A whale of a problem?

Heavy fuel oil, exhaust gas cleaning systems, and British Columbia's resident killer whales

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ICCT CONSULTING REPORT

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EXECUTIVE SUMMARY

In 2020, the International Maritime Organization (IMO) will begin to enforce a fuel sulfur limit of 0.5% by mass (5,000 ppm), down from a maximum limit of 3.5%. Some shipowners have invested in exhaust gas cleaning systems, known as "scrubbers," in order to comply with the regulations without having to switch to cleaner and more expensive fuels. Scrubbers, especially open-loop systems, have harmful unintended consequences on the marine environment. Open-loop systems continuously discharge warm, acidic washwater that contains carcinogenic substances such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals. When released into the ocean, these substances pose a threat to aquatic wildlife, including threatened and critically endangered pods of resident killer whales that live off the coast of British Columbia.

The waters surrounding British Columbia's Vancouver Island are home to northern and southern resident killer whales (RKWs), which, respectively, are listed as threatened and endangered. This analysis estimates the amount and location of heavy fuel oil (HFO) carriage, HFO use, and washwater discharge from ships operating off the coast of British Columbia in three scenarios: ships fitted with scrubbers as of 2017, ships predicted to be fitted with scrubbers by 2020, and an extreme scenario where nearly all HFO-capable ships use scrubbers. These results were overlaid with the locations of RKW critical habitats to illustrate where washwater discharge could impact these threatened and critically endangered species.

We found that:

- In 2017, 30 scrubber-equipped ships emitted nearly 35 million tonnes of scrubber washwater. Cruise ships were responsible for 90% of these discharges.
- Approximately 10% of scrubber washwater discharges occurred within RKW critical habitats, even though these locales represent only 0.6% of the study area.
- Nearly 90% of all HFO carried in the study area passes through RKW critical habitats.
- Carriage of HFO is expected to fall nearly 90% from 2017 to 2020 due to the IMO's 2020 fuel sulfur regulation. However, HFO use and scrubber washwater discharges are expected to grow by 35% as more ships, particularly container ships, bulk carriers, and roll-on/roll off ferries, begin to use scrubbers.
- Cruise ships will account for two-thirds of HFO use and washwater discharges in 2020 despite the exponential growth in scrubber use in other ship types.

Without rules requiring closed-loop or zero-discharge operations, the use of open-loop or hybrid scrubbers operating in open-loop mode is expected to grow, increasing washwater pollution discharges which worsen water quality, and perpetuating the risk of an HFO spill. Using hybrid- or closed-loop scrubbers in zero-discharge mode would eliminate water pollution emissions from these systems but the risk of an HFO spill would remain. Using marine gas oil (MGO) inside the North American Emission Control Area (ECA) and very low sulfur fuel oil (VLSFO) outside would obviate the use of scrubbers but could still pose a residual fuel spill risk. While there will always be negative consequences in the event of a fuel oil spill, using only MGO would eliminate the need for scrubbers and eliminate the chances of a residual fuel spill.

INTRODUCTION

This report investigates the use and carriage of heavy fuel oil (HFO) and the discharge of washwater from exhaust gas cleaning systems (EGCS), also called "scrubbers," from ships operating in the North American Emission Control Area (ECA) off the coast of British Columbia, including in and near critical habitat for threatened and critically endangered resident killer whales (RKWs). Southern RKWs are critically endangered, with only 76 individuals remaining, and northern RKWs are threatened with 309 animals remaining. We consider three scenarios: status quo based on actual 2017 ship traffic observed by Automatic Identification System (AIS) data and output from the ICCT Systematic Assessment of Vessel Emissions (SAVE) model; year 2020 based on predicted scrubber uptake; and an extreme case scenario where most HFO-capable ships use open-loop scrubbers. For each scenario, we map HFO carriage and open-loop scrubber washwater discharge, estimate total HFO carriage, HFO use, and washwater discharge within RKW critical habitat, and discuss the potential impacts on these animals.

BACKGROUND

The British Columbia coast is home to a biologically diverse ecosystem as well as busy seaports. Shipping traffic is dense in this area, as shown in Figure 1. Many ships take the Juan de Fuca Strait, the large channel separating Vancouver Island from the continent, to reach Vancouver or travel south through Puget Sound to reach Seattle. Cruise ships make their way through the smaller, scenic Northern Passage, including the Johnstone strait, to Alaska.

British Columbia's waters fall within the North American ECA. Inside the ECA, ships either use lower sulfur fuels, such as marine gas oil (MGO), or high-sulfur fuels, such as HFO, with an EGCS.[1] Outside of the ECA, ships can use HFO without a scrubber. Nearly 2,500 of the 3,000 ships operating in the ECA in 2017 were capable of using HFO. Thirty of them used HFO with a scrubber. Ships with scrubbers use HFO at all times but scrub the exhaust when they enter the ECA. Ships without scrubbers use MGO in the ECA but keep HFO on board so they can use it once they exit the control area.

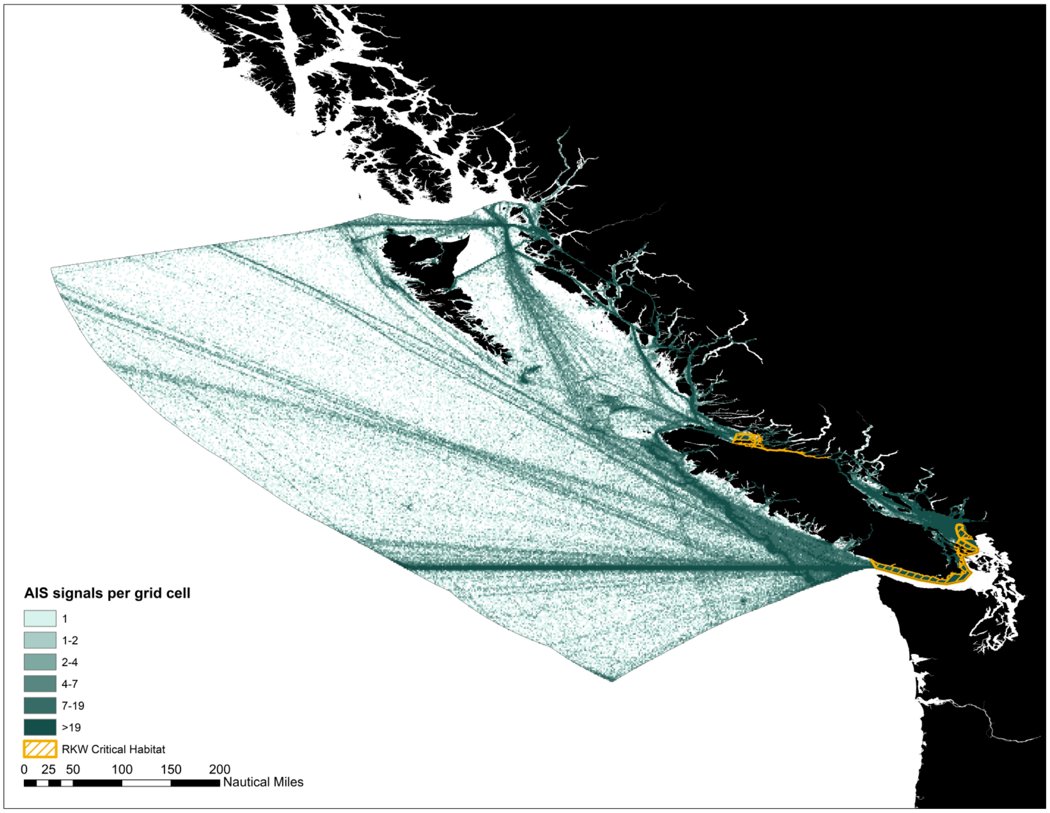

Figure 1. 2017 ship traffic in the Canadian portion of the North American ECA off the coast of British Columbia.

