https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Ocean Science Discussions

Model for leisure boat activities and emissions - implementation for the Baltic Sea

Lasse Johansson[1], Erik Ytreberg[4], Jukka-Pekka Jalkanen[1], Erik Fridell[2], K. Martin Eriksson[4], Maria Lagerström[4], Ilja Maljutenko[3], Urmas Raudsepp[3], Vivian Fischer[6] and Eva Roth[5]

[1]Finnish Meteorological Institute, Erik Palmenin aukio 1, 00101 Helsinki, Finland
[2]IVL Swedish Environmental Research Institute, Aschebergsgatan 44, 41133 Gothenburg, Sweden
[3]Marine Systems Institute, Tallinn University of Technology, Ehitajate tee 5, 12616 Tallinn, Estonia
[4]Chalmers University of Technology, Gothenburg, 41296, Sweden
[5]University of Southern Denmark, Esbjerg, Niels Bohrs Vej 9-10, 6700, Denmark
[6]Helmholtz-Zentrum Geesthacht, Max-Planck-Straße 1, Germany

Correspondence to: Lasse Johansson (lasse.johansson@fmi.fi)

Abstract. The activities and emissions from leisure boats at the Baltic Sea have been modelled in a comprehensive approach for the first time, using a new simulation model leisure boat emissions and activities simulator (BEAM). The model utilizes survey data to characterize the national leisure boat fleets. Leisure boats have been categorized based on their size, usage and engine specifications and for these sub-categories emission factors for NO_x, $PM_{2.5}$, CO, NMVOCs and releases of copper (Cu) and zinc (Zn) from anti-fouling paints have been estimated according to literature values. The modelling approach also considers the temporal and spatial distribution of leisure boat activities, which are applied to each simulated leisure boat separately. According to our results the CO and NMVOC emissions from leisure boats, as well as Cu and Zn released from antifouling paints, are significant when compared against the emissions originating from registered commercial shipping in the Baltic Sea. CO emissions equal 70 % of the registered shipping emissions and NMVOC emissions equal 160 % when compared against the modelled results at the Baltic Sea in 2014. Modelled NO_x and $PM_{2.5}$ from the leisure boats are less significant compared to the registered shipping emissions. The emissions from leisure boats are concentrated on the summer months of June, July and August and are released in the vicinity of inhabited coastal areas. Given the large emission estimates for leisure boats, this commonly overlooked source of emissions should be further investigated in greater detail.

Keywords: shipping emissions, leisure boats, anti-fouling paint leach, the Baltic Sea

1. Introduction

Shipping activities and emissions for the global commercial fleet can be estimated with modelling approaches that utilizes AIS-data and combines this activity data with vessel's technical details (Jalkanen et al. 2012, Johansson et al., 2017). The vessel activities are well known due to the availability and high update rate of AIS-data and these activities can be combined with ship specific technical description. Together, these information sources facilitate the estimation of instantaneous water resistance, engine power use, fuel consumption and ultimately the emissions for each vessel. However, for private leisure boats there are no such direct activity data available that could be used to quantify the emission of air pollutants or water emissions of e.g. toxic compounds, so called biocides, from antifouling paints. Unfortunately, even top-down approaches for leisure boat emission estimation are difficult to utilize since reliable fuel consumption data for leisure

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

boats do not exist. As a consequence, emission inventories with temporal and spatial variability for the leisure boat fleet do not exist.

