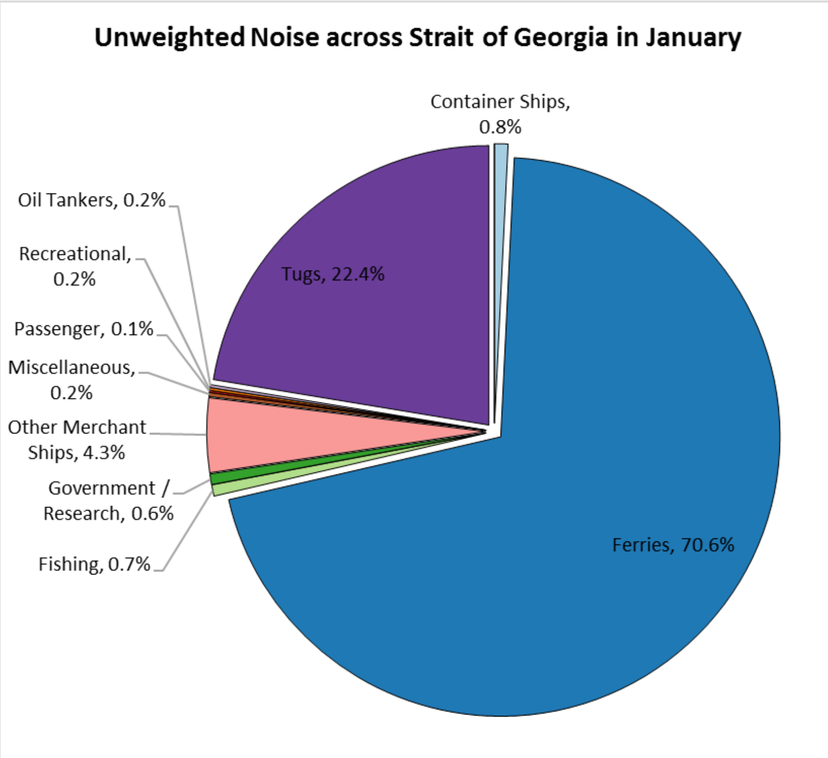
Vessel category	Total mean squared sound pressure (kPa^2)	Percent contribution
Container Ships	0.00200	0.3%
Ferries	0.70429	88.4%
Fishing	0.00132	0.2%
Government / Research	0.00681	0.9%
Other Merchant Ships	0.01502	1.9%
Miscellaneous	0.00203	0.3%
Passenger	0.00001	0.0%
Recreational	0.00133	0.2%
Oil Tankers	0.00022	0.0%
Tugs	0.06350	8.0%
Whale Watch	0.00002	0.0%
All Categories	**0.79654**	**100.0%**

Figure D-5. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in Gulf Islands sub-region, for January. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



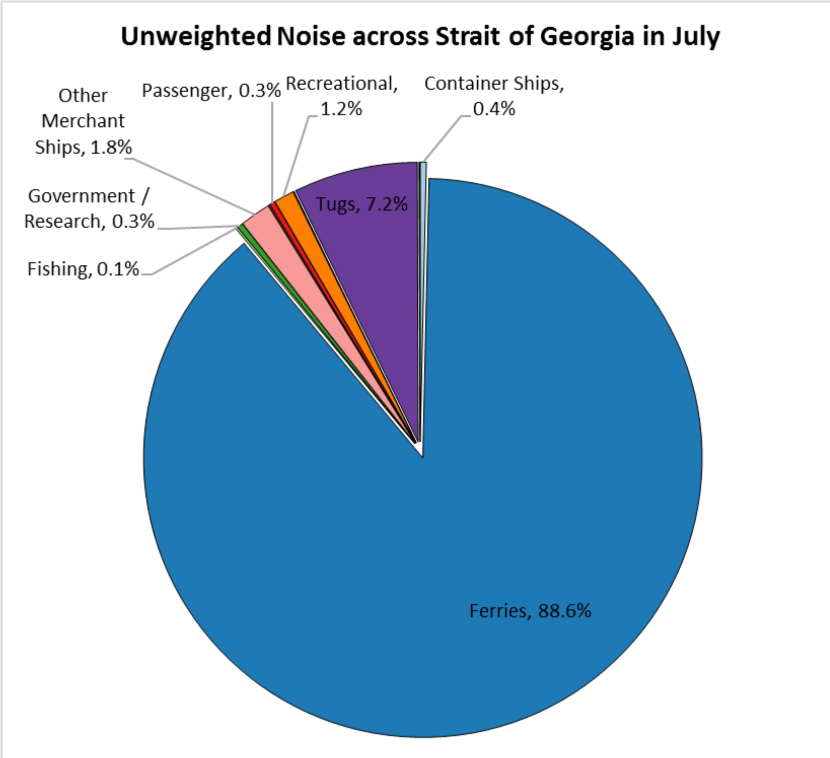
Vessel category	Total mean squared sound pressure (kPa^2)	Percent contribution
Container Ships	0.00047	0.1%
Ferries	0.69565	94.7%
Fishing	0.00131	0.2%
Government / Research	0.00288	0.4%
Other Merchant Ships	0.00188	0.3%
Miscellaneous	0.00047	0.1%
Passenger	0.00026	0.0%
Recreational	0.01141	1.6%
Oil Tankers	0.00001	0.0%
Tugs	0.01856	2.5%
Whale Watch	0.00138	0.2%
All Categories	**0.73428**	**100.0%**