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[1] California does not allow the use of EGCS to comply with the 0.1% sulfur limit in state waters (out to 24 nautical miles) and China, Singapore, and Fujairah and several other ports have forbidden the use of open-loop scrubbers over concerns that scrubber washwater effluent is harmful to the environment

HEAVY FUEL OIL

Heavy fuel oil, also referred to as residual fuel, is extremely viscous leftover material from the oil refining process. It is the dominant fuel used by the marine sector due to its wide availability and cheap price, accounting for more than 80% of fuel used (Comer et al., 2017a). When burned, HFO releases greenhouse gases, short-lived climate pollutants such as black carbon, and air pollutants. It contributes to ambient fine particulate matter ($PM_{2.5}$) and ground-level ozone that harm human health by contributing to respiratory infections, cardiovascular disease, and lung cancer. Unlike other fuels, HFO does not evaporate but instead emulsifies in the water. This creates a mixture that is much larger than the original volume spilled, and one that is nearly impossible to completely clean up (Comer, 2019). Because HFO persists in the marine environment, it poses a long-term threat to aquatic wildlife in the event of a spill.[2]

EXHAUST GAS CLEANING SYSTEMS: "SCRUBBERS"

There are three types of scrubbers used on ships: open-loop, closed-loop, and hybrid. According to DNV-GL, open-loop scrubbers are the most popular among the three, making up 80% of the current market, followed by hybrid at 18%, with the remaining scrubbers being closed-loop or unknown (DNV GL, 2019). Open-loop scrubbers use continuously pumped-in seawater as an alkaline solution to dissolve sulfur oxide (SO_X) emissions. The washwater effluent is optionally treated to remove solids and raise pH before being discharged back into the ocean. If solids are stored as sludge on board, they are retained for shoreside disposal (Figure 2).

Closed-loop scrubbers, which use a freshwater and caustic soda alkaline solution, can operate in a zero-discharge mode or allow small, but potentially still contaminated, amounts of "bleed-off" water to be discharged overboard (Figure 3). Both sludge and bleed-off water can be stored on board and discharged shoreside. We are not aware of any prohibition on discharging bleed-off water to the sea, but IMO guidelines suggest that sludge residues should not be discharged at sea or burned on board and that residue disposal should be recorded in an EGC log. Hybrid scrubbers can operate in open-loop or closed-loop mode. The circulation pump in a hybrid system can be switched from seawater to a freshwater reservoir onboard and discharge can be routed from overboard to the circulating tank (American Bureau of Shipping, 2018).

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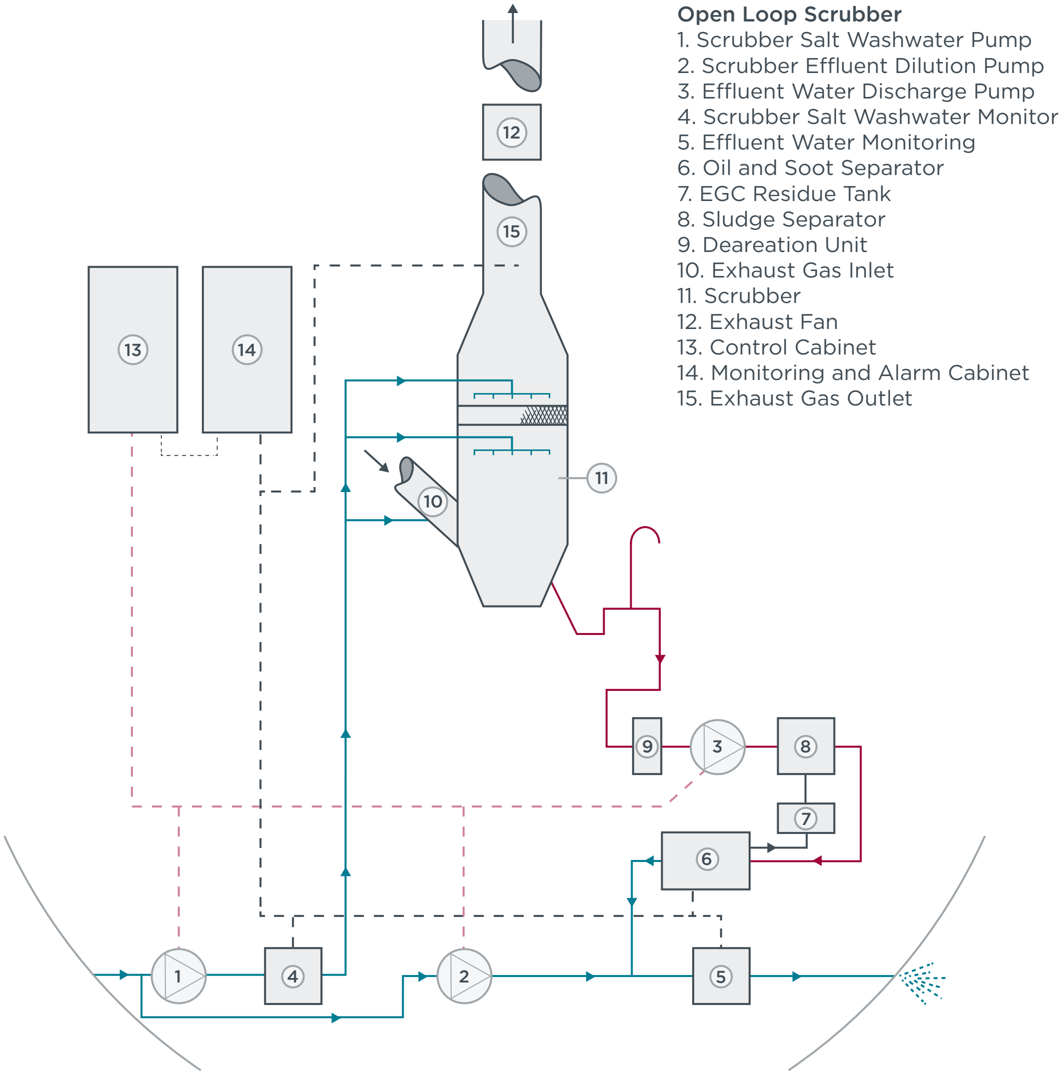
[2] For more information on the prevalence of HFO use in the shipping sector, see Comer et al. (2017a; 2017b); for commentary on the risks of HFO, see Comer and Olmer (2016).



Open Loop Scrubber

1. Scrubber Salt Washwater Pump
2. Scrubber Effluent Dilution Pump
3. Effluent Water Discharge Pump
4. Scrubber Salt Washwater Monitor
5. Effluent Water Monitoring
6. Oil and Soot Separator
7. EGC Residue Tank
8. Sludge Separator
9. Deareation Unit
10. Exhaust Gas Inlet
11. Scrubber
12. Exhaust Fan
13. Control Cabinet
14. Monitoring and Alarm Cabinet
15. Exhaust Gas Outlet

Figure 2. Open-loop scrubber design (Adapted from EGCSA, 2019)

