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VTI PM 2023:15A
Published 2023
vti.se/publications

VTI PM 2023:15A

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Implementing a bottom-up method to calculate spatiotemporal ship emissions to air

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Translated title: Skepp ohoj, jag vill beräkna dina utsläpp – implementering av en metod för beräkning av fartygs spatiotemporala utsläpp till luft
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Reg. No., VTI: 2021/0127
Publication: VTI PM 2023:15A
Published by VTI 2023

Kort sammanfattning

Denna promemoria presenterar en beräkningsmodell baserad på International Maritime Organizations (IMO) studie Fourth Greenhouse Gas Study 2020. Med hjälp av denna modell kan man uppskatta spatiotemporala utsläpp (liksom bränsle- och energiförbrukning) för enskilda fartyg. Vi använder automatic identification system-data (AIS) från Baltic Marine Environment Protection Commission (HELCOM) och data om fartygsegenskaper från IHS Markits kommersiella fartygsdatabas. Urvalet täcker fartyg som anlöpt svenska hamnar och var skyldiga att betala farledsavgifter mellan 2008–2020. Vi presenterar uppskattningar för följande utsläpp av luftföroreningar och växthusgaser: koldioxid (CO_2), svaveloxider (SO_x), kväveoxider (NO_x), partiklar (PM_{10} och $PM_{2.5}$), metan (CH_4), kolmonoxid (CO), dikväveoxid (N_2O) och flyktiga organiska ämnen utom metan (NMVOC). Utsläppen beräknas för fartyg inom kommersiell sjöfart år 2019 för två geografiska områden: svenskt territorium och en större region vilken inkluderar Sverige och Östersjön. Det är dock värt att notera att detta arbete fortfarande pågår och presenterade siffror och uppskattningar sannolikt redan har förbättrats och ändrats vid publiceringstillfället. Se därför detta som ett koncepttest.

Nyckelord

AIS, Utsläpp till luft, Sjöfart, Östersjön, Modellering av utsläpp, IMO GHG 4

Abstract

This memorandum presents a model based on the International Maritime Organization (IMO) study Fourth Greenhouse Gas Study 2020. Using this model, one may estimate spatiotemporal emissions (as well as fuel and energy consumption) for individual ships. We utilize automatic identification system (AIS) data provided by the Baltic Marine Environment Protection Commission (HELCOM) and data on ship characteristics from a custom sample from IHS Markit's commercial vessel database. The sample is covering ships that made calls at Swedish ports and were required to pay fairway dues between 2008–2020. We present emission estimates including carbon dioxide (CO_2), sulphur oxides (SO_x), Nitrogen oxides (NO_x), particular matter (PM_{10} and $PM_{2.5}$), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O) and non-methane volatile organic compounds (NMVOC). The emissions originate from commercial shipping in 2019 for two geographical areas: Swedish territory and a larger region including Sweden and the Baltic Sea. However, it is worth noting that this is work in progress and presented numbers and estimations are likely to have already been improved and changed at the time of publication. Hence, consider this a proof-of-concept.

Keywords

AIS, Air emissions, Maritime transport, Baltic Sea, Emission modelling, IMO GHG 4

Förord

Detta arbete startade på VTI under 2021 i syfte att förbättra förmågan till analyser av sjötransporter, där en av aktiviteterna har varit att implementera IMO:s metod för att beräkna sjöfartens utsläpp. Många har bidragit till tolkning, implementering och utveckling av den beräkningsmodell som nu presenteras i denna promemoria, förutom Karin Ek (författare) däribland även João Patrício samt Axel Merkel. Därtill har bland annat Inge Vierth bidragit med konstruktiv feedback vad gäller modellens utfall. Att denna promemoria nu publiceras 2023 har möjliggjorts av samtliga inblandade.

Stockholm, december 2023

Joar Lind
Projektledare

Granskare/Examiner

Hulda Winnes, Sjöfartsverket.

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1. Introduction

The majority of global freight is transported on water, making up 80 percent of total trade by volume (UNCTAD, 2023) and 70 percent of freight tonne kilometres (ITF, 2023). The importance of shipping in global trade is likely to remain. The International Transport Forum (ITF, 2023) projects that, given current policy developments, the mode share of shipping will remain stable to 2050 while total freight tonne-kilometres will nearly double.

Given shipping's importance, it is essential to have reliable methods and data for evaluations and research, for example for conducting reliable cost-benefit analyses and policy evaluations. One such data source are AISs. In accordance with regulation from IMO, all ships of 300 GT or larger engaged on international voyages, cargo ships of 500 GT or larger engaged on domestic voyages, and all passenger ships irrespective of size, must be fitted with an AIS transponder that provide information about the ship and its ongoing voyage to other ships and coastal authorities automatically (IMO, 2015).

Given the regulation, AIS data provides an extensive source of spatiotemporal information on shipping and has since been used for various research and evaluation purposes. A significant area of ongoing study is the contribution of shipping to greenhouse gas emissions and air pollution, which represents a major negative externality of the shipping industry. AIS is for example used in models such as STEAM (Jalkanen, et al., 2009; Jalkanen, et al., 2012; Johansson, Jalkanen, & Kukkonen, 2017), MoSES (Schwarzkopf, et al., 2021) and, for the case of Sweden, Shipair (Windmark, Jakobsson, & Segersson, 2017; SMHI, 2019) developed and used by the Swedish Meteorological and Hydrological Institute (SMHI) and since 2020 used as part of the basis for Sweden's official statistics on greenhouse gas emissions from domestic shipping (Swedish Environmental Protection Agency, 2023a).

Additionally, IMO has since 2000 released four greenhouse gas studies (IMO, 2000; IMO, 2009; IMO, 2014; IMO, 2020), taking inventory of global air emissions from shipping where the second, third and fourth greenhouse gas study implement bottom-up tank-to-wake approaches utilizing AIS data. Apart from presenting estimations of global air emissions from shipping, IMO's greenhouse gas studies are also comprehensive summaries of current research on air emission estimation presenting frameworks and recommendations for estimating air emissions from shipping.

For this project, we implement the bottom-up approach from the latest study (IMO, 2020). The aim is to eventually make the code available as open source. A self-implemented calculation model gives us a way to perform tailored transport economic analysis, but the project is also motivated by a matter of transparency and accessibility.

IMO (2020) defines relationships between information provided by AIS and technical specifications of vessels, setting up a framework that allows for the estimation of hourly energy consumption, fuel consumption and emissions in AIS observed spatiotemporal points. We implement this framework and use the instantaneous estimates to integrate vessels' air emissions, fuel consumption and energy consumption over time. Estimated air emissions include carbon dioxide (CO_2), sulphur oxides (SO_x), Nitrogen oxides (NO_x), particular matter (PM_{10} and $PM_{2.5}$), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O) and non-methane volatile organic compounds (NMVOC).

Part of the purpose of this memorandum is to present example output estimated using the calculation model. However, it is worth noting that this is work in progress and presented numbers and estimations are likely to have already been improved and changed at the time of publication. Therefore, consider this a proof-of-concept. In this memorandum, we present aggregate estimates from commercial shipping in 2019 for two geographical areas: Swedish territorial sea and internal waters (referred to as Swedish territory) and, for validation purposes, Swedish internal waters, the Swedish exclusive economic zone, and the Baltic Sea (referred to as Sweden and the Baltic Sea). We utilize AIS data provided by the Baltic Marine Environment Protection Commission (HELCOM, 2021) and data on ship characteristics from a custom sample from IHS Markit's commercial vessel database (IHS Markit, 2020) covering ships that made calls at Swedish ports and were required to pay fairway dues between 2008–2020.

Given our data, we can estimate emissions from 95 percent of ships that made calls at Swedish ports and were required to pay fairway dues in 2019 and 58 percent of ships identified in our AIS data in Swedish territory. Initial validation of these estimates looks promising, and further development will focus on testing the model using more extensive input data.

The memorandum is structured as follows. We first present our interpretation of the conceptual framework for bottom-up estimation of air emissions presented in IMO (2020). We then show our implemented model of said framework which is derived from IMO's (2020) recommendation, and the data used. Then follows an overview of differences between our implementation and that of IMO (2020) followed by a review of validation points used and their relevance given the scope of this memorandum. We then present results in terms of our estimates and comparisons between them and our chosen validation points. Lastly, we discuss our results and further development of the model.

2. Conceptual framework

This section describes our implementation of the conceptual framework for bottom-up estimation of instantaneous maritime air emissions presented in IMO's fourth greenhouse gas study (IMO, 2020). Presented equations are either lifted directly from the IMO report, although written with different notation, or derived from the report's running text.

IMO (2020) differentiates between fuel-based and energy-based pollutants and applies slightly different approaches when estimating the respective air emissions. CO_2 and SO_x are estimated as fuel based while NO_x, CH_4, $PM_{2.5}$ and PM_{10}, CO, N_2O and NMVOC are energy based. The two approaches are presented below.

2.1. Fuel-based emissions

At each observable spatiotemporal point (*t*), a given ship's *(j)* hourly emissions of a given fuel-based pollutant (*p*), from its main engine, auxiliary engine, or boiler, (*i*) are all estimated using the same basic equation:

$$EM_{i,j,p,t} = fEF_{i,p} \cdot FC_{i,j,t} \tag{1}$$

In other words, hourly emissions $EM_{i,j,p,t}$ are estimated by multiplying the hourly fuel consumption $FC_{i,j,t}$ with a fuel-based emission factor, $fEF_{i,p}$. The emission factor, $fEF_{i,p}$, is related to the type of fuel used for engine i, and $FC_{i,j,t}$ is estimated using:

$$FC_{i,j,t} = SFC_{i,j,t} \cdot W_{i,j,t} \tag{2}$$

I.e., the energy-specific fuel consumption, $SFC_{i,j,t}$ times the instantaneous hourly power demand, $W_{i,j,t}$. For main engines (*ME)*, the $SFC_{i,j,t}$ depends on the main engine load:

$$SFC_{i=ME,j,t} = SFC_{base_{i=ME,j}} \cdot \left(0.455 \cdot Load_{j,t}^2 - 0.710 \cdot Load_{j,t} + 1.280\right) \tag{3}$$

Where SFC_{base} is the baseline specific fuel consumption, defined by IMO (2020) as the lowest SFC seen on an engine's loading curve, in other words – the engines most fuel-efficient point. The expression within the parentheses is the load correcting factor and sets the main engine's most efficient point at around 80 percent capacity. For auxiliary engines (AU) and boilers (BO), $SFC_{i,j,t}$ is assumed to not depend on engine load, making $SFC_{i=AE|BO,j,t} = SFC_{base_{i=AE|BO,j}}$.