Figure D-6. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in Gulf Islands sub-region, for July. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



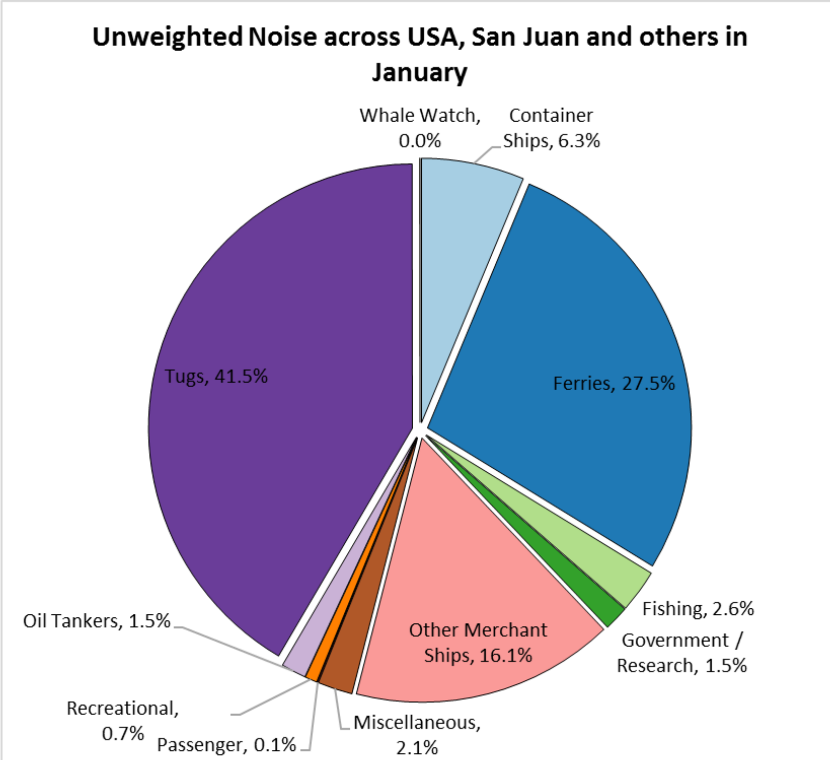
Vessel category	Total mean squared sound pressure (kPa^2)	Percent contribution
Container Ships	0.01147	0.8%
Ferries	1.04859	70.6%
Fishing	0.00968	0.7%
Government / Research	0.00908	0.6%
Other Merchant Ships	0.06367	4.3%
Miscellaneous	0.00347	0.2%
Passenger	0.00172	0.1%
Recreational	0.00229	0.2%
Oil Tankers	0.00248	0.2%
Tugs	0.33251	22.4%
Whale Watch	0.00002	0.0%
All Categories	**1.48499**	**100.0%**

Figure D-7. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in Strait of Georgia sub-region, for January. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