Since there are several hundred thousand leisure boats being actively used at the Baltic Sea in Sweden alone (Swedish Transport Agency (2010, 2015)) and their activities are mostly situated near populated coastal areas, there is a demand for detailed emission inventories for the leisure boat fleet. Due to its semi-enclosed properties, low biodiversity and slow water exchange, the Baltic Sea is considered to be particularly sensitive to pollution (Tedengren and Kautsky 1987). According to the latest integrated assessment of hazardous compounds, the entire Baltic Sea fail to reach good environmental status (GES), with respect to descriptor 8 and 9, as described in the Marine Framework Directive (HELCOM 2018). One significant emission source of hazardous compounds to the Baltic Sea is antifouling paints (Lagerström et al 2018; Ytreberg et al 2016). Antifouling paints are used to prevent fouling, i.e. the settlement and attachment of marine organisms such as barnacles and algae on boat hulls. The paints leach biocides into the water as a means to deter or poison fouling organisms (Almeida et al 2007). Most commonly, paints containing cuprous oxide (Cu_2O) are used, resulting in the emission of copper (Cu) to the marine environment (Dafforn et al. 2011). As the paints also contain zinc oxide (ZnO), added as a means to control the polishing rate of the paint, zinc (Zn) is emitted concurrently (Yebra et al 2016). Antifouling paints containing Cu_2O are biocidal products and require authorization at national level to be sold within a specific country. Specific restrictions for certain regions within a country may also apply (Lagerström et al., 2018). The biocidal content of antifouling paints available on the market can therefore differ both between and within Baltic Sea States. Hence, the environmental pressure of biocides along the coastline of the Baltic Sea is a function of boat density and prevailing legislation.

General concern of air pollution is associated with human health effects, which are strongly connected to air concentration of particulate matter (PM). These small particles enter human pulmonary system and have been shown to contribute to cardiovascular diseases and childhood asthma (Lepeule, 2012; Zheng, 2015). Particulate matter is not only emitted from internal combustion engines, but it is also formed as a result of atmospheric processes. There are several other pollutants which contribute to this process, like nitrogen oxides (NOx), volatile organic compounds (VOC) and ozone. For coastal areas, waterborne traffic, and especially boats, contribute to air quality problems. However, the data and existing literature concerning the air emissions of small boats is scarce. Some studied for the spatial and temporal characteristics of recreational boating do exist (Montes et al 2018; Sidman et al 2005; Gray et al 2011), however, isolated case studies for such characteristics alone are not yet sufficient for the estimation of dynamic emission datasets on a multi-national level.

Air emission limits of leisure craft engines (EU, 2013) are significantly different from those of large marine diesel engines used in ships (IMO Marpol Annex VI, 2008). This concerns especially carbon monoxide (CO) and hydrocarbon emissions. Also, the fuel efficiency of small recreational boat engines is poor compared to large diesel engines. For example, the recommended (EEA, 2016) consumption per power unit for small boat engines can be two to five times higher than a typical marine diesel engine.

In this paper we present the first holistic approach and a model (BEAM) for the assessment of leisure boat activities and emissions for $PM_{2.5}$, NO_x, non-methane VOC's (NMVOC), CO and selected antifouling paint (AFP) contaminants (copper and zinc). We have used the model for leisure boats at the Baltic Sea and in our modelling approach both the temporal and spatial distribution of emissions are considered. We have utilized a wide range of information sources and data processing techniques in our modelling, including: i) AIS-data processing for non-registered marine traffic, ii) scanning of the Baltic coastline satellite imagery iii) existing survey material for several Riparian states of the Baltic Sea, iv) available information on marina locations and sizes and v), local land use information near marinas.

Our aim in this study is to introduce the BEAM model and provide estimates for the annual leisure boat emissions for selected pollutants, for each Riparian state and boat category separately. We also aim to address the temporal and spatial variability of emissions and compare leisure boat emissions against the ones from the registered marine fleet. The presented modelling approach is not exclusive to the Baltic Sea, and can be extended to other regions, given that necessary input data sets are available.

2. Model formulation

In our modelling approach we assume that the whole leisure boat fleet to be modelled can be represented as a large collection of marinas. Each of these marinas host a number of leisure boats, which are assumed to operate in the vicinity of their marinas. Each of these marinas have a specified maximum capacity of boats they can host and the actual amount of boats at the marina can change dynamically depending on the time of year.

To illustrate the modelling process, let us consider a selected marina with a latitude coordinate c at a given hour of year t with a total amount of N leisure boats at the selected marina. The amount of boats at the marina can be represented as a collection of "bins" and the boats are distributed into these bins according to their boat class and engine-setup; for each of these bins an "average" leisure boat can be defined to represent all individual boats in the bin, while the nationality and location of the marina can affect the attributes of this averaged boat. The averaged attributes include, e.g., an average travel distance per year, speed, water surface area, engine load, installed engine power and the mix of used antifouling paint grades.