$Load_{j,t}$ is the main engines power demand expressed as a fraction of the main engine's maximum capacity:

$$Load_{j,t} = \frac{W_{i=ME,j,t}}{W_{ref}} \tag{4}$$

The main engine's power demand is in turn derived from:

$$W_{i=ME,j,t} = \frac{\delta_j W_{ref} \cdot \left(\frac{t_{j,t}}{t_{ref}}\right)^{0.66} \cdot \left(\frac{v_{j,t}}{v_{ref}}\right)^3}{\lambda_j \cdot \eta_j} \tag{5}$$

Where $t_{j,t}$ is the instantaneous draught and t_{ref} the reference draught, $v_{j,t}$ is the instantaneous speed over ground (SOG) and v_{ref} the reference speed. λ_j and η_j are weather- and fouling correcting factors and δ_j is a speed-power correcting factor. Ideally all reference values (W_{ref}, t_{ref} and v_{ref}) should correspond to the value of the given variable when the engine is at maximum capacity. However, due to data limitations, maximum speed is quite commonly unknown, and a ship's service speed is instead used as the reference. Since the service speed for ships, on average, corresponds to a main engine power output at 85 percent capacity, δ_j is set to 0.85 to adjust for the lower v_{ref} value. Alternatively, when known, W_{ref} is set to the power output at service speed. In that case or when v_{ref} is set to the maximum speed, $\delta_j = 1$.

For auxiliary engines and boilers $W_{i=AUX|BO,j,t}$ is assumed based on the ship's operational mode at time *t*.

2.2. Energy-based emissions

Energy-based emissions are estimated in a similar way to fuel-based emissions, the main difference being that an assumed energy-based emission factor is multiplied with the main engine, auxiliary engine, or boiler's power output instead of fuel consumption:

$$EM_{i,j,p,t} = eEF_{i,j,p} \cdot W_{i,j,t} \cdot LLF_{i,p} \tag{6}$$

$W_{i,j,t}$ is estimated as described above in section 2.1 while the energy-based emission factors, $eEF_{i,j,p}$, depend on engine types and fuel types used. Another added caveat when estimating energy-based emissions is the low loading factor ($LLF_{i,p}$). Main engines' combustion efficiencies are lower at loads below 20%, and thus, emissions increase at a different rate compared to higher loads. When estimating fuel-based emissions this is already accounted for since fuel consumption directly depend on the main engine load. However, for energy-based emissions, estimations need to be adjusted at lower loads. For auxiliary engines and boilers, $LLF_{i=AU|BO,p} = 1$.

3. Implementation

Continuing, this section presents our estimation strategy given the above outlined framework and IMO's (2020) recommendations. First, assumed values of all variables in the conceptual framework are derived and each observed point is assigned an operational mode as this determines which machinery is assumed to be in use and at what capacity. Second, emissions between observed points are estimated using integration, and lastly, all estimates are aggregated at the desired level.

3.1. Instantaneous emissions

The variables included in the conceptual framework can be divided into two types, vessel-specific and voyage-related. Voyage-related variables can vary between and during ongoing voyages while vessel-specific variables are assumed to be fixed over the estimated time period.

SOG and draught are treated as voyage related. Information on a ship's instantaneous SOG and draught are included in AIS observations and thus observable at different times. However, AIS data can be faulty or contain missing values. To account for this, all SOG values that are 1.5 times or larger than a ship's service speed are replaced by the ship's maximum speed and all draught values that exceeds a ship's maximum draught are replaced by the ship's maximum draught. [1] If either SOG or draught is missing from an AIS observation, the observation is dropped.

All other variables in the framework are treated as vessel specific and are assigned using information from a commercial ship database. The ships in our dataset are identified using IMO numbers which allows us to match vessel-specific information with AIS observations. Ships' reference speeds (v_{ref}), reference draughts (t_{ref}) and main engine maximum capacities (W_{ref}) are all available at the individual ship-level; however, all other needed vessel-specific information is not directly available and need to be derived. To do this, we follow IMO's (2020) recommendations and implement them as follows. A detailed discussion about differences and deviations between our implementation and IMO (2020) can be found in section 5.

For all non-observable variables in their framework, IMO (2020) divides ships into groups based on their known technical specifications and assign representative values for each group. For our estimations, we replicate IMO's (2020) group division and assign the same values as presented in the report.

IMO (2020) categorizes ships into 19 different ship types based on their Statcode5 classifications. Each ship type is then divided by size with the number of size categories as well as the size unit used varying between ship types. These ship types and size combinations are henceforth referred to as ship categories.

Fouling and weather correcting factors (λ_j, η_j) are assigned based on these ship categories as well as auxiliary engine and boiler power output ($W_{i=AUX|BO,j,t}$), however, auxiliary engine and boiler power output also depend on a ship's operational mode and the main engine power output.

Since we cannot observe which parts of a ship's machinery that are engaged and at what capacity at each AIS observation, this must be assumed. IMO (2020) defines four operational modes: at berth, anchored, manoeuvring and sea. They then assign each AIS observation one of these modes based on its estimated main engine power output, observed SOG and the proximity to land or a port area. In turn, each ship category has an assumed auxiliary engine and boiler power output for each operational mode (see IMO (2020), table 17). Boilers are assumed to be at their highest power output while at berth and at their lowest (often zero) while at sea, however, differences in power output between modes vary greatly between ship categories. For auxiliary engines, the most and least power intensive

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[1] When the maximum speed of a ship is unknown, the value is instead replaced by the ship's service speed.

operational modes vary between ship categories but in general, auxiliary engines are assumed to be at their highest power output when ships are manoeuvring.

However, in some cases, operational mode specific power output assumptions are overwritten. If the main engine power output is lower than 150 kW, auxiliary engines and boilers are assumed to not be engaged and if the main power output lies between 150 kW and 500 kW, auxiliary engine power output is assumed to be five percent of the main engine installed power. Lastly, if the main engine power output is estimated to be lower than 7 kW, it is set to zero.

$SFC_{base_{i,j}}$ depend on the fuel type used, engine type and the engines year of build. For main engines, IMO (2020) assigns ships one of four main engine fuel types, Heavy fuel oil (HFO), distilled fuel oil (MDO), gas boil-off (LNG) or methanol, using available vessel-specific technical specifications.[2] If only insufficient information is available, ships are assigned the most common main engine fuel type of their ship category. Additionally, IMO (2020) assumes that ships using HFO switches to MDO while travelling within a SECA. The Baltic Sea, i.e., the geographical area of study in this memorandum, lies within a SECA, and thus, all ships assigned HFO are reassigned MDO. For auxiliary engines and boilers, we assume that all ships use MDO.

A ship's fuel type, together with the main engine's revolutions per minute (RPM) and propulsion description as listed in the dataset, are then used to assign ships a main engine type; slow-speed diesel (SSD), medium-speed diesel (MSD), high-speed diesel (HSD), gas turbine, steam turbine or LNG-engine. If no engine type can be assigned, ships are assigned the most common engine type of their ship category. For auxiliary engines and boilers, IMO (2020) do not differentiate between engine types. Each engine- and fuel type combination has three different $SFC_{base_{i,j}}$ values. One for engines built before 1983, one for engines built between 1984 – 2000 and one for engines built after 2001. Newer engines are assumed to be more fuel efficient.

Lastly, all emission factors are applied following IMO's (2020) recommendations. Emission factors for CO_2 only depend on an engine's assumed fuel type and is derived from each fuel type's average carbon content. SO_x emission factors also depend on fuel type; however, it is also affected by the year of study since the concentration of sulphur in marine fuels has decreased over time due to more stringent IMO regulations (IMO, 2020).

NO_x emissions are also affected by IMO regulation. Engines are divided into four tiers based on their year of built – the newer the engine the higher the tier and the lower the allowed NO_x emissions. NO_x emission factors are applied under the assumption that ships comply with their respective tier regulation. Additionally, diesel engines are assumed to be more NO_x efficient at higher RPMs, thus, NO_x emission factors for these types of engines are a function of the engines RPM.

PM_{10} emissions are assumed as a function of fuel type used and said fuel type's sulphur content. The emission factor for $PM_{2.5}$ is assumed to correspond to 92 percent of a ship's PM_{10} emission factor. Lastly, CH_4, CO, N_2O and NMVOC all depend on engine type and fuel type used.

With all the necessary voyage-related and vessel-specific information in place, hourly emissions for each AIS observation are estimated as shown in Figure 1. First, the main engine power output is estimated using equation (5). This estimate can then be plugged into equation (6) and equation (2) to estimate main engine energy-based emissions and main engine fuel consumption respectively. Lastly, for the main engine estimates, equation (1) is used to estimate main engine fuel-based emissions.

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[2] IMO (2020) also assign ships the fuel types "nuclear" and "coal", however emissions are not estimated for these types of ships.

The main engine power output, together with the ship's SOG and position, also lets us determine each AIS-observations operational mode using table 16 in IMO (2020). In turn, the operational mode gives us the auxiliary engine and boiler power output from table 17 in IMO (2020). As for the main engine estimates, equations (6), (2) and (1) can then be applied to estimate the auxiliary engine and boiler energy-based emissions, fuel consumption and fuel-based emissions respectively.

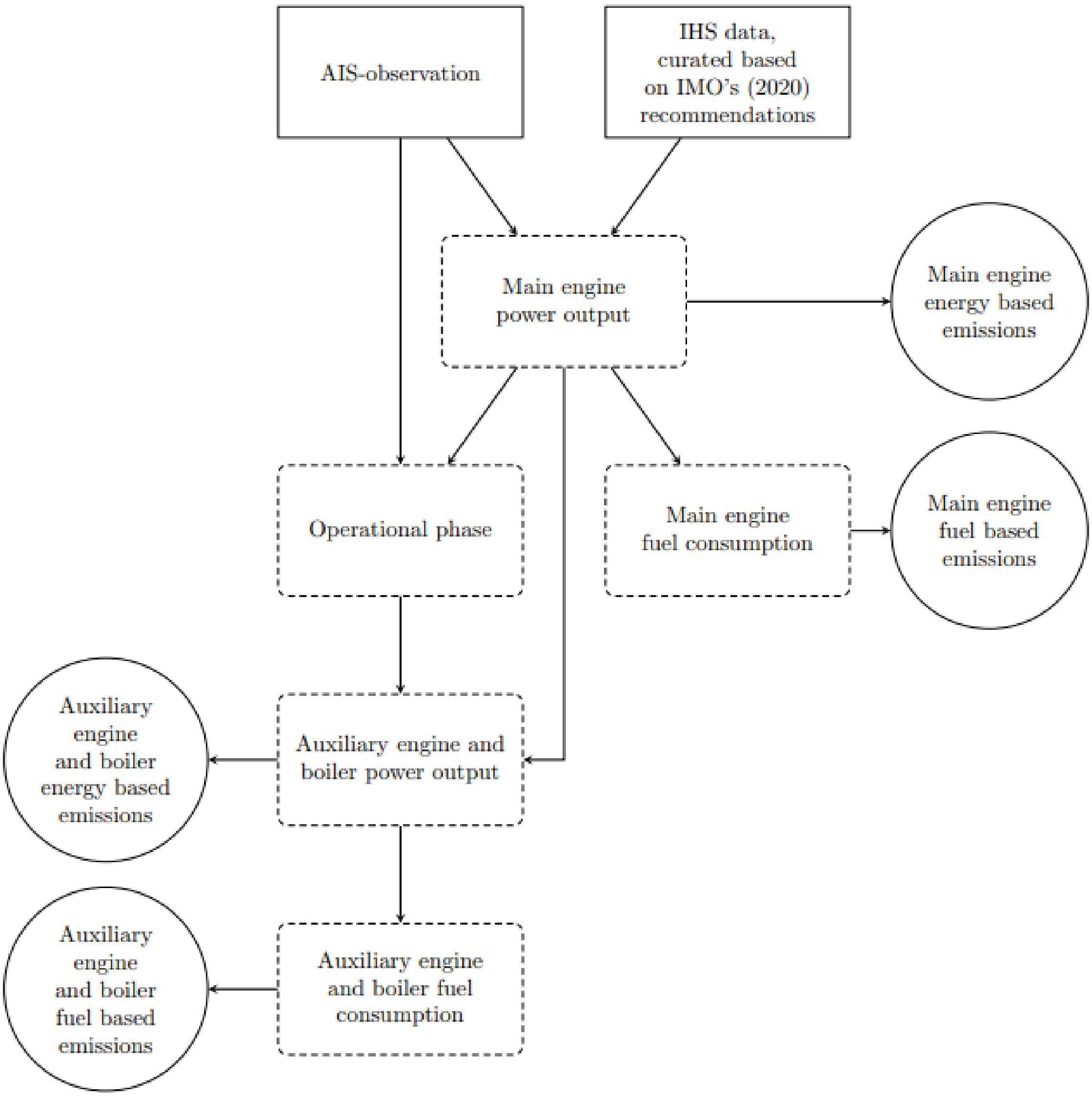

Figure 1. Implementation of the conceptual framwork for estimating instantaneous emissions, fuel consumption and, energy consumption. Rectangles with solid lines represent data input, circles last step emission output, and dashed rectangles calculation steps.