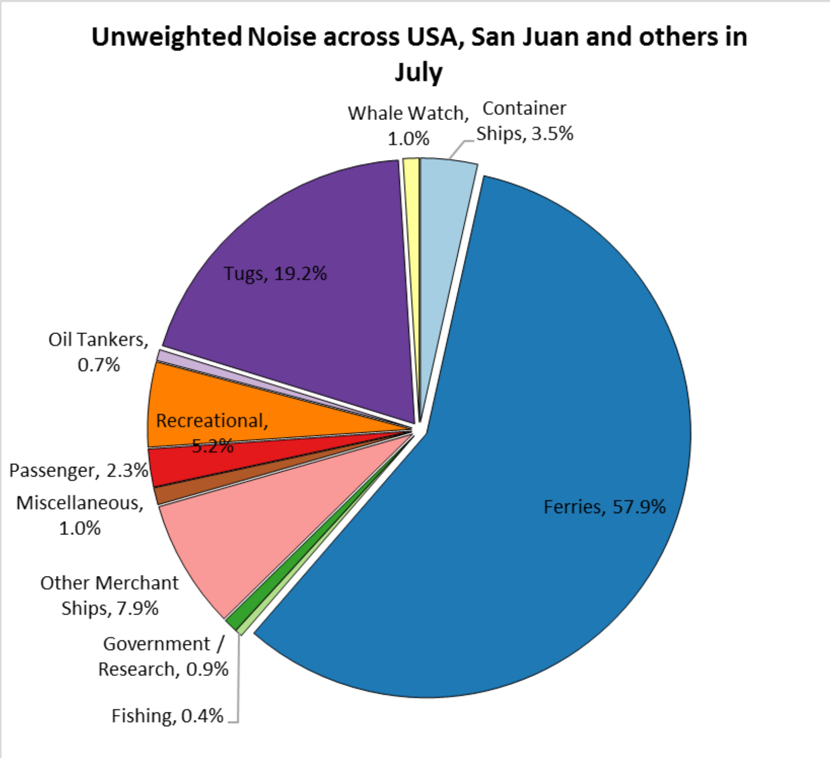
Vessel category	Total mean squared sound pressure (kPa²)	Percent contribution
Container Ships	0.00114	0.4%
Ferries	0.28324	88.6%
Fishing	0.00042	0.1%
Government / Research	0.00102	0.3%
Other Merchant Ships	0.00567	1.8%
Miscellaneous	0.00027	0.1%
Passenger	0.00100	0.3%
Recreational	0.00375	1.2%
Oil Tankers	0.00013	0.0%
Tugs	0.02292	7.2%
Whale Watch	0.00017	0.1%
All Categories	**0.31973**	**100.0%**

Figure D-8. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in Strait of Georgia sub-region, for July. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



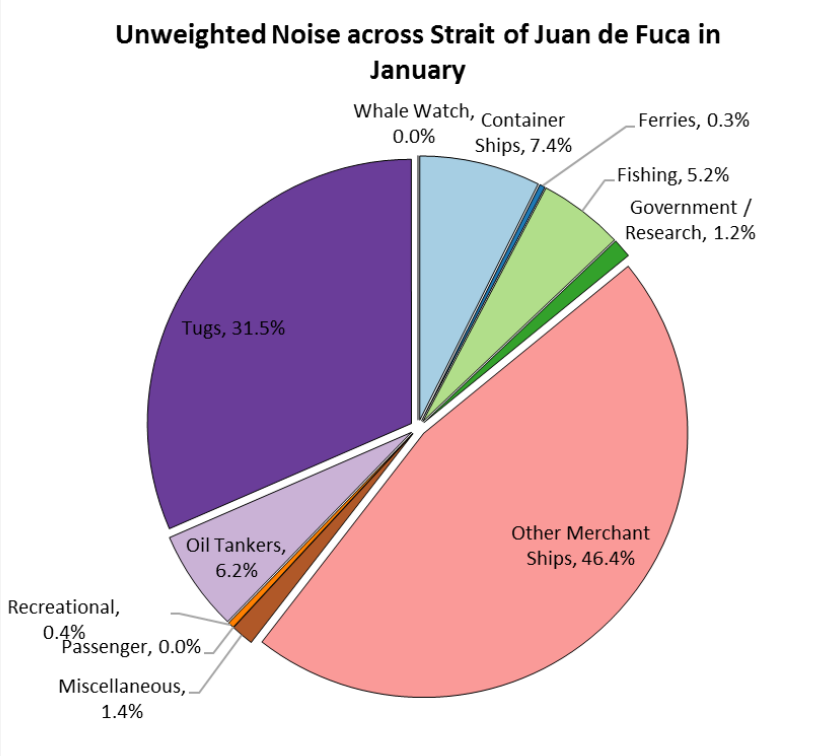
Vessel category	Total mean squared sound pressure (kPa²)	Percent contribution
Container Ships	0.03695	6.3%
Ferries	0.16111	27.5%
Fishing	0.01543	2.6%
Government / Research	0.00888	1.5%
Other Merchant Ships	0.09452	16.1%
Miscellaneous	0.01252	2.1%
Passenger	0.00042	0.1%
Recreational	0.00432	0.7%
Oil Tankers	0.00895	1.5%
Tugs	0.24362	41.5%
Whale Watch	0.00010	0.0%
All Categories	**0.58682**	**100.0%**