In the modelling approach all of these boat bins can be modelled independently. For simplicity let us consider a single boat bin i. Let $n_i(t)$ be the amount of boats of this type that are currently situated at the marina during this hour of the year. The amount of boats currently at the marina can be split into "active" and "inactive" boats. This split is to be done using a fraction of activities associated to this hour $f(t,c)$, also taking into account the climatic limitations in the marina as a function latitude (c). The amount of active boats $A_i(t)$ and inactive boats $I_i\,(t)$ are given by

$$A_i(t) = \frac{N_i D_i f(t,c)}{v_i},\qquad I_i = n_i(t) - A_i(t) \tag{1a-b}$$

where N_i is the maximum amount of boats (at 100% capacity) at marina of type i, D_i is the average annual travel amount for boat type $i, f(t,c) \in [0,1]$ is the fraction of total activities occurring during hour t and v_i is the average travel distance per hour for a boat of type i. In the modelling $A_i(t)$ is not restricted to be a natural integer value (e.g., values 0.1 or 1.5 can be used) but $A_i(t)$ is required to be less or equal to $n_i(t)$, which asserts that there can be no activities in the marina in case there are no modelled boats at the marina currently.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

The assessment and geographical distribution of emissions (to air and water) that are caused by $A_i(t)$ active boats and $I_i(t)$ amount of inactive boats at the marina is modelled as follows: Inactive boats do not release exhaust emissions but contribute to anti-fouling paint leach at a rate that is assumed to equal the rate for $A_i(t)$. The amount of fuel consumed [kg] during a time of one hour is given by

$$FC_i(t) = A_i(t)F_{hi}$$
$$F_{hi} = SFOC_i \times P_i \times EL_i \quad \text{(2a-b)}$$

where F_{hi} is the average unit fuel consumption, i.e., the amount of fuel a boat of type i consumes during one full hour of activity. $SFOC_i$ is the specific fuel consumption [g/kWh], P_i is the average engine power rating [kW] for boat bin i and EL_i [0,1] is the average engine load associated with the boat class with the assumed average speed). Finally, the emission releases for species k can be computed by multiplying $FC_i(t)$ with emission factors e_{ki}, given by

$$q_{ki}(t) = FC_i(t)e_{ki} \quad (3)$$

For active boats we assume that the geographic distribution of activities can be expressed with a), a finite collection of discretely mapped locations around the marina and b), a probability distribution for these mapped locations. Then the modelled emissions $q_{ki}(t)$ can be distributed to the mapped locations according to the distribution. The annual emission total Q_k [g] is given by

$$Q_k = \sum_{t=1}^{T} \sum_{m=1}^{M} f(t,c) \sum_{i=1}^{N} \frac{e_{ki}N_iD_iF_{hi}}{v_i} \quad (4)$$

where e_{ki} is the emission factor for species k for the boat bin i (of which there are N in total), T is the total amount of hours per year, m defines the marina of which there are M in total.

The modelling of Cu and Zn released from antifouling paints differs from exhaust emission modelling. The main reason is that both active and inactive boats act as emission sources. Secondly, the emission factors for contaminants are affected by the geographical distribution of the marina (different paints and release rates are applied). Finally, the emission factor, i.e. the release rates of Cu and Zn from antifouling paints, is dependent on time – specifically on the amount of days spent at sea (t_s). This means that the emission factor is time dependent and unique for each boat. For a selected boat in class bin i and time t, the hourly release rates of Cu and Zn for contaminant k is given by

$$q_{ik} = a_i e_k(t_s, \mathbf{r}) \quad (5)$$

where a_i is the average water surface area for boat type i and $e_k(t_s, \mathbf{r})$ is the emission factor for contaminant k that depends on the marina location ($\mathbf{r}$) as well as the amount of days spent at sea t_s. Given that the dynamic emission factor $e_k(t_s, \mathbf{r})$ can be pre-processed into marina and time dependent form $e_k(t, m)$ for each boat, the total annual release of contaminants is given by

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Ocean Science
Discussions

$$Q_k = \sum_{m=1}^{M} \sum_{t=1}^{T} \sum_{i=1}^{n(t)} a_i e_{ki}(t,m) \tag{6}$$

Where the index i iterates over all boats in the marina m that are present during the hour t.