3.2. Integration to obtain consumed and emitted quantities

The hourly emissions of each ship's machinery (and similarly hourly fuel consumption and energy output) are calculated for each spatiotemporal point. To obtain the emitted quantities, simplified integration over time is performed. For each two consecutive points, the average hourly emission is calculated and multiplied by the time between them yielding the quantity, as illustrated in Figure 2. If two consecutive points are more than one hour apart, the emitted quantities are set to zero since the data is too scarce for any reliable estimations[3]. The threshold of one hour is arbitrarily chosen but necessary and further efforts should be made to find a suitable threshold. Similarly, if either the hourly value EM_1 or EM_2 is NA (i.e., not applicable, which might happen if necessary data is not available), then the emitted quantities are set to zero.

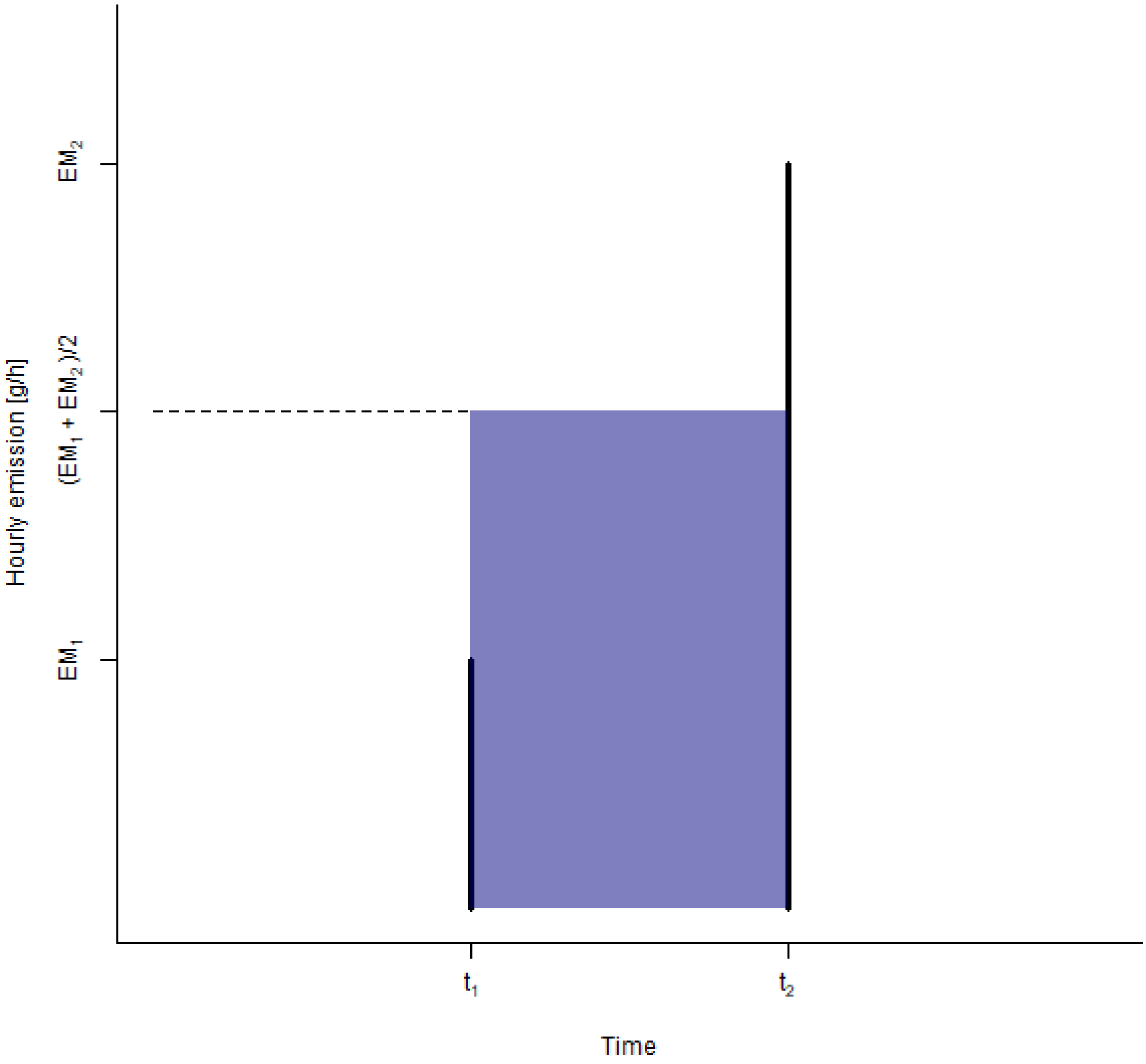

Figure 2. Calculating ethe emitted quantity from hourly emission estimates. The emitted quantities are calculated according to the coloured area between each pair of consecutive observations.

3.3. Aggregation

Since calculation are made for each spatiotemporal point per individual ship, any aggregation from this unit is possible. For this memorandum, consumed and emitted quantities are aggregated per ship, region (grid) and pollutant to annual figures.

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[3] This might occur if the ship travels outside the region or if the AIS-transponder is not working correctly.

3.4. The computation design

Code is written both in R and in PostgreSQL with the PostGIS extension. Due to hardware restrictions, data is pre-filtered by a region and calculated in batch. This may lead to underestimation of the fuel consumed and emissions since some journeys might be interrupted. For example, a journey over a region border is cut of and the emissions from the last point to the border is hence omitted.

4. Data

Estimations in this memorandum are based on three main data sources: AIS data provided by HELCOM (2021), vessel-specific characteristics from a custom sample from IHS Markit's commercial vessel database (IHS Markit, 2020) and non-observable ship characteristics from IMO's fourth greenhouse gas study (IMO, 2020). Note that these datasets are to be considered as representative data, i.e., the model is dependent on the specific data but not dependent on these datasets in particular.

The raw AIS data for 2019 covers 328 196 843 observations from 8 491 ships, whereof 53 462 548 observations from 6 862 ships are in Swedish territory.[4] Movements and emissions in Swedish territory are identified using area polygons (HELCOM, 2022; Flanders Marine Institute, 2019a; Flanders Marine Institute, 2019b; Flanders Marine Institute, 2019c; Marine Regions, 2005a). Notably only AIS observations that include an IMO number are represented in the data. [5] IMO numbers are manually entered by the crew and can be omitted. Thus, our AIS sample is likely not comprehensive. However, looking at ships that made calls at Swedish ports and paid fairway dues in 2019 (Swedish Maritime Administration, n.d.), 96 percent are covered in our AIS sample.

Our sample from IHS Markit covers vessel-specific technical specifications for ships that made calls at Swedish ports and were required to pay fairway dues during 2008–2020. The approach by IMO (2020) is also based on data provided by the IHS Markit, thus, we can closely follow their recommendations when deriving our estimation variables. Table 1 lists the vessel-specific information we use and for what purpose. As mentioned above, model variables not directly available in the IHS Markit dataset are derived in following IMO's (2020) recommendations and variables identified by this method and their source tables in the IMO report are listed in Table 2.

The performed data curation is illustrated in Figure 3. The vessel-specific dataset includes 9 606 ships, 9 559 of these ships are of a ship type covered in IMO (2020) and we can construct complete profiles for 9 235 ships. Using this sample, we are able to match 3 956 ships in our AIS data in Swedish territory and 4 153 ships in Sweden and the Baltic Sea. In Swedish territory, this corresponds to 58 percent of ships in our AIS data and 61 percent of observations. The coverage for Sweden and the Baltic Sea is as expected lower, corresponding shares being 51 and 52 percent.

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[4] Ships are identified via their IMO numbers.

[5] Our data provider very likely performed data curation.

Table 1. List of data provided by IHS Markit (IHS Markit, 2020) and its use in the modelling.

IHS variable	**Description**	**Use**
Cargo Capacity	Text that describes a vessel's cargo capacities.	Size classification for Container (TEU) and Liqufied gas tanker (CBM).
Date of build	The date a ship was delivered to its original owner.	To determine vessel and engine age.
Deadweight, tonne	The weight of a vessel's cargo in metric tonnes when the vessel is loaded to her maximum summer draught.	Size classification for Bulk carrier, Chemical tanker, General cargo, Oil tanker, Other liquids tanker, Refrigerated bulk, and Ro-Ro.
Maximum draught, metre	A vessel's maximum draught in meters.	Reference draught, t_{ref}.
Fuel type 1	The lightest type of fuel.	To assign the main engine fuel type.
Fuel type 2	The second lightest type of fuel.	To assign the main engine fuel type.
Gross tonnage, GT	A unitless measure of the moulded volume of all a ship's enclosed spaces.	Size classification for Ferry pax-only, Cruise, and Ferry-RoPax, into size categories.
IMO number	A ship's unique lifelong identifying code assigned under IMO Resolution A.1117(30).	Matching IHS Markit data with AIS observations.
Maximum main engine RPM	The rotations per minute (RPM) of the main engine at maximum power.	To assign engine type and to estimate NO_x emission factors for diesel engines.
Propulsion type	Indicates the type of power configuration between the prime mover and the drive connection.	To assign engine type.
Maximum speed, knots	The maximum speed in knots of a vessel when its engine is running at maximum continuous rating (MCR).	Reference speed, v_{ref}.
Service speed, knots	The service speed in knots.	Reference speed, v_{ref} when a ship's maximum speed is unknown.
Service speed power, kW	Power output of the prime mover at service speed in kilowatts.	Reference power, W_{ref} when a ship's maximum speed is unknown and service speed is used instead.
StatCode5	A seven-character code used as a ship type standard.	To sort ships into ship types.
Total Kilowatts of Main Engines, kW	The total power produced by the main engine(s) in kilowatts.	Reference power, W_{ref}.

Table 2. List of data presented in IMO (2020) that we use in our modelling.