Figure D-9. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in USA, San Juans, and Other sub-region, for January. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



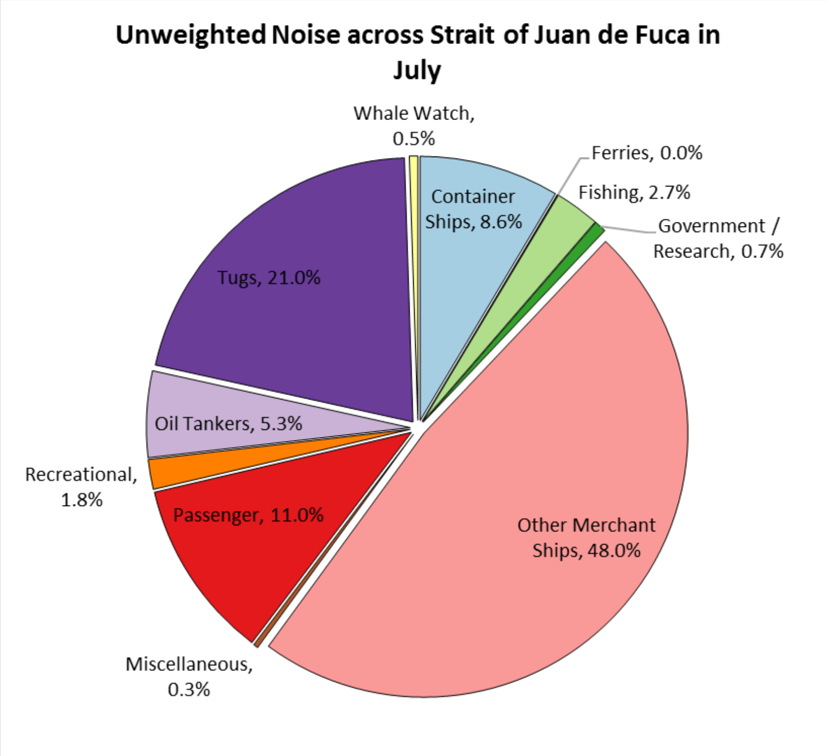
Vessel category	Total mean squared sound pressure (kPa^2)	Percent contribution
Container Ships	0.00839	3.5%
Ferries	0.13929	57.9%
Fishing	0.00108	0.4%
Government / Research	0.00207	0.9%
Other Merchant Ships	0.01900	7.9%
Miscellaneous	0.00252	1.0%
Passenger	0.00557	2.3%
Recreational	0.01250	5.2%
Oil Tankers	0.00162	0.7%
Tugs	0.04628	19.2%
Whale Watch	0.00237	1.0%
All Categories	**0.24069**	**100.0%**

Figure D-10. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in USA, San Juans, and Other sub-region, for July. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



Vessel category	Total mean squared sound pressure (kPa^2)	Percent contribution
Container Ships	0.02462	7.4%
Ferries	0.00109	0.3%
Fishing	0.01733	5.2%
Government / Research	0.00386	1.2%
Other Merchant Ships	0.15431	46.4%
Miscellaneous	0.00462	1.4%
Passenger	0.00001	0.0%
Recreational	0.00126	0.4%
Oil Tankers	0.02062	6.2%
Tugs	0.10483	31.5%
Whale Watch	0.00002	0.0%
All Categories	**0.33256**	**100.0%**

Figure D-11. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in Strait of Juan de Fuca sub-region, for January. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.



Vessel category	Total mean squared sound pressure (kPa^2)	Percent contribution
Container Ships	0.01038	8.6%
Ferries	0.00004	0.0%
Fishing	0.00333	2.7%
Government / Research	0.00088	0.7%
Other Merchant Ships	0.05808	48.0%
Miscellaneous	0.00035	0.3%
Passenger	0.01334	11.0%
Recreational	0.00221	1.8%
Oil Tankers	0.00639	5.3%
Tugs	0.02546	21.0%
Whale Watch	0.00063	0.5%
All Categories	**0.12108**	**100.0%**

Figure D-12. Pie chart (left) and table (right) showing the relative noise contribution of all vessel categories in Strait of Juan de Fuca sub-region, for July. The contribution of each category is proportional to total number of vessels, the amount of time they spend in the region, and their source level.