2.1 The BEAM model

In order to determine the leisure boat emissions based on the assumptions presented in the paper, a new simulation model for the leisure boat activities and emissions has been developed. This model, called the "leisure boat emissions and activities simulator" (BEAM) is illustrated in Fig. 1. In general, the model combines leisure boat characteristics, a derived temporal profile and a geographic distribution of marinas to function. For the Baltic Sea - for which the model is being used in this study - we utilize survey data and other available study material to characterize national leisure boat fleets and derive emission factors for the modelled leisure boats (Sect. 2.2 and 2.3). For the assessment of general temporal profile of activities, AIS-data for the Baltic Sea has been collected for the years of 2014-2016. Using data filters we have separated a collection of ships from the AIS-data that exhibit the behaviour associated specifically to leisure boats; based on this filtered AIS-data we have used the STEAM model (Jalkanen et al., 2012) to predict a temporal variation of leisure boat activities (Sect. 2.4). For the spatial variability of activities we have compiled an extensive list of marina locations with boat count estimates. The list includes more than 3000 marina locations at the Baltic Sea hosting approximately 250 000 leisure boats.

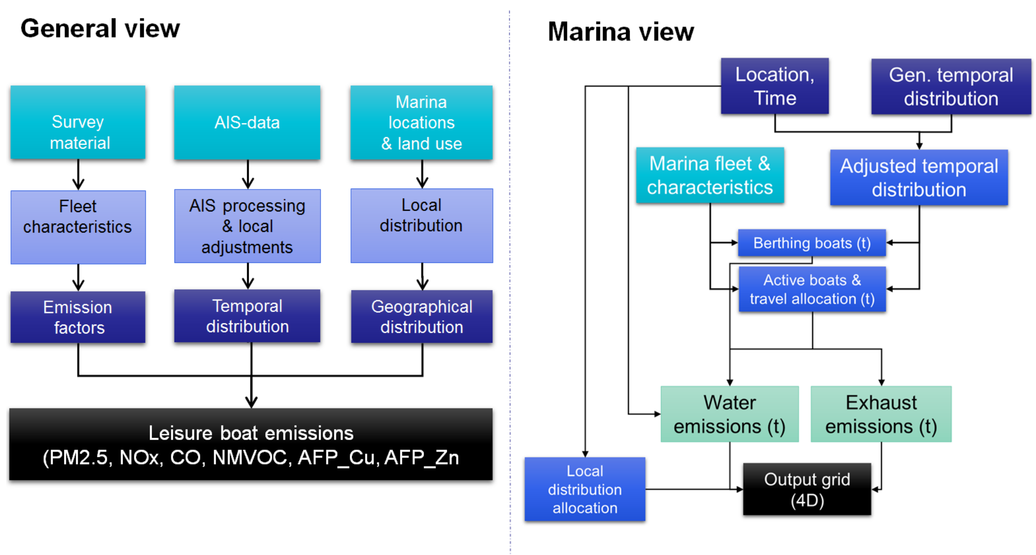

Figure 1a-b: A diagram describing the general modelling approach for the assessment of leisure boat activities and emissions.

The modelling approach in a more detailed overview has been illustrated in Fig. 1b. For each listed marina location the amount of boats and their fleet characteristics are assessed. Throughout the simulation, the date of appearance and departure of each modelled boat in marinas are being tracked, which will facilitate more realistic modelling of loads of Cu and Zn from anti-fouling paints. The temporal profile of leisure boat activities is modelled on an hourly basis, also taking into account the marina location and the estimated boating season length in that location. In particular, for each hour based on

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Ocean Science Discussions

the activity profile, boats are split into active and inactive (berthing) boats as in Eqs. (1a-b); the active leisure boats are simulated to operate in the coastal area near the marina, contributing to air emissions according to their fuel consumption, engine properties and emission factors associated to their engine setup (Sect. 2.3).