Variable	**Dependencies**	**Unit**	**Source**
Fouling correction factor λ_j	Ship size and ship type.	-	IMO (2020) Annexes table 44
Weather correction factor, η_j	Ship size and ship type.	-	IMO (2020) Annexes table 44
Baseline energy-specific fuel consumption, $SFC_{i,j,base}$	Engine type, fuel type and year of build.	g/kWh	IMO (2020) table 19
CO_2 emission factor, $fEF_{i,p}$	Fuel type.	g emissions / g fuel	IMO (2020) table 21
SO_x emission factor, $fEF_{i,p}$	Fuel type and year of the AIS observation.	g emissions / g fuel	IMO (2020) Annexes tables 47 and 48
Low loading factor, LLF_p	Energy based pollutant.	-	IMO (2020) table 20
NO_x emission factor, $eEF_{i,j,p}$	Engine RPM, fuel type and age.	g emissions / kWh	IMO (2020) table 23 and IMO (2020) Annexes table 50
PM_{10} emission factor, $eEF_{i,j,p}$	Engine and fuel type.	g emissions / kWh	IMO (2020) Annexes tables 52,53 and 54
$PM_{2.5}$ emission factor, $eEF_{i,j,p}$	Engine and fuel type.	g emissions / kWh	IMO (2020) Annexes tables 52,53 and 54
CH_4 emission factor, $eEF_{i,j,p}$	Engine and fuel type.	g emissions / kWh	IMO (2020) Annexes tables 55 and 56
CO emission factor, $eEF_{i,j,p}$	Engine and fuel type.	g emissions / kWh	IMO (2020) Annexes tables 57 and 58
N_2O emission factor, $eEF_{i,j,p}$	Engine and fuel type.	g emissions / kWh	IMO (2020) Annexes tables 59 and 60
NMVOC emission factor, $eEF_{i,j,p}$	Engine and fuel type.	g emissions / kWh	IMO (2020) Annexes tables 61 and 62

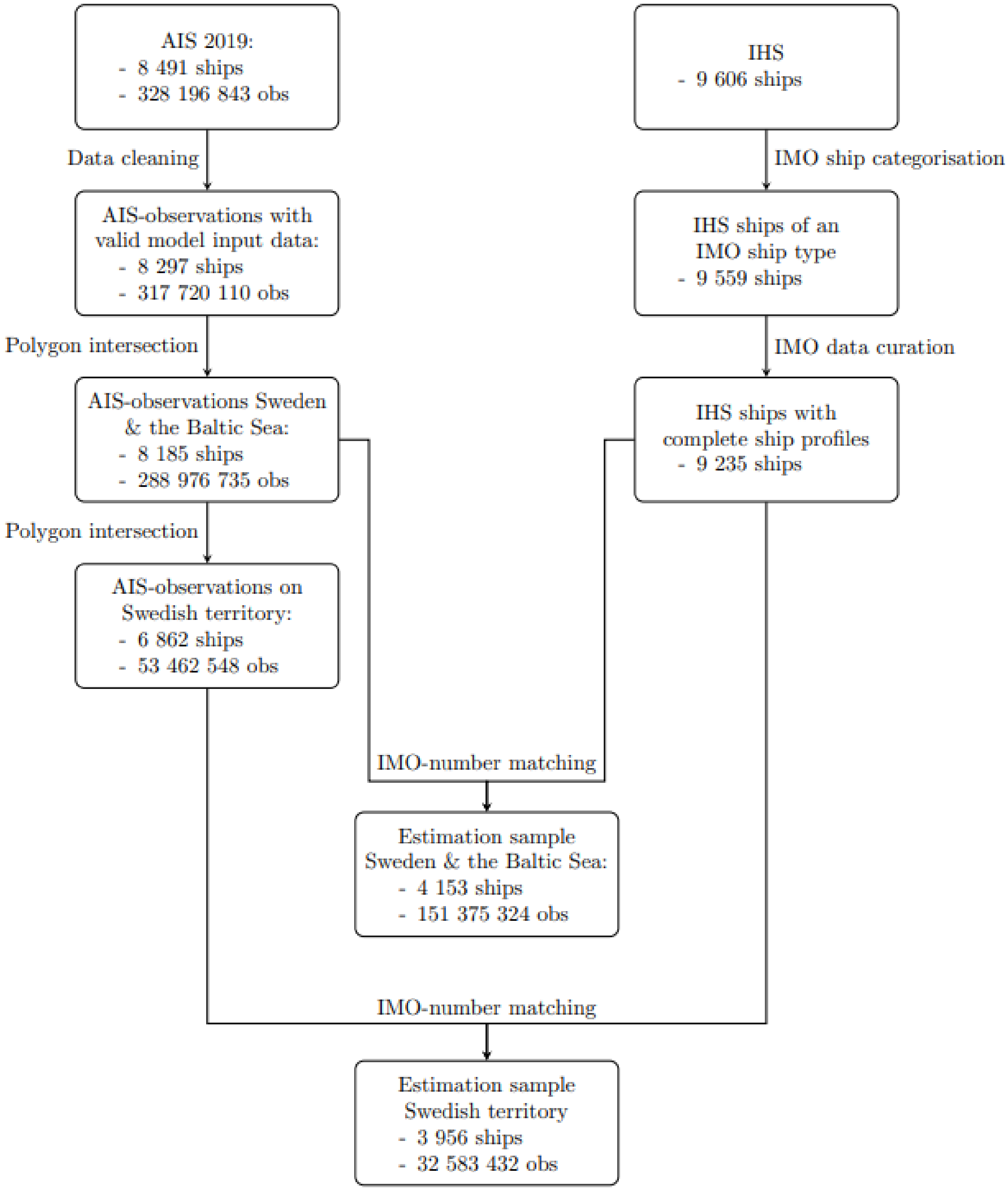

Figure 3. Illustration of performed data curation. Note that when estimating, duplicate AIS observations are removed from the estimation samples, excluding 2 929 respectively 352 observations.

5. Differences and deviations compared to IMO

Even though the approach of this project is based on the bottom-up method in IMO (2020), both our current data and implementation differ in a few ways. This section presents the main differences and the reasoning behind them.

5.1. Conceptual framework

The conceptual framework of our model follows that of IMO (2020) closely. However, IMO (2020) presents their framework in report format, which might result in interpretation errors. For example, equation (4) is only described in running text and never written out as an equation.

We also handle the speed-power correcting factor, δ_j, in equation (5) differently. IMO (2020) includes δ_j in their framework since they find that the information they use for reference speed not consistently reports ships' maximum speed – the intended reference speed. For most ship categories, they find that the information, on average, represents ships' maximum speed and set δ_j to one. However, for some container ship categories, ships' service speeds appear to be more commonly reported than their maximum speed. For these cases IMO (2020) sets δ_j to 0.75 to approximate the service speed capacity as the reference capacity to account for the use of the service speed as the reference speed.

We, on the other hand, have separate information on ships' maximum speeds and service speeds, and, for some ships, we have both their maximum and service speed capacity. Since IMO (2020) apply δ_j to correct for the use of service speed as a reference, we apply δ_j for individual ships where we know that service speed is used as a reference (due to maximum speed being unknown). Furthermore, when service speed is used as a reference and service speed capacity is known, we instead use service speed capacity as the reference capacity. Since δ_j is applied by IMO (2020) to approximate the service speed capacity, using the actual service speed capacity should provide a more accurate reference.

Lastly, IMO (2020) finds that their bottom-up model tends to overpredict power output for cruise ships since they have different propulsion system and hotel load being a larger portion of their fuel consumption compared to other ship types. For cruise ships they set δ_j to 0.7 to account for this overprediction. Since we interpret this as a calibration measure, and thus somewhat data dependent, simply implementing the correction value as it is seems inappropriate, and given the scope of this memorandum, we chose to not do any calibration of our own.

5.2. Implementation

When deriving ship profiles, we follow IMO's (2020) recommendations as presented in the report, but unintended differences might still occur. We use data on ship characteristics delivered by the same data broker as used by IMO (2020), however, there is still room for differences in interpretation. Furthermore, translating the data presented by IMO (2020) in report format to a tabular format might involve human error.

In terms of matching AIS with ship characteristics, IMO (2020) divides ships into four types.

- Type 1, vessels that have a matching IMO number in both the AIS dataset and the ship characteristic dataset.
- Type 2, vessels that have a matching MMSI number in both the AIS dataset and the ship characteristics dataset, but do not have a valid IMO number in the AIS dataset.
- Type 3, vessels that are observed in the AIS dataset, cannot be matched as Type 1 or Type 2 vessels, but have valid MMSI entries in the AIS dataset, at least one period of continuous activity lasting longer than 24 hours, and are larger than 100 GT.

- Type 4, vessels that appear as ‘active’ in the ship characteristics dataset but are not observed in the AIS dataset by their IMO or MMSI number, and are between 100 and 300 GT.

All four types are what IMO (2020) consider estimation targets. Given our current AIS data, we only estimate emissions for type 1 vessels. As mentioned, our AIS dataset only includes observations with an IMO number. Although some IMO numbers are non-valid, the share of type 2 matches is so small that we do not include them for this project. Given our current data, we are unable to identify type 3 matches. We also cannot identify type 4 vessels for our current implementation since we cannot determine if a ship listed as active has been active in the Baltic Sea under a given year of study. However, in future iterations with more comprehensive AIS data, type 2 and type 3 vessels should be considered.

When determining AIS observations’ operational modes, we follow IMO’s (2020) recommendations in terms of SOG and load values, however geographical definitions a treated somewhat differently. IMO (2020) looks at ships’ distances from ports while we have defined port polygons, which is a simplification. IMO’s (2020) distance-to-port values are replaced by checking if an observation occurred within a port area. IMO (2020) also increase the allowed port distance for different operational modes for tanker vessels, but since we model port proximity as binary, this is not applied.

Looking at ship profiles, we do not replace any missing technical specifications. When certain information is missing for a ship, IMO (2020) runs regression using ships with known information in the same ship category to estimate replacements values. Since such a small share of ships in our sample have missing technical information, for the scope of this memorandum, estimating replacement values are not considered. Instead, ships with incomplete technical information are dropped. However, estimating replacement values should be implemented if the scope requires it.

We also experienced some data limitations. IMO (2020) differentiates between four types of LNG-engines: LNG-Otto SS, LNG-Otto MS, LNG-diesel and LBSI. In our ship characteristics sample we do not have sufficient information to differentiate between the different LNG-engines. Instead, ships using LNG are assigned the most common type of LNG-engine, LNG-Otto MS, (given that they are not using steam- or gas-turbines). This can be amended given more extensive data on ship characteristics.

Lastly, we also use a simplification in assuming that all ships use MDO as their auxiliary engine and boiler fuel. IMO (2020), to our knowledge, does not give any clear recommendations on how to derive auxiliary engine and boiler fuel but do recommend against simply assuming that ships use the same fuel as for their main engine. Since all our observations lie within a SECA, we can disregard HFO as an auxiliary fuel which makes our simplified assumption reasonable for the estimates of this memorandum.

5.3. Sampling

IMO (2020) resample their AIS data into hourly observations.[6] Their main motivation is that they are interested in comparing air emissions from shipping between years. The quality of AIS data has increased over the years and, subsequently, AIS data from later years are more comprehensive. Thus, to limit the effects of quality improvements of the AIS data between years when comparing emission estimates, IMO (2020) resamples their data such that the estimations for each ship in each year are based on the same number of observations.