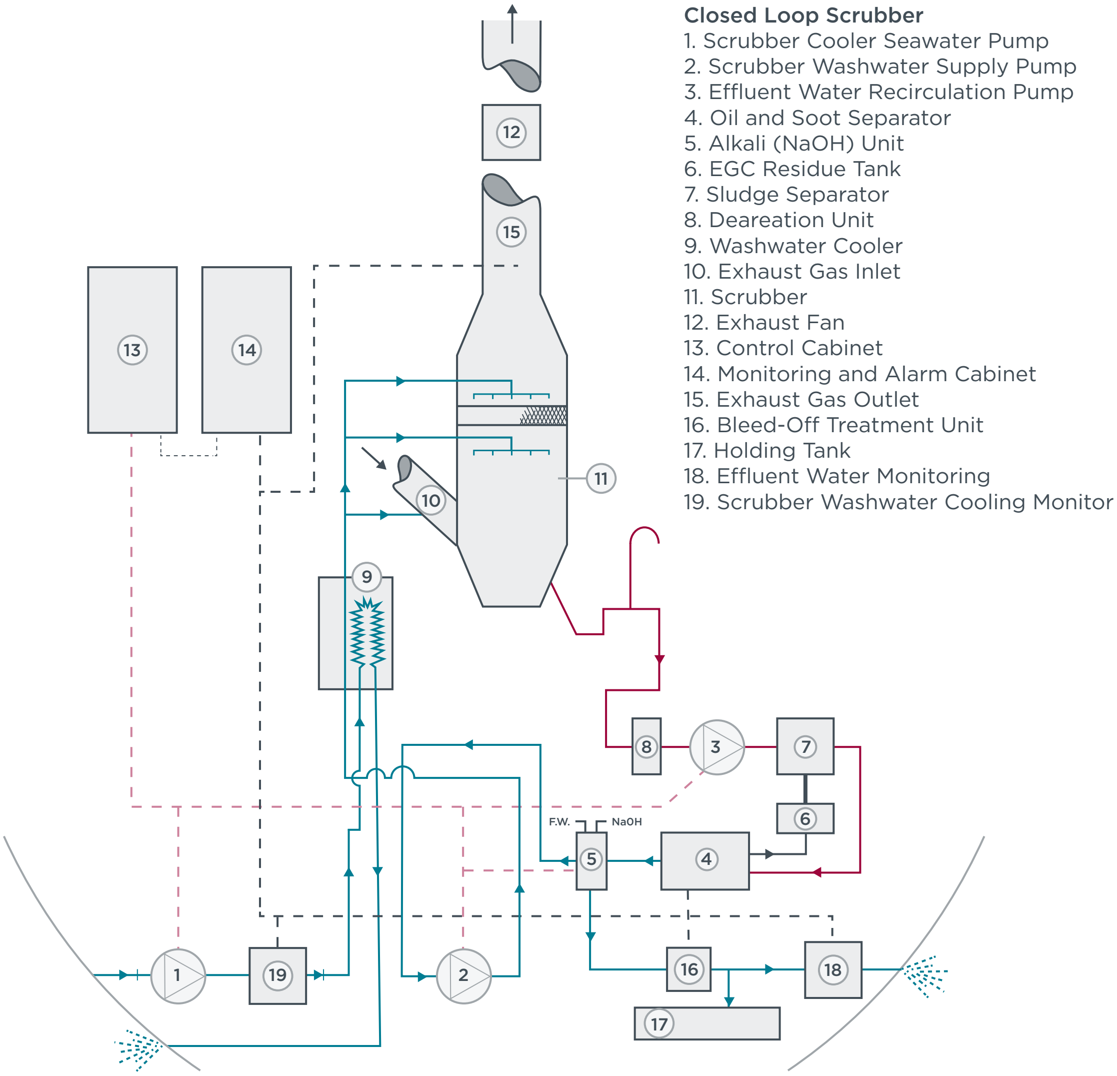


Figure 3. Closed-loop scrubber design (Adapted from: EGCSA, 2019)

Scrubber washwater effluent can contain heavy metals, polycyclic aromatic hydrocarbons (PAH), nitrates, sulfates, and particulate matter. Washwater can also be more acidic and warmer than ambient water. Exposure to washwater can harm aquatic organisms (Koski, Stedmon, & Trapp, 2017; Magnusson, Thor, & Granberg, 2018), and disruptions early in the food web, such as to zooplankton, can lead to negative impacts throughout the ecosystem. Heavy metals and PAHs are persistent in the marine environment and can accumulate in sediment which negatively affects bottom-feeders (Endres et al., 2018). Fish can suffer liver damage and reduced fertility even when exposed to even low PAH concentrations (Lange, Markus, & Helfst, 2015). Additionally, nitrates can cause an increase in pelagic phytoplankton and an increased risk of eutrophication in the summer months when algal bloom and cruise ships schedules overlap (Endres et al., 2018). Low pH and heavy metals can also act synergistically, with lower pH changing the solubility of heavy metals and in some cases leading to increase toxicity (Koski, Stedmon, & Trapp, 2017).[3]

The IMO developed guidelines in resolution MEPC.259(68) to ensure that EGCSs provide SO_x reductions that are equivalent to using compliant fuel. They recommend that the ship operator continuously monitor and record pH, PAH concentrations, turbidity, and temperature when the scrubber is operated in ports, harbors, or estuaries. The guidelines also include discharge limits for selected pollutants. Because these are guidelines, the discharge limits are not mandatory. However, flag states and classification societies may insist that EGCSs meet these limits and comply with parameters in the guidelines before a scrubber is approved as an equivalent compliance option.

KILLER WHALES

Killer whales (*Orcinus orca*) are one of the most recognizable cetaceans and are the largest members of the dolphin family, Delphinidae. Considered one species, there are three ecotypes off the coast of British Columbia: northern resident killer whales (NRKW), southern resident killer whales (SRKW), and transient Biggs killer whales. All three ecotypes are separated by genetics, behavior, and dietary preferences. Transient whales prefer marine mammals such as harbor seals, while residents have a strong preference for salmonid fish. NRKWs and SRKWs have different genetics and engage in different behaviors. The populations overlap but are rarely seen interacting or interbreeding (Fisheries and Oceans Canada, 2018a). As of 2017, there were 309 NRKWs divided into pods of about 10 to 25 individuals; they are listed as threatened under the Canadian Species at Risk Act, or SARA (Government of Canada, 2002). There are fewer SRKWs, with only 76 individuals divided into three pods; they are listed as endangered by SARA (Government of Canada, 2002). RKWs are primarily found off the coast of British Columbia, including in long inlets, narrow channels, and deeper bays. SRKWs congregate near the southern Strait of Georgia in the summer to intercept migrating salmon (Fisheries and Oceans Canada, 2018a).

The Canadian Species at Risk Act defines and describes the critical habitat for RKWs, which for SRKWs includes the Juan de Fuca Strait, Boundary Pass, Salish Sea, the Haro Strait, and the southern section of the Georgia Strait. Although the SRKW critical habitat stops at the Canadian border, it technically includes transboundary areas of British Columbia and Washington State and expands into the Puget Sound according to the United States' Endangered Species Act (ESA) definition of SRKW critical habitat (NOAA Fisheries, 2019). The NRKW critical habitat is found primarily in the Johnstone Strait and expands to the Charlotte Strait. The beaches in this area are important for the beach rubbing behavior, an activity specific to the NRKWs. Both resident killer whale populations have vast ranges (Figure 4). Only critical habitat was considered in this analysis due to the confirmed presence of RKWs in these areas and because these locales are, as the name suggests, critical to conserving these species.

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[3] For additional information on scrubber washwater characteristics, see Endres et al. (2018), Koski et al. (2017), Lange, Markus, and Helfst (2015), Magnusson, Thor, and Granberg (2018), 't Hoen & Boer (2015), and US Environmental Protection Agency (2011).

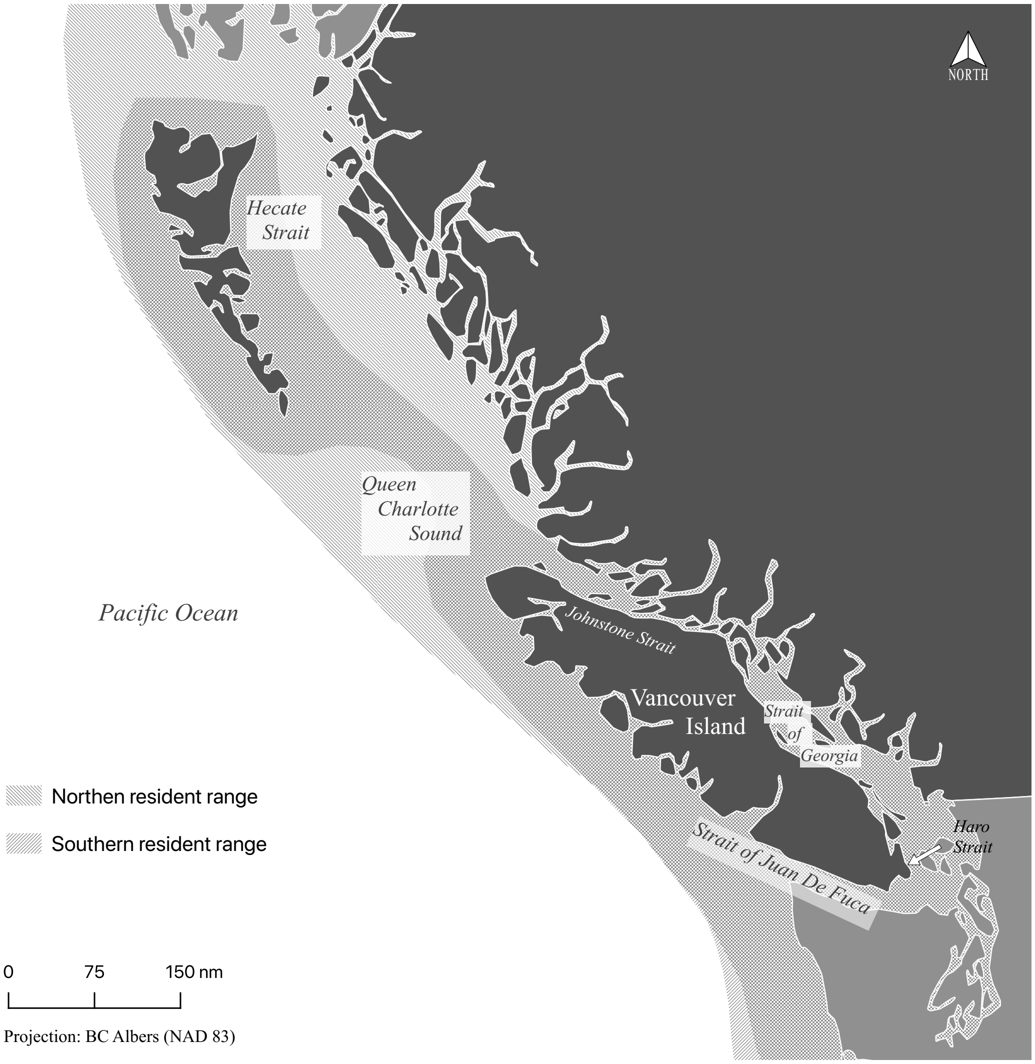

Figure 4. Resident killer whale ranges.