2.2 Boat characteristics

For the assessment of boat characteristics available information describing the leisure boat fleets for each riparian states of the Baltic Sea were gathered. The most important source for information was survey data and existing reports based on the surveys (Sweden (Swedish Transport Agency (2010, 2015), Germany, and Denmark), but also prior local modelling results (Finland) and port statistics (Baltic states and Denmark) were utilized. For some riparian states (Poland, Russia) little or no information was available to characterize the national leisure boat fleets.

The most detailed information on the characterization of national leisure boat fleet composition by far was available for the Swedish fleet. A detailed questionnaire survey was conducted by the Swedish Transport Agency (2010, 2015). The survey included qualitative information on the activities of 881 000 leisure boats in Sweden, including fleet characteristics, qualitative fuel consumption and travel habits. The Swedish fleet is the largest one at the Baltic Sea and the Swedish coastline covers a large part of the Baltic coastline, ranging from the northern parts of the sea all the way down to the southern parts of the sea. This national study uses a 4-tier classification for leisure boats (OSB, MB, LMB and LMSB, Table 1) and for each of them there are 5 possible engine setups, the exception being "open small boats" (OSB) which we assume are all gasoline powered. This characterization with 18 different boat "bins" was also adopted in the BEAM model.

Table 1: leisure boat classes and assigned attributes based on Swedish survey data (Swedish Transport Agency, 2010 and 2015). For different engine setups three values have been specified in the following order: share of engine setup, the average maximum engine power rating and the average engine load.

Description	**OSB** Open small boat (engine <7kW)	**MB** Motorboat (engine>7kW, no overnight stay)	**LMB** Large motorboat with overnight stays	**LMSB** Large motor sailing boat
Share of fleet	11 %	53 %	22 %	15 %
Water surface [m2]	7	11	16	26
Travel distance [km/a]	57	228	323	695
Average speed [km/h]	12	28	29	29
Older diesel engines	-	8.7% 40kW(50%)	21% 150kW(50%)	40% 150kW(10%)
Newer diesel engines	-	11% 40kW(50%)	27% 150kW(50%)	51% 150kW(10%)
Older Gasoline 2-stroke	28%, 6kW(70%)	17% 50kW(50%)	5.4% 80kW(50%)	1.4% 50kW(10%)
Newer Gasoline 2-stroke	56% 6kW(70%)	33% 50kW(50%)	11% 80kW(50%)	2.8% 50kW(10%)
Gasoline 4-stroke	15% 6kW(70%)	31% 50kW(50%)	36% 80kW(50%)	4.8% 50kW(10%)

For practical modelling purposes the qualitative survey information on travelling and fuel consumption habits have been converted into quantitative information. As an example, in the questionnaire the number of boats that report travelling 5 to 10 nautical miles per year is available, and we interpret that each of these vessels travel 7.5 nautical miles on the average (see Appendix B for more information). To obtain average operational speed we have used the survey data that describes the maximum operational speed multiplied with 0.7 (for LMSB this information was not available and the speed value is assumed to equal to the one listed for LMB).

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

The survey also contains detailed information about engine setups (e.g., stroke type of the engine, fuel type) which was used for all the four leisure boat classes. To calculate the fuel consumption and emissions, assumptions are needed to be made about the effective engine load factor, i.e. the fraction of installed engine power that is used on average while the boat is moving. There is no data available for this parameter and as a base case we have used the value in the Guidebook (EMEP/EEA 2016) of 50 %. For sailboats we have modified this value to account for that these boats do not use the engine for all travelling. Further, for OSB the installed engine power is usually low and used with a slightly higher average engine load factor (70 %).