Since we do not compare estimates between years, the quality improvements of AIS data over time are not an issue. Thus, we do not resample our data and instead calculate instantaneous energy

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[6] See IMO (2020) section 2.2.3 for details.

consumption, fuel consumption and emissions for all spatiotemporal points, then perform integration over time. Provided that the data quality is good enough, this should lead to better estimates.

Since we do not resample, we also handle missing or invalid SOG, draught and coordinates data differently. If any of these values are missing or invalid for an hourly observation, IMO (2020) uses different approaches to infill them. We, on the other hand, simply drop observations that include missing or non-valid values. Given the large number of observations per time and vessel used in our estimations the share of dropped observations is small. Additionally, a slightly longer period being integrated is unlikely to systematically yield worse estimates compared to infilling the missing values and then integrating based on infilled values.

6. Validation approach

To assess the validity of our approach, our results are compared with other estimates and measurements of maritime air emissions, energy, and fuel consumption. In general, validation points are chosen based on comparability in terms of time and geographical area. The chosen validation points are presented in Table 3. Our motivation for choosing these validation points and a discussion of their comparability with our results are presented below.

Table 3. Used validation points, their scopes and sources.

Type of estimate	**Time resolution and period**	**Sample**	**Compared estimates**	**Source**
Official statistics	Year, 2019	Domestic traffic, commercial and leisure boats	Greenhouse gas emissions, expressed in carbon dioxide equivalents	(Swedish Enviromental Protection Agency, 2023b)
Official statistics	Year, 2019	International bunkering	Greenhouse gas emissions, expressed in carbon dioxide equivalents	(Swedish Enviromental Protection Agency, 2023c)
Official statistics	Year, 2019	Domestic and international traffic	Energy consumption	(Swedish Energy Agency, 2023)
Reported emissions	Year, 2019	Voyages to, from and within the EEA	CO_2 emissions and fuel consumption	(EMSA, 2023)
Emission modelling, Shipair	Year, 2018 and 2021	Swedish territory, domestic and international traffic	Fuel consumption	(van Dongen, Johansson, & Windmark, 2022)
Emission modelling, STEAM2	Year, 2015	Maritime traffic within the Baltic Sea	CO_2, SO_x, NO_x, $PM_{2.5}$, CO, and fuel consumption	(Johansson & Jalkanen, 2016)

6.1. Official statistics

The Swedish Environmental Protection Agency reports annual official statistics on greenhouse gas emissions from Swedish maritime traffic. In accordance with the United Nations Framework Convention on Climate Change (UNFCCC) Sweden is required to do yearly national inventories of anthropogenic CO_2 equivalent (CO_2e) emissions by source. However, for maritime traffic only domestic emissions, defined as emissions from voyages that depart and arrive at ports in the same country, are required to be reported in relation to the UNFCCC and Kyoto Protocol commitments (Swedish Environmental Protection Agency, 2023a). The Swedish Environmental Protection Agency still reports data on emissions from international traffic, but with some significant methodological differences.

Statistics on domestic CO_2e emissions include commercial traffic and leisure boats and is based on estimated fuel consumption. For commercial traffic, fuel consumption is mainly estimated using SMHI's Shipair model complemented by surveying of the largest shipping actors for domestic traffic. Leisure boats' fuel consumption is based on four separate surveys, with interpolated fuel consumption in between surveyed years. Fuel consumption is then multiplied by emission factors, with some applied within the Shipair model (Swedish Environmental Protection Agency, 2023a).

International maritime emissions are instead based on a monthly survey on supply and delivery of petroleum products and is estimated as the difference between the total supply of fuel in the monthly survey and the estimated energy consumption for national statistics.

We also compare our estimated energy use with official national statistics on maritime transport energy use from the Swedish Energy Agency (2023). The statistics are based on model estimations based on AIS data (non-specified model) and information gathered from shipping companies and fuel providers. International traffic energy estimates are based on bunkering data (Swedish Energy Agency, 2022).

Due to the methodological differences, comparisons between our estimates and the official statistics are not straightforward. Both in terms of how the estimates are done (bought fuel and used fuel and not directly comparable) and which ships and voyages that are included. However, we still utilize the official statistics as a validation point since it is an important benchmark.

6.2. Reported statistics

In 2015, the EU introduced the monitoring, reporting, and verification system (MRV) for maritime CO_2 emissions (EU, 2015). In accordance with the regulation, ships of 5000 GT or larger that call at ports within the European Economic Area (EEA) are required to report, on a yearly basis, their total fuel use and total carbon emissions when travelling to, from or between EEA ports. Using IMO numbers, we can match the vessels in our estimation sample with their reported MRV values for 2019, allowing for validation of our estimates at the individual ship level for 2 576 ships.

MRV reported values are only reported at highly aggregated levels; thus, we cannot isolate emissions within our geographical estimation area. However, MRV also includes ships’ average fuel consumption and average CO_2 emissions per sailed nautical mile. Using our AIS data, we estimate travelled nautical miles for ships in our sample and, using our model estimations, their average fuel consumption, and average CO_2 emissions per nautical mile. To make our estimates and the MRV reported values as comparable as possible, estimated averages per nautical mile are based on AIS data from the entire Baltic Sea, i.e., our largest possible area of estimation given our sample.

Since this validation point allows us to compare our estimates at the individual ship level, our estimation coverage is much less of an issue compared to aggregated comparisons, since it only results in fewer comparison points but does not affect the comparability. MRV values are measured and not estimated which also removes issues with methodological differences. However, it is still not a perfect comparison since we compare average fuel consumption and emissions from voyages to- from and within the entire EEA with our estimates of average fuel consumption and emissions from voyages within the Baltic Sea. It is possible that ships systematically change behaviours within the Baltic Sea, for example in terms of SOG, tonnage and share of time spent in ports versus at sea, compared to when sailing outside of the area. These differences could result in actual differences in average fuel consumption (and in turn CO_2 emissions) between the two areas and we cannot discern if differences in our estimates compared to MRV values are due to our estimation approach or behavioural differences. However, since data from the Baltic Sea is included in the MRV values, actual differences can be assumed to not be substantial for most ships.

6.3. Other estimation models

In addition to being the basis for Swedish official statistics, Shipair estimates have also been published on their own for example in van Dongen, Johansson, & Windmark (2022). The report includes Shipair fuel consumption estimates for 2018 and 2021 for the Baltic Sea, the Swedish exclusive economic zone, and Swedish territorial waters respectively. However, van Dongen, Johansson, & Windmark (2022) only include voyages that either depart and/or arrive at Swedish ports while we include all voyages within each estimation area. Since differences between traffic that calls at Swedish ports and all traffic within a geographical area should increase at further distances from Sweden, we choose to compare our estimates with the Shipair estimates for Swedish territorial waters. Apart from the differences in studied traffic, the fact that we are comparing estimates from different years introduces some further insecurity, however, our data and the data for the Shipair estimates should be similar in terms of geographical scope and ship sample size, although exact differences in the ship sample size used in the estimations cannot be determined since van Dongen, Johansson, & Windmark (2022) only disclose the sample size for the Baltic Sea divided into domestic and international traffic (where some overlap in ships can be expected).

We also compare our estimates with estimated, CO_2-, SO_x-, $PM_{2.5}$-, and CO-emissions in the Baltic Sea in 2015 as reported in Johansson & Jalkanen (2016). For their estimates, Johansson & Jalkanen (2016) utilized the STEAM2 model (see Jalkanen, et al. (2012)). Johansson & Jalkanen's (2016) estimates are based on a far greater sample of ships, ~ 20,000, compared to our sample for Sweden and the Baltic Sea. Thus, their estimates are used both as an upper limit to compare our estimates to, and to compare the relative amounts of different estimated air emissions.

7. Results

The output from this model is estimated emissions to air, however, following the method, both fuel and energy consumptions are estimated since emissions are based upon these two entities. Note that each step adding information increases the uncertainty. Compared to fuel and energy consumption, emissions are further down the pipeline and those numbers are probably subject to greater uncertainty. We therefore present fuel and energy consumption for transparency and validation purposes.

As for the presentation of data, all calculations are performed on individual ship level and then aggregated in various ways. Results presented here are examples of how estimates can be aggregated, other levels of aggregation and geographical divisions are possible. Also, again, notice that the results are not based on comprehensive samples of maritime traffic in either of the estimated regions as discussed in section 4.

7.1. Output

For the results, fuel and energy consumed and emitted quantities are presented. Estimated pollutants include CH_4, CO, CO_2, N_2O, NMVOC, NO_x, PM_{10}, $PM_{2.5}$ and SO_x. Results are calculated for two regions, Sweden and the Baltic Sea, and Swedish territory (the respective regions are visualized in the Appendix). Specifically, the following is presented:

- Total emitted quantities per pollutant (Table 4)
- Total fuel quantity consumed per machinery and fuel type (Table 5)
- Total energy quantity consumed per machinery and fuel type (Table 6)

The model output is also presented graphically, visualised in

- Distributions of ship's emitted quantities reported per pollutant (Figure 4)
- Rasterized/gridded annual CO_2 emissions (Figure 5)

Each individual ship emits quantities annually. The distributions of these quantities emitted in Swedish territory are seen in Figure 4. As seen, CO_2 and NO_x emissions yields the highest annual quantities (like the quantities in Table 4). The distributions have a single peak shape. Notice however that the x-scale is transformed by log10 for visualisation purposes – which means that the underlying distribution is right-skewed. Moreover, it is worth noticing that the distributions span many orders of magnitude. This may indicate that ships' emissions differ greatly, however the emitted quantity is closely related to the amount of activity in the region analysed (this is further analysed in section 7.2.2 in the MRV comparison).

In Figure 5, the CO_2 emissions are visualised on a 1 km x 1 km grid. CO_2 is used here as an example, but any pollutant may be visualized this way. Areas with higher activity are in darkgreen, for example outside the Gothenburg area, west and east of Gotland, along the southern coast passing east of Öland, outside the Stockholm area, and east of the Umeå area. The grid unit with the highest emission is found close to Helsingborg.

Table 4. Emitted quantities in kilotonnes by pollutant in regions Sweden and Baltic Sea and Swedish territory for the year 2019.

Pollutant	**Quantity [ktonne] 2019 Sweden and Baltic Sea (4 153 ships)**	**Quantity [ktonne] 2019 Swedish territory (3 956 ships)**
CH_4	2.38	0.738
CO	2.61	0.580
CO_2	9220.	1780.
N_2O	0.485	0.0932
NMVOC	8.62	1.65
NO_x	199.	37.4
PM_{10}	2.80	0.532
$PM_{2.5}$	2.58	0.490
SO_x	3.86	0.737

Table 5. Fuel quantity consumed in kilotonnes by machinery and fuel type in regions Sweden and Baltic Sea and Swedish territory for the year 2019. Note that methanol has been excluded due to the small number of ships using it.

Machinery	**Fuel type**	**Fuel [ktonne] 2019 Sweden and Baltic Sea (4 153 ships)**	**Fuel [ktonne] 2019 Swedish territory (3 956 ships)**
Auxiliary engine	MDO	399.	78.7
Boiler	MDO	15.9	1.10
Main engine	LNG	66.3	20.2
Main engine	MDO	2390.	457.