Note: Range shapefiles kindly provided by the British Columbia Cetacean Sightings Network

METHODOLOGY

IDENTIFYING SHIPS WITH SCRUBBERS

For our analysis, a database of ships with scrubbers was created by first identifying ships that were capable of using HFO and then searching through publicly available data to identify which ships have scrubbers installed. The sources confirming scrubber installation for each ship are included in the Appendix.

We found that of the 30 ships with scrubbers installed, 16 had open-loop scrubbers and 14 had hybrid scrubbers. It is possible that some ship operators sometimes voluntarily operate in closed-loop mode. That said, more than half of the ships studied used open-loop scrubbers that do not have a "closed loop" option. We are not aware of any prohibitions on operating in open-loop mode in the study area and operating in closed-loop mode generates additional labor, operating, maintenance, and disposal costs. Without mandatory prohibitions on operating in open-loop mode, we assume that ships with hybrid scrubbers operate them in open-loop mode at all times. While it is possible that we are overestimating washwater effluent by this assumption, this is mitigated by the following: (1) the study area is large, with much of the HFO use and discharge away from land; (2) we assume a normalized washwater effluent discharge rate consistent with IMO guidelines—actual rates could be lower or higher and we have seen rates more than two times greater than our assumption; (3) only half of the scrubber-equipped ships in 2017 had hybrid systems, the rest were open loop; and (4) any decision to operate in closed-loop mode would be a company policy which could be reversed. Finally, if ships with hybrid scrubbers voluntarily operate in closed-loop mode within 3 nm of land, discharges elsewhere can make their way to near-shore areas through currents, wind, and waves.

ESTIMATING HFO CARRIAGE

In the 2017 scenario, we assume that all HFO-capable ships carried HFO on board. Ships with scrubbers burn HFO at all times and ships that are capable of burning HFO but do not have a scrubber will burn ECA-compliant fuel inside the ECA and HFO outside the ECA. Consistent with our previous work (e.g., Olmer, Comer, Roy, Mao, & Rutherford, 2017), we assume that the ship's bunker fuel tanks are 65% full at all times.

Beginning in 2020, we assume that only scrubber-equipped ships will carry HFO on board. Other HFO-capable ships will use very low sulfur fuel oil (VLSFO) that is <0.50% S by mass or MGO when they are outside of an ECA. Fuel choice will depend on shipowner/operator confidence in the quality of VLSFO and the relative price between different grades of fuel.

In the extreme scenario, we assume that most[4] HFO-capable ships use scrubbers and therefore all these ships carry HFO. This assumption results in slightly smaller estimates for HFO carriage compared to the 2017 "status quo" scenario. As we mentioned earlier,

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[4] There were a few HFO-capable ships from other ship types, such as fishing vessels, not represented in Table 1. These ship types are, so far, not installing scrubbers. We assume that will continue to be the case. Therefore, the extreme case assumes that most, but not all, HFO-capable ships install scrubbers.

in the 2017 status quo scenario we assumed that all HFO-capable ships carried HFO on board, including those without scrubbers, because they could use HFO when they are outside of ECAs.

ESTIMATING HFO USE

Within the study area, only ships equipped with scrubbers are allowed to burn HFO. For these ships, we estimated HFO use using ICCT's SAVE model, which combines AIS data with IHS ship characteristics data to estimate fuel consumption and emissions for every ship for every hour. Given that we know the location of each ship from the AIS data, we can also map fuel carriage, fuel consumption, and emissions. Olmer et al. (2017) provides a detailed methodology for the SAVE model.

The SAVE model estimates fuel consumption for each hour by first estimating the ship's power demands. For main engines, power demand is a function of ship speed. For auxiliary engines and boilers, power demand varies depending on whether the ship is cruising, maneuvering, anchored, or at berth. For each hour, SAVE estimates fuel consumption by multiplying the total power demand of the ship (main engines + auxiliary engines + boilers) by a CO_2 emission factor and then divides by a fuel-specific carbon factor to convert from CO_2 emitted to fuel consumption:

$$FC_{i,t} = \mathrm{TED}_{i,t} \times \frac{\mathrm{EF}_{CO_2}}{\mathrm{C}_f}$$

$FC_{i,t}$ = fuel consumption for ship i over time t
$TED_{i,t}$ = total energy demand of ship i over time t in kWh
EF_{CO_2} = emission factor for CO_2 for a given fuel and engine combination in g/kWh
C_f = carbon factor for the fuel in g CO_2/g fuel

ESTIMATING SCRUBBER WASHWATER DISCHARGE

We estimated scrubber washwater discharges for open-loop scrubbers and hybrid scrubbers, which we assume are always operating in open-loop mode. We assume that exhaust gas from all onboard machinery is treated by the scrubber although, in practice, some ships will only treat their main engine exhaust, opting to use low-sulfur distillate fuels to power auxiliary machinery. In such instances, the total amount of exhaust flowing through the scrubber system would be reduced. Consequently, the amount of washwater discharged would also be lower.

Washwater discharges for each ship for each hour is estimated as follows:

$$D_{i,t} = \frac{TED_{i,t}}{1000} \times r$$

$D_{i,t}$ = washwater discharge of ship i over time t in tonnes
$TED_{i,t}$ = total energy demand of ship i over time t in kWh
r = normalized washwater discharge rate in tonnes per MWh

We assume a normalized washwater discharge rate (r) of 45 t/MWh, which is consistent with IMO guidelines for EGCSs in Resolution MEPC.259(68). Although this rate is identified by the guidelines as typical for open-loop scrubber systems, ships discharge washwater at variable flow rates depending on the specific scrubber system installed, the alkalinity of the scrubbing solution, exhaust flow, fuel sulfur content, and other parameters. Other studies have used average open-loop discharge rates of 100 t/MWh (German Federal Maritime and Hydrographic Agency, 2019). The pollutant discharge concentration limits in the IMO guidelines vary as a function of discharge rate such that the mass of pollutants discharged per MWh remains constant.

SCENARIOS

For this analysis, we modeled the following three scenarios:

Scenario 1: 2017 status quo. This scenario analyzes estimated scrubber washwater discharges in the study area in 2017, based on 2017 AIS data and publicly available scrubber installation records (see Appendix).

Scenario 2: 2020 predicted. In this scenario, we estimated scrubber washwater discharges in the study area in 2020, based on 2017 ship activity and trends in scrubber installations. We used DNV-GL (2019) Alternative Fuels Insight Scrubber Data, which tracks installations and orders of scrubbers. Table 1 shows estimates of the proportion of ships that will have open-loop or hybrid scrubbers installed in 2020, broken down by ship type. We assume that the same proportion of the British Columbia fleet will be equipped with scrubbers as the world fleet and that those ships will operate scrubbers in open-loop mode. Finally, we randomly selected ships on which to apply scrubbers and predicted 2020 scrubber washwater discharges by assuming that they, or a similar ship, would engage in the same activity in 2020 as they did in 2017.

Table 1. Proportion of global fleet with open-loop or hybrid scrubbers by ship type in 2020

Ship type	Proportion of ships
Bulk carrier	11%
Chemical tanker	5%
Container	15%
Cruise	69%
General cargo	1%
Oil tanker	7%
Roll-on/roll-off	26%
Vehicle carrier	4%

Source: DNV-GL (2019) and IHS (2018)

Scenario 3: Extreme case. In the final scenario, we estimated scrubber washwater discharges, based on 2017 ship activity, assuming all HFO-capable ships of all ship types represented in Table 1 had scrubbers installed and that all of them were operated in open-loop mode.

RESULTS

In this section, we first present information on ships that had open-loop or hybrid scrubbers installed in 2017. We then present HFO carriage and HFO use and associated scrubber washwater discharges under three scenarios: 2017 status quo; 2020 predicted; and an extreme case.

SHIPS WITH SCRUBBERS

Table 2 summarizes the number of ships using open-loop or hybrid scrubbers in open-loop mode in each scenario. Each scenario is described in more detail in this section.

Table 2. Number of ships using open-loop or hybrid scrubbers in open-loop mode.

			Ships with Scrubbers		
Ship type	**Total ships (all fuel types)**	**HFO-capable ships**	**Scenario 1: 2017 Status quo**	**Scenario 2: 2020 Predicted**	**Scenario 3: Extreme case**
Bulk carrier	1,446	1,446	1	159	1,446
Chemical tanker	118	118	0	6	118
Container	330	330	3	46	330
Cruise	44	32	23	23	32
General cargo	161	156	0	1	156
Oil tanker	91	90	0	6	90
Roll-on/roll-off	10	4	0	1	4
Vehicle carrier	193	193	3	8	193
Other ship types	657	63	0	0	0
Total	**3,050**	**2,432**	**30**	**250**	**2,369**

Scenario 1: 2017 Status quo.

In 2017, 3,050 ships operated within the Canadian portion of the North American ECA off the coast of British Columbia. Of those, 2,432 were HFO-capable and 30 had scrubbers installed.

For the 30 scrubber-equipped ships, 14 used hybrid scrubbers and 16 used open-loop; no ships used closed-loop scrubbers. Twenty-three of the 30 scrubber-equipped ships, or 77%, were cruise ships, followed by three container ships, three vehicle carriers, and one bulk carrier. Cruise ships have been early adopters of scrubber technology because they tend to spend more time in ECAs than other ship types. This results in faster payback periods and greater returns on investment for scrubber technologies than ships that only occasionally operate in ECAs.

Scenario 2: 2020 predicted.

In 2020, based on DNV-GL (2019) scrubber uptake statistics for 2020 for the global fleet, we predict that 250 ships operating in the study area will have scrubbers, the majority of which will be bulk carriers.[5] This reflects a trend towards more bulk carriers using scrubbers globally and the fact that nearly half of the ships operating in the study area in 2017 were bulk carriers. We also predict a large increase in container ships with scrubbers, up from three in 2017 to 46 in 2020. Some ship types that did not have scrubbers installed in 2017 are expected to by 2020, including chemical tankers, general cargo ships, oil tankers, roll-on/roll-offs, and vehicle carriers.

Scenario 3: Extreme case.

In this case, we assume that all of the HFO-capable bulk carriers, chemical tankers, container ships, cruise ships, general cargo ships, oil tankers, roll-on/roll-offs, and vehicle carriers we observed in the study area in 2017 installed scrubbers which operate in open-loop mode at all times. In total, this would equal 2,369 ships with scrubbers. Bulk carriers, container ships, general cargo ships, and vehicle carriers would see the most dramatic increases in the use of scrubbers.

HFO CARRIAGE

The maps in Figure 5 show the pattern of HFO carriage under each scenario. Figure 6 shows HFO carriage by ship type for each scenario.

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[5] Based on DNV-GL (2019) as of July 23, 2019. Note that, DNV-GL predicts that, globally, 69% of cruise ships will have either open-loop or hybrid scrubbers installed in 2020. In 2017, we observed that 77% of cruise ships in the study area had scrubbers; therefore, we assume that in 2020, the same number and proportion of cruise ships will have scrubbers installed as in 2017

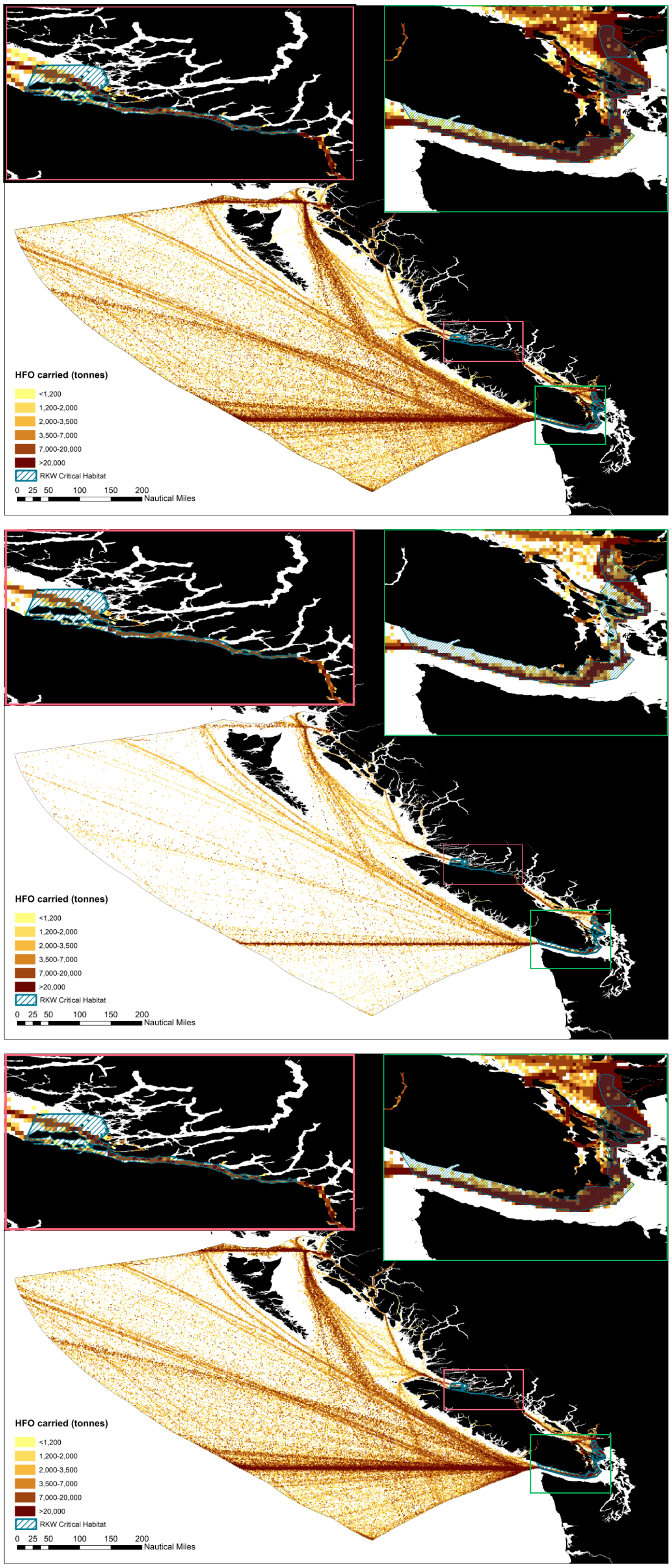

Figure 5. Heavy fuel oil carried in 2017 (top), 2020 (predicted, middle), and an extreme case (bottom), in tonnes

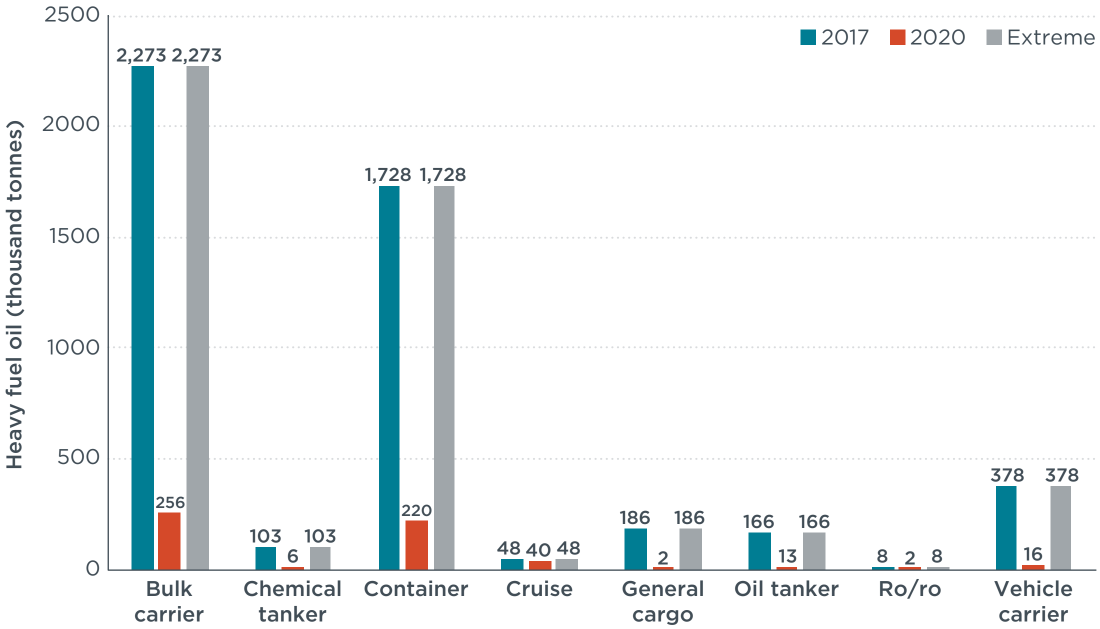

Figure 6. Heavy fuel oil carriage by ship type for each scenario.