Table 6. Energy quantity consumed in TWh by machinery and fuel type in regions Sweden and Baltic Sea and Swedish territory for the year 2019. Note that methanol has been excluded due to the small number of ships using it.

Machinery	**Fuel type**	**Energy [TWh] 2019 Sweden and Baltic Sea (4 153 ships)**	**Energy [TWh] 2019 Swedish territory (3 956 ships)**
Auxiliary engine	MDO	2.13	0.419
Boiler	MDO	0.0496	0.00343
Main engine	LNG	0.415	0.126
Main engine	MDO	13.1	2.48

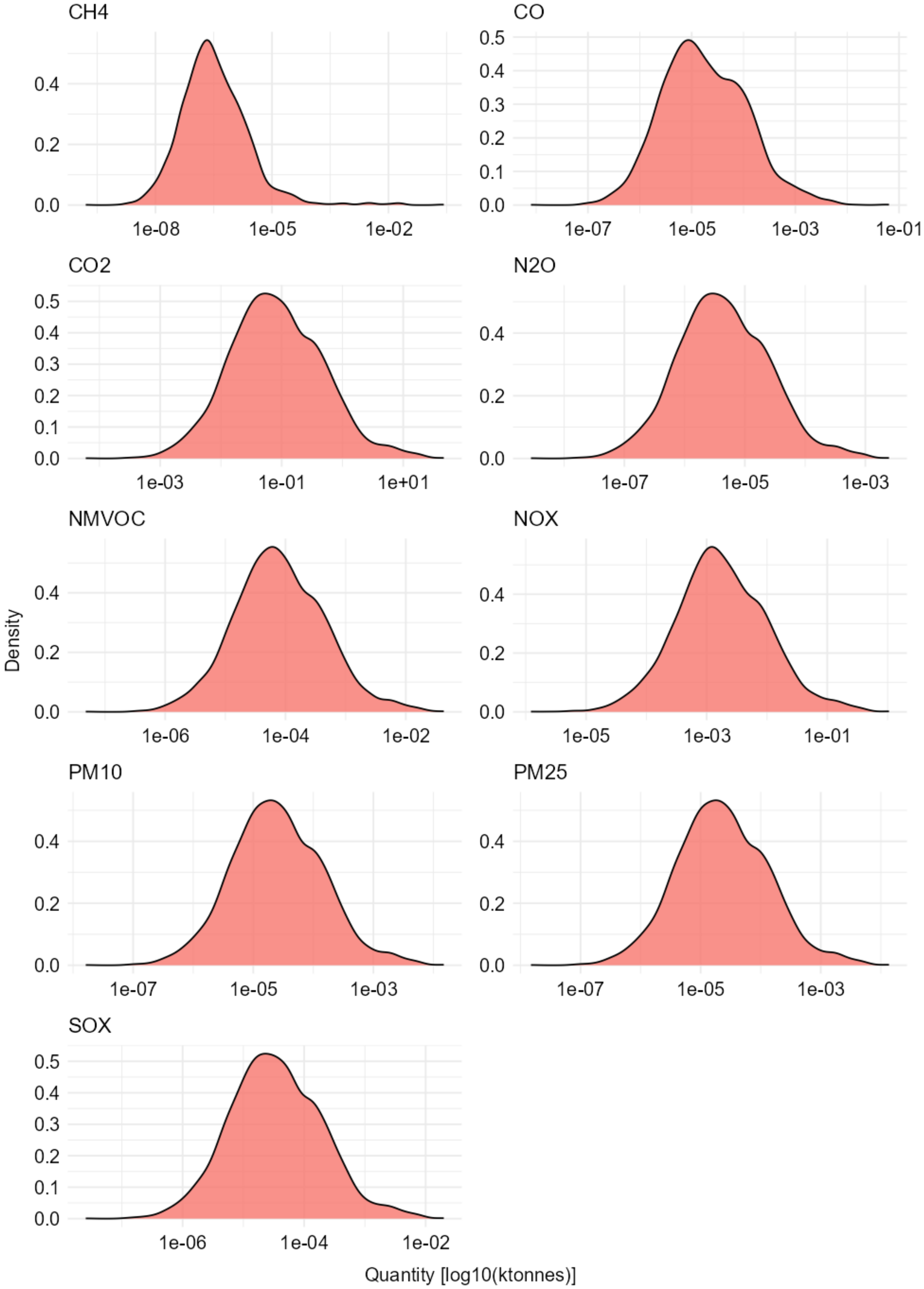

Figure 4. Emissions by pollutant. Each ship emits an annual pollutant quantity. Shown here are distributions of those quantities, in kilotonnes, for ship in Swedish territory. Note that the x-axis is log10-transformed, that is 0 represents 1 kilotonne, and that the axis scales differ.

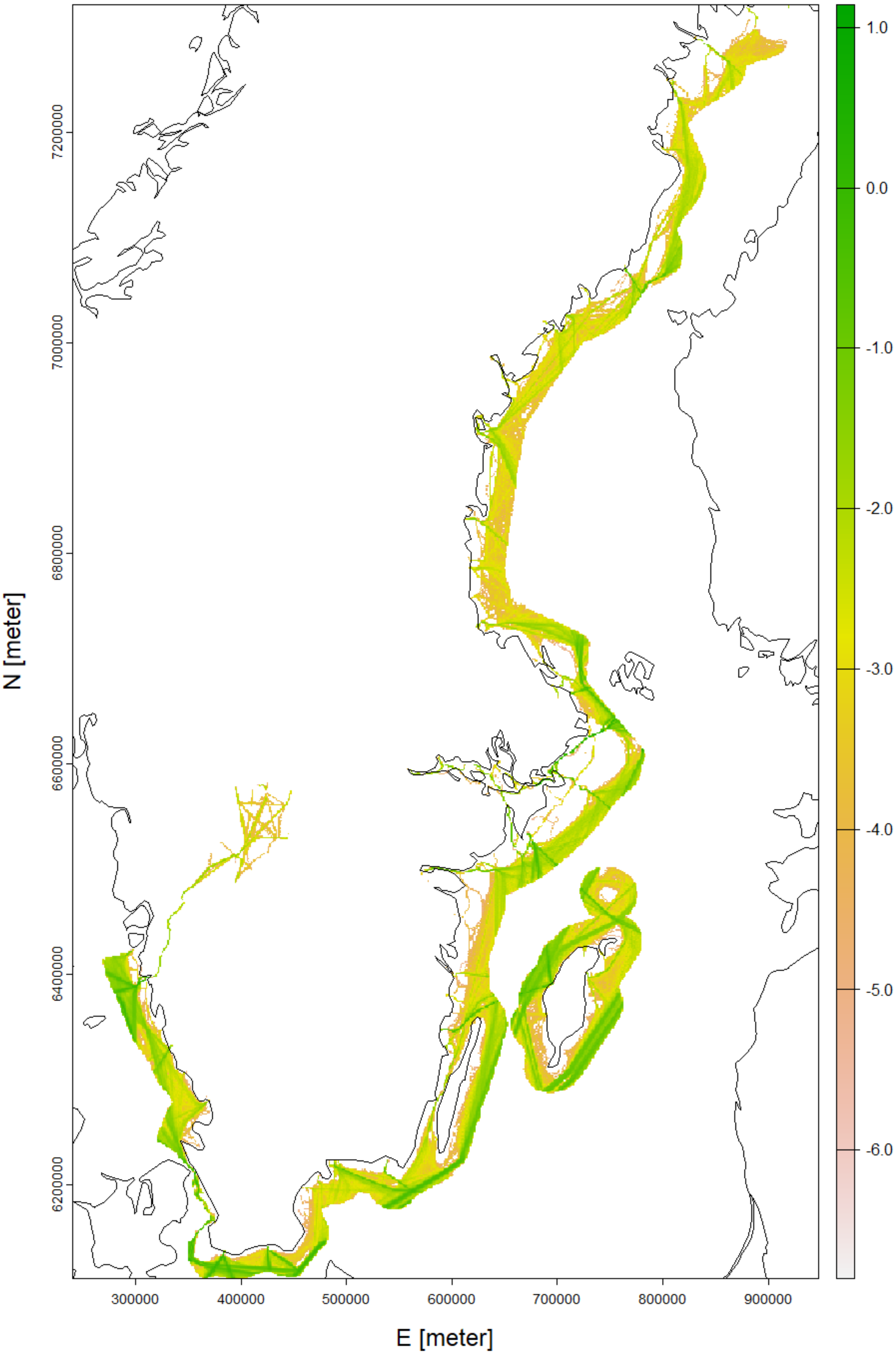

Figure 5. Emitted CO_2, in kilotonnes, in Swedish territory aggregated on a 1 km x 1km grid. Note that the value scale is log10-transformed, that is 0 represents 1 kilotonne.

7.2. Validation

This section presents comparisons between our estimates and the chosen validation points presented in section 6.

7.2.1. Official statistics

According to official statistics, domestic maritime traffic emitted 0.685 million tonnes of CO_2 equivalents and international traffic, estimated based on international bunkering, emitted 6.995 million tonnes in 2019 (Swedish Enviromental Protection Agency, 2023b; Swedish Enviromental Protection Agency, 2023c). Converting CH_4 and N_2O to CO_2e, our total estimate lands at 1.825 million tonnes CO_2e in Swedish territory.[7] In terms of energy use, in 2019 maritime traffic used 26 TWh where 24 TWh was ascribed to international shipping (Swedish Energy Agency, 2023), while we estimate about 3 TWh.

Our current model iteration cannot differentiate between domestic and international traffic. However, total estimates for Swedish territory, both in terms of CO_2e emissions and energy consumption, lands above the statistic for domestic traffic and quite a bit below the statistic for international traffic which is reassuring. As mentioned above, differences in method and scope makes comparisons between our model and official statistics somewhat complicated, however, given the scopes and methods described in section 6.1, our estimates should be higher than domestic estimates and most likely lower than international estimates.

7.2.2. Reported statistics

Figure 6 shows a comparison between estimated average fuel consumption per nautical mile and corresponding values in MRV. Figure 7 shows the comparison for CO_2-emissions. The figures only cover ships larger than 5000 GT since that is the lower limit of inclusion in MRV.

Comfortingly, there seems to be some clustering around the 45-degree lines in both figures indicating correlation. However, the figures also seem to indicate that our model tends to underpredict. As discussed in section 6.2, it is hard to discern if this is only due to our modelling approach or if behavioural differences play a part as well.

However, one known reason for deviations is that our current model iteration assigns all ships one of three main fuels, MDO, LNG or Methanol. This is of course a simplification. As mentioned, in accordance with IMO (2020) we assume that ships using HFO swich to MDO when sailing within the Baltic Sea to comply with SECA. However, ships can also use HFO and still comply with SECA by using scrubbers that collect SO_x emissions. According to IMO's (2020) bottom-up approach, for the same engine type, using HFO will result in a higher fuel consumption compared to using MDO. In 2018 approximately 180 ships in the Baltic Sea used scrubbers and in 2021 the number had increased to 600 ships (Ytreberg, 2022). Thus, this might explain some underprediction, however, we cannot identify which ships in our sample that use scrubbers.