In 2017, nearly five million tonnes of HFO were carried as fuel throughout the Canadian portion of the North American ECA off the coast of British Columbia, most of which (4.5 million tonnes) was also carried through RKW critical habitats at one time or another. We assumed that all HFO-capable ships carried HFO in 2017 for use outside of ECAs. Bulk carriers and container ships carried the most HFO on board in 2017 (Figure 6).

In 2020, we expect the amount of HFO carried on board ships to decrease by almost 90% to about half a million tonnes in the study area. HFO carriage in RKW habitats will also fall approximately 90%. Beginning in 2020, only scrubber-equipped ships will carry HFO on board. However, HFO-capable ships that do not use scrubbers may comply with IMO's 0.5% fuel sulfur limit by using VLSFO, which may be a blended fuel that contains HFO or that behaves like HFO when burned or spilled. Alternatively, ships may use MGO to comply with the limit. Fuel choice will depend on shipowner/operator confidence in the quality of VLSFO and the relative price between different grades of fuel. Like in the 2017 scenario, we expect bulk carriers and container ships to carry the most HFO fuel on board.

In the extreme scenario, most HFO-capable ships are assumed to use scrubbers and, therefore, would carry HFO on board at all times. Because few HFO-capable ships fall outside of the ship types we assume will use scrubbers, we estimate HFO carriage to be roughly the same for the status quo and extreme scenarios—about 5 million tonnes, with bulk carriers and container ships carrying the most fuel.

HFO USE AND WASHWATER DISCHARGE

The maps in Figure 7 show the pattern of washwater discharge under each scenario; the pattern for HFO use is similar.

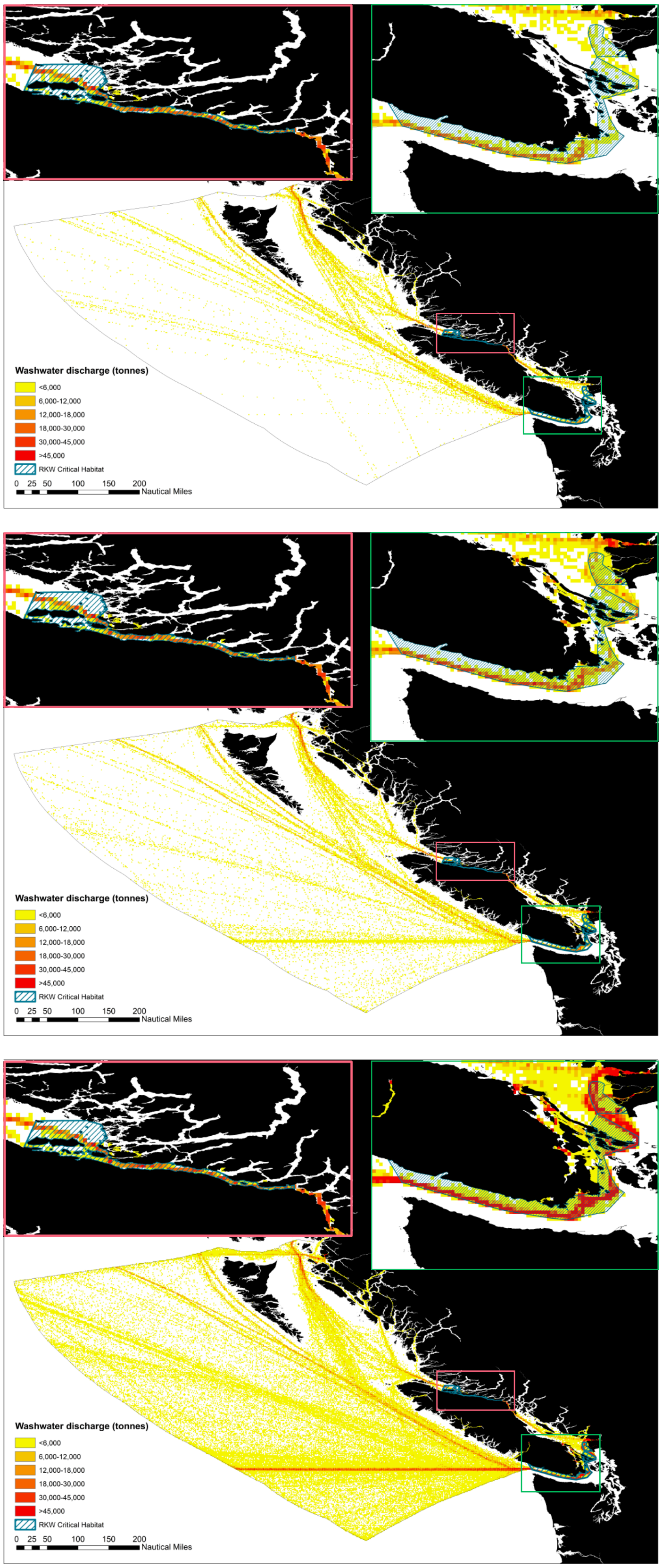

Figure 7. Washwater discharge in in 2017 (top), 2020 (predicted, middle), and an extreme case

Figure 8 shows HFO use and Figure 9 shows washwater discharges by ship type for each scenario.

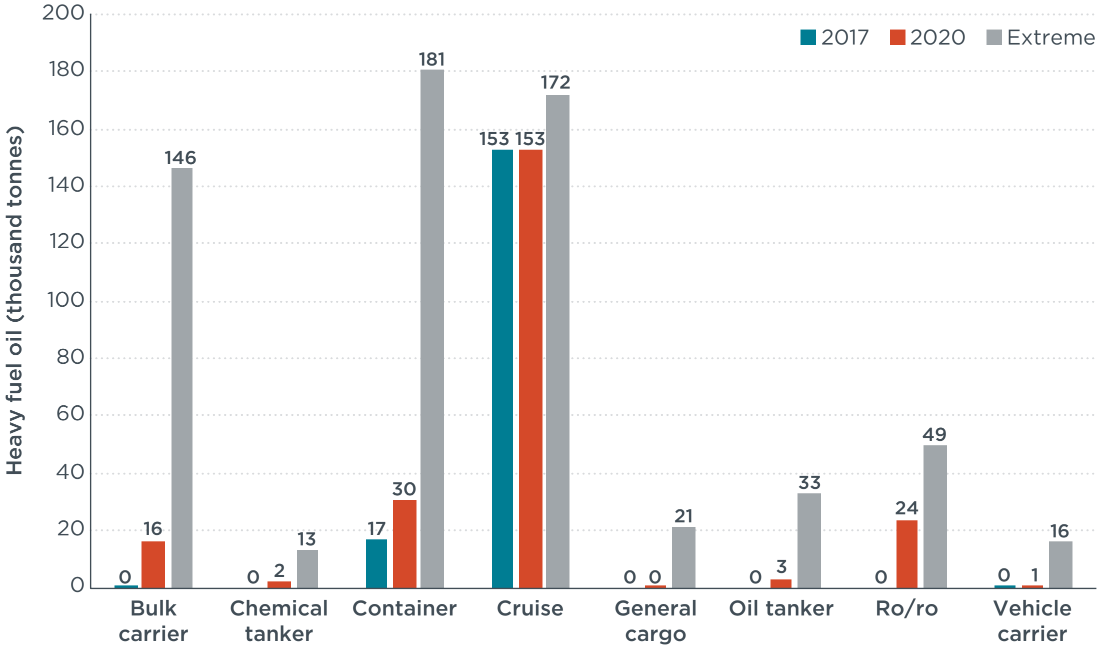

Figure 8. Heavy fuel oil use by ship type for each scenario.

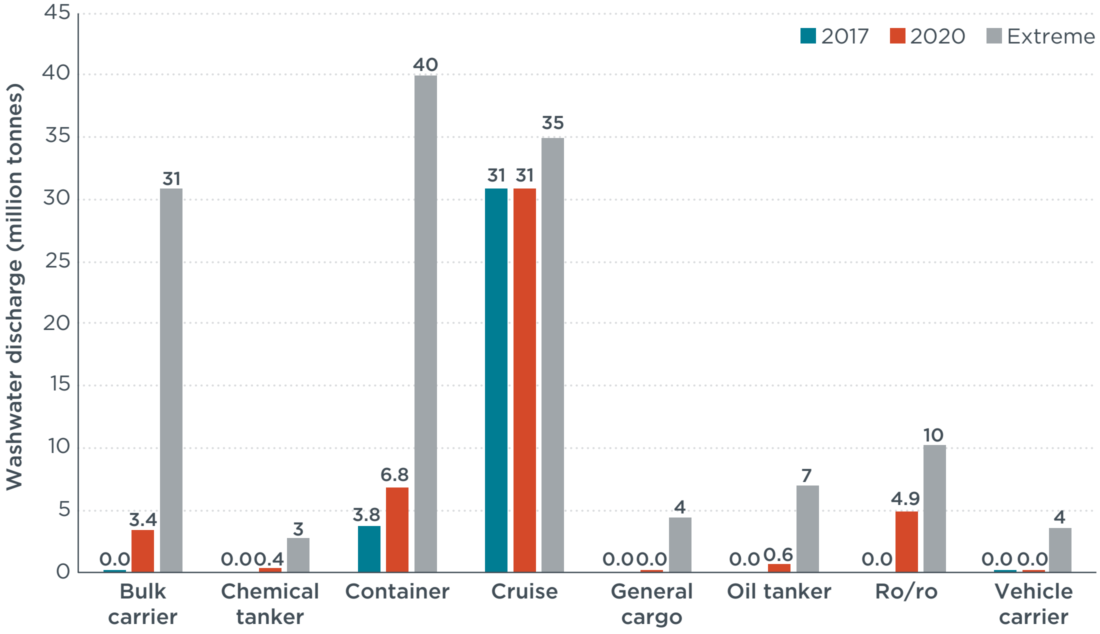

Figure 9. Washwater discharge by ship type for each scenario.

In 2017, ships used about 170 thousand tonnes of HFO in the study area. Total HFO use is expected to grow by 34% to 230 thousand tonnes in 2020 and, in an extreme case, by 270% to 630 thousand tonnes. As HFO use increases due to an increase in scrubber uptake, we expect more HFO to be used in the study area and within RKW critical habitats, leading to increases in washwater discharges.

In 2017, washwater discharges, totaled 35 million tonnes. About 10% of discharges occurred within RKW critical habitat, even though, geographically, these habitats represent only 0.6% of the study area. In 2017, HFO use and washwater discharges were mainly from cruise ships, with container ships a distant second (Figure 8). Cruise ships accounted for 23, or 77%, of the 30 ships with scrubbers in 2017. They emitted 31 million, or nearly 90%, of the 35 million tonnes of washwater discharged in the region (Figure 9). Cruise ships often sail through the Johnstone Strait, leading to high washwater discharges inside the northern RKW critical habitat. When cruises leave Victoria, washwater discharges occur within the southern RKW critical habitat.

By 2020, we predict a 35% increase in total scrubber washwater discharges to about 47 million tonnes. Washwater discharges within RKW critical habitat is expected to grow by 45% to nearly 5 million tonnes by 2020. We predict HFO use and washwater discharges to increase from 2017 to 2020 for container ships and bulk carriers (Figure 9). Additionally, we expect some ship types that were not outfitted with scrubbers in 2017 to start using them, including roll-on/roll-offs, oil and chemical tankers, general cargo ships, and others.

Under an extreme scenario, washwater discharges nearly quadruple from 2017, reaching more than 130 million tonnes in total, with 18 million tonnes in RKW critical habitat. Container ships, cruise ships, and bulk carriers discharge the greatest quantities of washwater in the extreme case.

DISCUSSION

As 2020 approaches, some ships will stop carrying and using HFO to comply with IMO's 0.5% fuel sulfur limit, while others will use scrubbers that enable them to continue to burn HFO. Without rules requiring closed-loop or zero-discharge operations, we expect the use of open-loop scrubbers—and hybrid scrubbers operating in open-loop mode—to grow, increasing washwater pollution discharges and perpetuating the risk of an HFO spill.

Additionally, even with scrubbers, ships will continue to emit air and climate pollution emissions such as particulate matter, sulfur oxides, nitrogen oxides, black carbon, and carbon dioxide. As a consequence, ships with scrubbers will continue to pose both direct and indirect risks to aquatic wildlife, including threatened and endangered species such as RKWs. Unfortunately, British Columbian killer whales are already considered the most contaminated marine mammal species in the world, as measured by polychlorinated biphenyl (PCB) concentrations, which increases their risk for toxic effects (Ross, Ellis, Ikonomou, Barrett-Lennard, & Addison, 2000).

HEAVY FUEL OIL SPILL RISKS

Carrying HFO in ships' fuel tanks perpetuates the risk of an HFO spill. In addition to the economic costs of a spill, there are ecological costs (Deere-Jones, 2016). Oil spills directly impact aquatic wildlife through ingestion, absorption, and– in the case of marine mammals—inhalation of fumes. Additionally, oil spills can have indirect effects by harming the food web and forcing wildlife to search for food in new locations (Ober, 2010).

WASHWATER CONTAMINANTS

Open-loop scrubbers and hybrid scrubbers in open-loop mode emit acidic washwater that is warmer than ambient sea water and contains heavy metals, PAHs, suspended particulate matter, and nitrates, all of which can harm RKWs. While the IMO has published guidelines in resolution MEPC.259(68) that contain continuous discharge limits for pH, PAH, turbidity, nitrates, and temperature for washwater, no scientific justification is given for these limits. These limits are not strictly mandatory, although flag states and classification societies can insist that these limits be achieved by scrubbers that are installed.

Polycyclic aromatic hydrocarbons and heavy metals are of particular concern for marine mammals. Even if ships discharge low concentrations of these contaminants, they accumulate in the environment and bioaccumulate in the food web. Over time, pollutant concentrations will increase, especially in shallow, coastal areas where dilution is limited and vessel traffic is high (Endres et al., 2018) Exposure to PAHs and heavy metals has been linked to negative health outcomes for other marine mammal species, such as beluga whales and pinnipeds. These effects are generalized to killer whales due to the similar physiological processes of marine mammals (Ross, 2000). Additionally, synergistic effects of exposure to scrubber washwater could be important. Researchers at IVL Swedish Environmental Research Institute suggested the combined effects of exposure to washwater contaminants on zooplankton, which form the basis of the food web for many species, may be dramatically different than the effect of exposure to only one pollutant (Magnusson et al., 2018).

Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons are produced by incomplete combustion of fossil fuels, such as HFO. When ships use HFO with scrubbers, larger PAHs will bind to particulates in the exhaust and smaller PAHs go into the washwater. Unfortunately, smaller PAHs are more toxic to marine life (Marsili et al., 2001). A detailed assessment of PAH discharge was beyond the scope of this analysis, but we can estimate the maximum "allowable" discharges under the IMO guidelines. The IMO guidelines set a PAH limit of 50 µg/L when the washwater discharge rate is 45 t/MWh. Based on our results, we estimate that 1,740 kg of PAHs were discharged in the study area in 2017, almost 10% of which, or 165 kg, was emitted within RKW habitat. We expect this to grow to 2,360 kg in the study area, with 10% (240 kg) in RKW habitat in 2020. In the extreme scenario, one could see 6,700 kg emitted in the study area, with 880 (13%) in RKW critical habitat.

PAHs are persistent organic pollutants, which means they resist biodegradation. When RKWs eat contaminated fish, PAHs are stored in the RKWs' fat reserves, including their protective blubber layer (Formigaro et al., 2014). When RKWs draw upon their fat reserves for energy, problems can occur. PAHs damage DNA, which can cause cancer (Munoz & Albores, 2011). On the east coast of North America in the St. Lawrence estuary, high PAH concentrations in Beluga whales corresponded to higher rates of digestive tract cancers (Martineau et al., 2002).