The fuel assumptions can also lead to overpredictions since the model does not consider the use of electricity, neither for propulsion nor the use of on shore power supply (OPS) when ships are at berth. Although the use of electricity for propulsion is rare, and thus should not significantly impact aggregate estimates, for the individual ships using electricity for propulsion estimates will be incorrect. The use of OPS is more common, however, it only affects the fuel consumption of the auxiliary engines and boilers and as shown in Table 4, auxiliary engines and boilers only account for 14 percent of the total estimated fuel consumption. So again, aggregated estimates should not be substantially affected, but estimates for individual ships might be.

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[7] Using a global warming potential of 25 for CH_4 and 268 for N_2O.

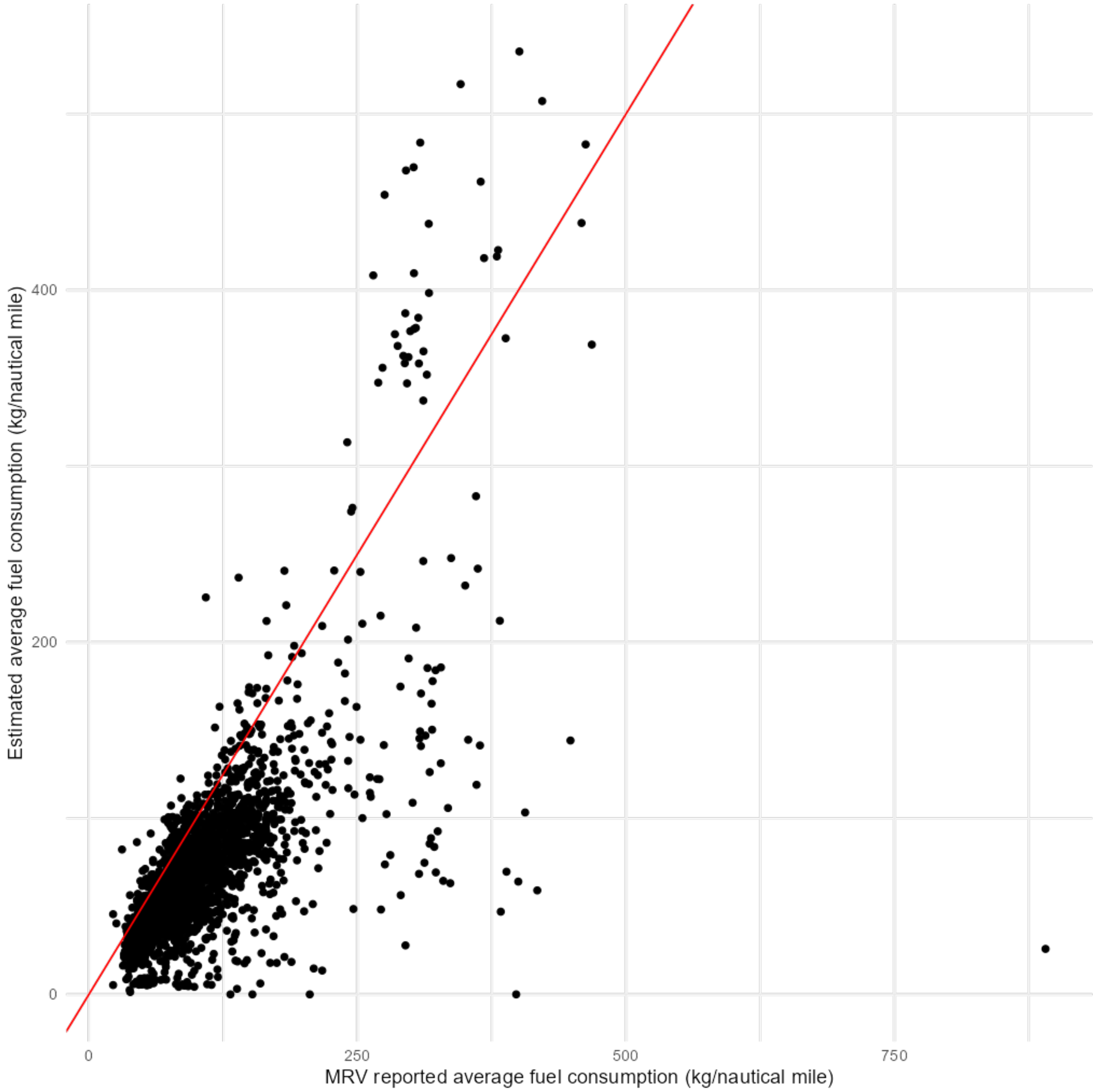

Figure 6. Comparison between MRV reported average fuel consumption and estimated average fuel consumption per ship larger than 5000 GT. The red line marks where points should land if there is no difference between the two.

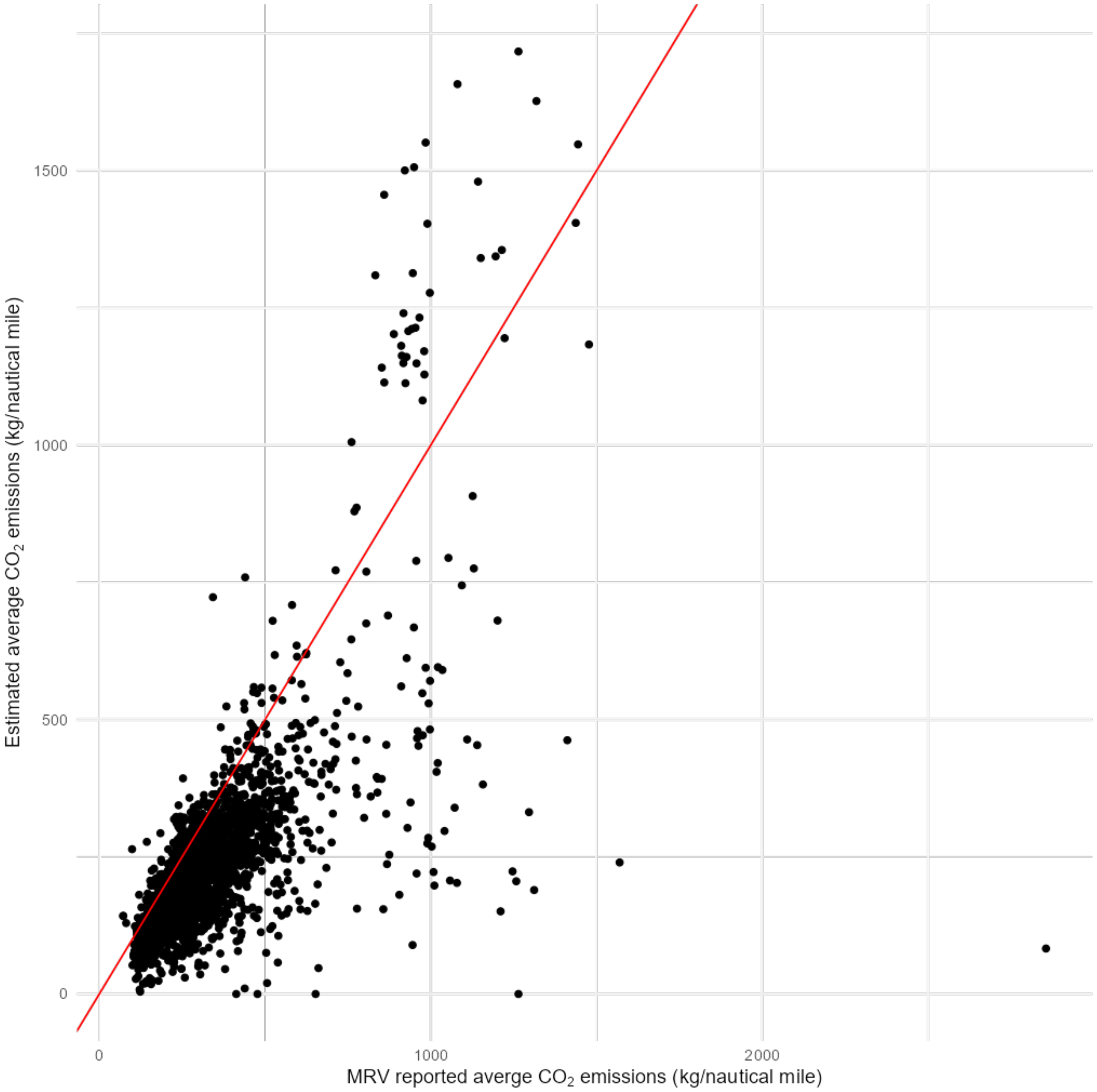

Figure 7. Comparison between MRV reported average CO_2 emissions and estimated average CO_2 emissions per ship larger than 5000 GT. The red line marks where points should land if there is no difference between the two.

7.2.3. Other estimation models

Figure 8 shows a comparison between Shipair estimated fuel consumption on Swedish territorial waters in 2018 and 2021 and our estimated fuel consumption in Swedish territory in 2019. As mentioned, the Shipair estimates only include voyages that departed and/or arrived at a Swedish port while our estimates include all voyages in Swedish territory (given the ships in our estimation sample).

Our estimate is higher than both Shipair estimates, by 15 percent compared to 2018 and 24 percent compared to 2021. Since we include more voyages, our estimates should indeed be larger. Looking at Swedish territory, it is also fair to assume that most ships sailing in Swedish territory also call at Swedish ports, thus differences in estimates of the two types of traffic should not differ by large magnitudes. However, since we cannot directly compare ship sample sizes, more precise conclusions than that our estimates do not appear obviously incorrect are hard to make.

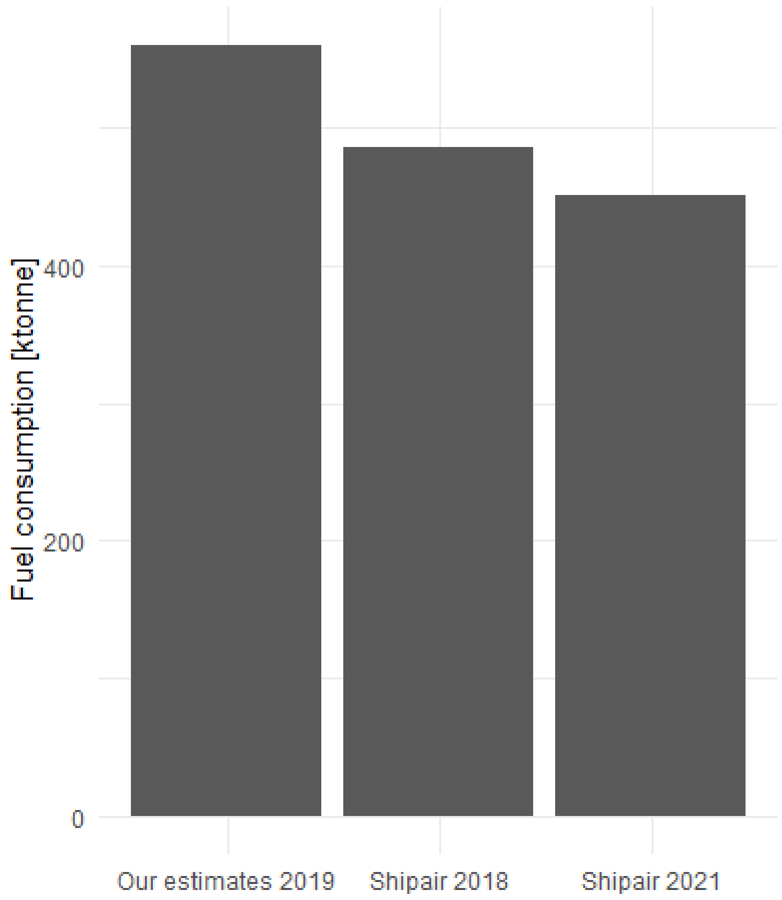

Figure 8. Comparison between our estimated fuel consumption for Swedish territory in 2019 and Shipair estimated fuel consumption on Swedish territorial waters from voyages that called at Swedish ports. Source for Shipair estimates: van Dongen, Johansson, & Windmark (2022).