Heavy metals

Heavy metals are naturally occurring elements found in the earth's crust. Some heavy metals are essential nutrients at lower concentrations, such as copper, zinc, and iron, while others, such as lead, mercury, and cadmium, are toxic in any amount. Heavy metals are neither biodegradable nor water soluble. They can bioaccumulate in tissues of animals, including the fish that RKWs eat. While Orcas, including RKWs, have proteins that bind and detoxify mercury, these capabilities are limited, and when mercury levels are high, they can bypass the proteins and cause toxicity (Buckman et al., 2011).

Heavy metals accumulate in the liver, bone marrow, and kidneys (Dosi, 2000). Stored heavy metals are released during pregnancy, lactation, migration, and when food is scarce (Marsili et al., 2001). With Chinook salmon fisheries declining, especially in southern British Columbia waters, nutritional stress is causing RKWs to tap into their blubber resources, releasing these stored pollutants (Fisheries and Oceans Canada, 2018b). Exposure to toxic compounds including PAHs and heavy metals were coincident with cancers in populations of beluga whales in the St. Lawrence River (Guise, Lagacé, & Béland, 1994). Besides carcinogenic effects, chronic intake of heavy metals suppresses the immune system (Kakuschke & Prange, 2007.). Exposure to copper, mercury, and lead has been associated with reproductive dysfunction, difficulty locating prey, and poor metabolism in marine mammals (Jakimska, Konieczka, Skóra, & Namiesnik, 2011).

FUTURE WORK

This analysis estimates HFO carriage, HFO use, and scrubber washwater discharges. While we know open-loop scrubbers continuously discharge, hybrid systems can operate in closed-loop mode. Future work could further investigate when and where ships could opt for closed-loop operations, including near shore. In addition, the impacts of voluntarily switching to compliant fuels or operating hybrid scrubbers in closed-loop mode near shore and in RKW critical habitats could be modelled. However, washwater discharges outside these areas can make their way inside through currents, wind, and waves.

Our results show where HFO was used and carried and where washwater was discharged, but it does not show the dispersal areas of an HFO spill or washwater discharge. The impacts of an HFO spill on RKWs would be better understood if the HFO carriage results were fed into a spill dispersion model. Likewise, RKW washwater exposure could be better estimated by feeding the washwater discharge location data into a water dispersion mode. Lastly, additional research on the impacts of scrubber washwater discharges on the food web is warranted, particularly on Chinook salmon, the RKWs main food source.

CONCLUSION

This study investigates HFO carriage, HFO use, and scrubber washwater discharges from ships in the Canadian portion of the North American ECA off the coast of British Columbia, including in and near critical habitat for threatened and critically endangered RKWs. We considered three scenarios: 2017 status quo based on actual HFO and scrubber use; 2020 based on predicted HFO and scrubber use; and an extreme case where most HFO-capable ships used scrubbers.

Resident killer whales, which are already facing environmental stressors, are currently exposed to contaminated scrubber washwater discharges. Ships are using hundreds of thousands of tonnes of HFO, resulting in millions of tonnes of scrubber washwater discharges, 10% of which is emitted directly in RKW critical habitats. In addition, RKWs are in danger of being exposed to an HFO spill from ships carrying HFO on board.

Unfortunately, threats to aquatic wildlife, such as RKWs, are expected to grow as more ships install scrubbers in order to comply with IMO's 2020 fuel sulfur regulations. While we expect HFO carriage to drop by almost 90% in 2020 as more ships use VLSFO to comply with IMO's fuel sulfur regulations, we predict HFO use and scrubber washwater discharges will increase about 35% from 2017 levels. In an extreme scenario, where nearly all HFO-capable ships use scrubbers, HFO carriage is estimated to be the same as in 2017, but HFO use and washwater discharges increase nearly four-fold from 2017 levels. In all scenarios, nearly 90% of all HFO carried in the study area passes through RKW critical habitats.

Cruise ships were responsible for the most HFO use and scrubber washwater discharge in 2017. We predict this will still be true in 2020, even though scrubber uptake by other ship types is expected to grow exponentially. In the extreme scenario, container ships use the most HFO and emit the most washwater, but cruise ships are not far behind. Cruise ships currently travel through the Johnstone Strait, which is also critical habitat for the northern RKWs. As other ship types use scrubbers, impacts on southern RKWs are expected to grow. The Juan de Fuca Strait, Georgia Strait, and Haro Strait have the highest ship density in the region and fall within SRKW critical habitat. As washwater discharges increase, so will acidic water, suspended particulate matter, nitrates, PAHs, and heavy metals.

Without rules requiring closed-loop or zero-discharge operations, we expect the use of open-loop scrubbers and hybrid scrubbers operating in open-loop mode to grow, increasing washwater pollution discharges that worsen water quality and perpetuating the risk of an HFO spill. Using hybrid or closed-loop scrubbers in zero-discharge mode would eliminate water pollution from these systems but maintain the risk of an HFO spill. Using MGO inside the North American ECA and VLSFO outside would obviate the use of scrubbers but could still pose a significant risk when spilled. While there will always be negative consequences in the event of a fuel oil spill, using MGO at all times would eliminate the risks of an HFO or VLSFO spill and remove altogether the need for scrubbers.

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APPENDIX: SHIPS WITH SCRUBBERS IN THE STUDY AREA IN 2017

Ship Name	IMO number	Ship Type	Scrubber Type	Source
Matson Anchorage	8419142	Container	Hybrid	Brehmer (2017)
Matson Tacoma	8419154	Container	Hybrid	Brehmer (2017)
Matson Kodiak	8419166	Container	Hybrid	Brehmer (2017)
Grand Princess	9104005	Cruise	Open loop	Alaska DEC (2018) CAO-20180701- 1882007070
Disney Wonder	9126819	Cruise	Hybrid	Sanders (2012)
Volendam	9156515	Cruise	Open loop	Alaska DEC (2018) CAO-20180605-1880073526
Zaandam	9156527	Cruise	Open loop	Alaska DEC (2018) CAO-20180613- 1880619899
Amsterdam	9188037	Cruise	Open loop	Alaska DEC (2018) CAO – 20180621- 1881189247
Celebrity Millennium	9189419	Cruise	Hybrid	Alaska DEC (2018) CAO-20180704 - 1882276275
Celebrity Infinity	9189421	Cruise	Hybrid	Alaska DEC (2018) CAO – 20180624- 1881375564
Golden Princess	9192351	Cruise	Open loop	Alaska DEC (2018) CAO-20180530- 1879720692
Star Princess	9192363	Cruise	Open loop	Alaska DEC (2018) CAO-20180607- 1880301750
Radiance of The Seas	9195195	Cruise	Hybrid	Alaska DEC (2018) CAO-20180610- 1880421643
Norwegian Sun	9218131	Cruise	Hybrid	Norwegian Cruise Line (2017)
Oosterdam	9221281	Cruise	Open loop	Andrews (2016)
Carnival Legend	9224726	Cruise	Open loop	Alaska DEC (2018) CAO-20180703- 1882100843
Coral Princess	9229659	Cruise	Open loop	Alaska DEC (2018) CAO-20180605- 1880142743
Noordam	9230115	Cruise	Open loop	Alaska DEC (2018) CAO-20180603- 1880002946
Island Princess	9230402	Cruise	Open loop	Alaska DEC (2018) CAO-20180529- 1879623355
Carnival Miracle	9237357	Cruise	Open loop	Brehmer (2017)
Norwegian Jewel	9304045	Cruise	Hybrid	Norwegian Cruise Line (2016)
Emerald Princess	9333151	Cruise	Open loop	Alaska DEC (2018) CAO-20180623- 1881279445
Norwegian Pearl	9342281	Cruise	Hybrid	Alaska DEC (2018) CAO-20180512- 1878516656
Eurodam	9378448	Cruise	Open loop	Alaska DEC (2018) CAO-20180623-1881279434
Nieuw Amsterdam	9378450	Cruise	Open loop	Alaska DEC (2018) CAO-20180524-1879375472
Ruby Princess	9378462	Cruise	Open loop	Alaska DEC (2018) CAO-20180602- 1879927959
Thermopylae	9702443	Vehicle	Hybrid	The Maritime Executive (2016)
Thalatta	9702455	Vehicle	Hybrid	The Maritime Executive (2016)
Theben	9722302	Vehicle	Hybrid	Wärtsilä (2016)
Nadeshiko	9757785	Bulk carrier	Hybrid	Ship Technology. (2016)

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