Table 8 presents a comparison between our estimated air emissions and estimated emissions values presented in Johansson & Jalkanen (2016). As mentioned, the comparison estimates are based on a vastly larger sample, so we do expect our estimates to be smaller, which they are. Our relative estimates of CO_2, and NO_x compared to estimated fuel consumption are also similar.

As shown in Figure 9, other estimates differ in terms of relative size. As seen, Johansson & Jalkanen (2016) estimates a larger relative share of SO_x. IMO (2020) assumes the sulphur content of fuels has decreased over the years, but differences are small. For example, MDO changed from 8 percent sulphur content in 2015 to 7 percent in 2018. Lower sulphur content also results in a lower $PM_{2.5}$ emissions since PM_x emissions depend on the sulphur content of the combustion fuel.

However, the different relative shares of SO_x and $PM_{2.5}$ emissions seem a bit too large to only be explained by lower sulphur contents. Furthermore, the relative share of CO emissions in Johansson & Jalkanen (2016) is a lot larger compared to our estimates.

Table 7. Output from the STEAM2 model for the Baltic Sea in 2015 as presented in Johansson & Jalkanen (2016) compared to our estimates for Sweden and the Baltic Sea in 2019.

Entity	**Total estimate [ktonne]**	**Percentage difference compared to our estimates [%] (based on Table 4 and Table 5)**
Fuel consumption	4976	+ 72
CO_2	15916	+ 72
SO_x	10.27	+ 166
NO_x	342.85	+ 72
$PM_{2.5}$	10.44	+ 305
CO	22.79	+ 774

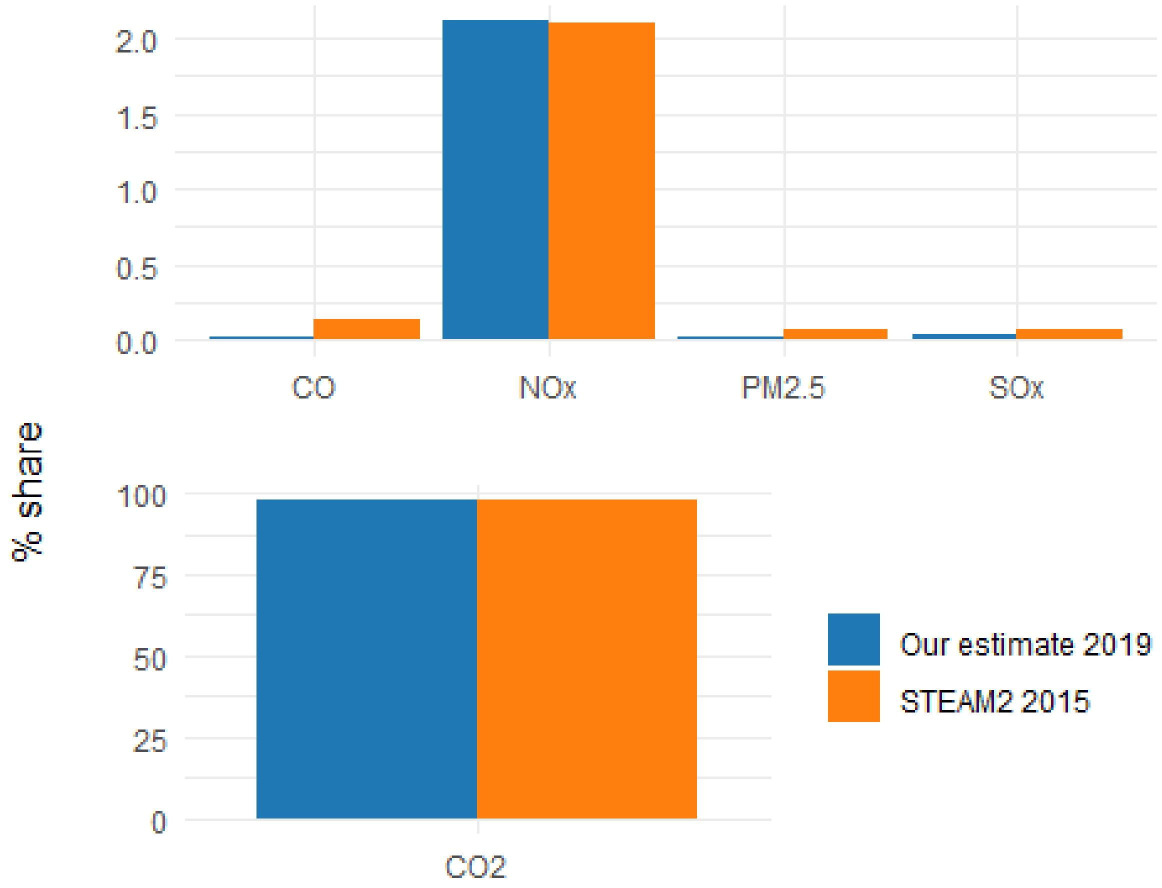

Figure 9. Relative share of STEAM2 estimated emission Johansson & Jalkanen (2016) compared to relative shares of the same emissions estimated in this memorandum.

8. Conclusion

This memorandum presents a model based on the IMO (2020) bottom-up method for estimating emissions to air from ships. With this, one may estimate spatiotemporal emissions (as well as fuel and energy consumption) for individual ships. The memorandum also includes example output from the model and validates it using different validation sources. Performing output validation is not easy. In this case, no validation statistic is a perfect match, and all show different aspects of the estimation. Nevertheless, none of the validations performed indicate that the estimates are obviously incorrect or significantly off in magnitude. Thus, considering this a proof-of-concept, we find that the model reaches reasonable outputs.

Ahead, many things might be improved. For example, details omitted from the IMO (2020) method may be implemented further improving the outcomes. Code efficiency may also be improved. New ship characteristics data covering a larger range of ships is much needed as well as more comprehensive AIS data. Another interesting topic to dive into would be to implement a calculation procedure for other externalities, such as noise, emission to water or congestion. Dispersion modelling is also an interesting way forward.

For the inspired reader, the model allows for output to be divided into subsets or aggregated as desired. Perhaps it is interesting to look at output by other subregions, ship categories, time periods or, for example, to answer questions such as what the emissions are in ports, what the emissions are per ship category or what the emissions are for each hour of the day. Perhaps it is interesting to assess trends or to study the impact of different policies.

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Appendix

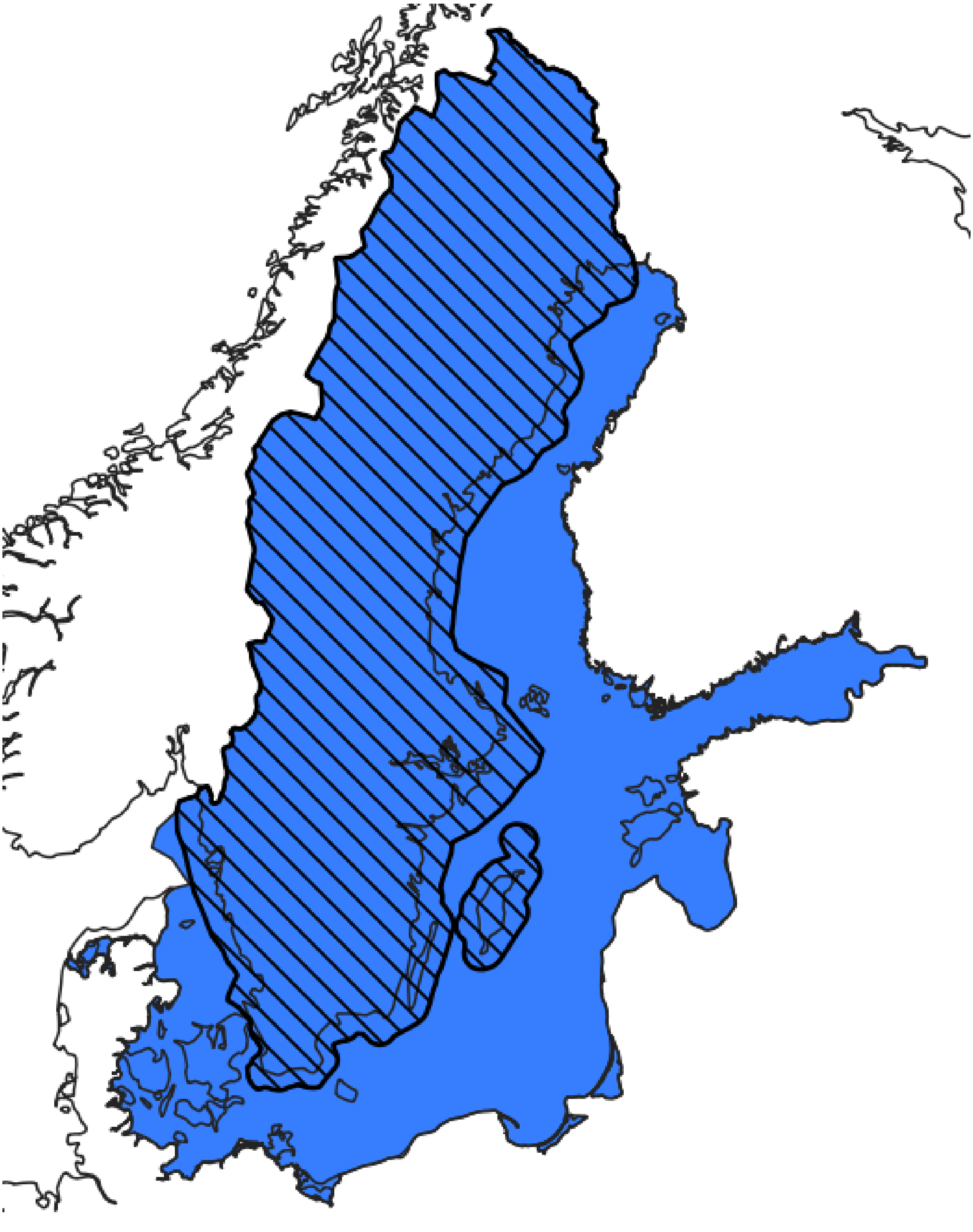

Figure 1. The geographical regions. The blue area is Sweden and the Baltic Sea marine area. The black backslash-dashed area is Swedish territory. Areas are created using (HELCOM, 2022; Flanders Marine Institute, 2019a; Flanders Marine Institute, 2019b; Flanders Marine Institute, 2019c; Marine Regions, 2005a). The country borders are from (Marine Regions, 2005b).

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