The Swedish national survey data also describes some qualitative fuel consumption statistics for the boat categories but these are not utilized directly in the modelling. Rather, we have used this information to verify that our assumptions on the key factors that define the fuel consumption rates are in agreement with the total fuel consumption statistics derived from the survey data (Appendix B). It should be noted that for most of the Riparian states other than Sweden, such a detailed characterization of the leisure boat fleet was not available; therefore the Swedish survey information is widely utilized in this study also for the other Riparian states, for which less information is available. The exceptions are for the Danish and German fleet for which existing information was available for "Share of fleet" in Table 1. A description of the available information on the fleet characteristics for other Riparian states has been presented in the Appendix A.

2.3 Emission factors and fuel consumption

Emission factors and fuel consumption factors are given for in EMEP/EEA 2016 for different boat types, fuel type (diesel/gasoline), and engine types (2-stroke/4-stroke for Otto engines) and emission class (divided into older conventional engines and engines following the 2003/44 EU standard). The boat types in EMEP/EEA 2016 do not exactly overlap the boat types used in the Swedish survey and therefore we have matched these to get usable emission factors (Table 2). It can be noted that the emission factors for CO and NMHC for older Otto-engines are very high; the same applies for NO_x for Diesel engines.

Table 2: Specific fuel consumption (SFOC) in g/kWh and emission factors in g / kg of fuel consumed for different boat classes and engine setups. "2S" and "4S" stand for the two-stroke and four-stroke gasoline engines. "_2003" stands for the newer type of engine (older type if not specified). "DSL" stands for diesel engine setups.

	Engine setup	SFOC (g/kWh)	PM (g/kg)	NOX (g/kg)	NMVOC (g/kg)	CO (g/kg)
LMSB	2S	791	12.6	2.5	322	539.8
	2S_2003	791	12.6	2.5	53.9	232.6
	4S	426	0.2	16.4	50.7	348
	DSL	281	5	64.1	7.7	19.8
	DSL_2003	281	3.6	34.9	6.7	18.6
LMB	2S	791	12.6	3.8	215.5	472.8
	2S_2003	791	12.6	3.8	39.8	169.4
	4S	426	0.2	28.2	21.1	293.4
	DSL	275	4.4	31.3	7.2	19.8
	DSL_2003	275	3.6	31.3	6.1	18.6
MB	2S	791	12.6	2.5	322	539.8
	2S_2003	791	12.6	2.5	57.5	232.6
	4S	426	0.2	16.4	50.7	431.9
	DSL	281	5	64.1	7.7	19.8
	DSL_2003	281	3.6	34.9	6.3	18.6
OSB	2S	791	12.6	2.5	322	672.6
	2S_2003	791	12.6	2.5	57.5	556.3
	4S	426	0.2	16.4	50.7	1032.9

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

For the modelling of emissions the averaged boat characteristics shown in Table 1 gives the average total annual travel distance (D_i) and the average speed for Eqs. (1a-b). For each boat class and engine setup the unit fuel consumption F_{hi} can be computed based on Eq. (2b) by combining the data shown in tables 1 and 2. By combining this information with the emission factors shown in Table 2 the emission can be computed given that the amount of active boats is known.

2.3.1 Antifouling

As previously mentioned, the antifouling paint market can differ between and within Baltic Sea states and Sweden has the most restrictive antifouling legislation. In Sweden, the use of biocidal paints is completely prohibited in the Gulf of Bothnia, and in the Baltic Proper (south of Öregrund to Trelleborg) products holding only low (5 - 8 %) Cu_2O are allowed. Only on the Swedish West Coast (North of Trelleborg), is the antifouling paint market comparable with the other Baltic Sea states, with authorised paints holding up to 40 % Cu_2O. The release rate of biocides have shown to be affected by salinity, and a lower release rate is expected in the less saline Baltic Sea as compared to fully marine waters (Ferry and Carritt, 1946, Rascio et al. 1988, Kiil et al. 2002, Adeleye et al. 2016). Recent field studies have also shown a 2-fold increase in copper release rate when five antifouling coatings were exposed in Gothenburg (salinity 14 PSU) as compared to when exposed in Stockholm archipelago (salinity 5 PSU) (Lagerström et al, 2018).

Table 3: Properties of the antifouling paints assumed to be used in the study. Data was obtained from the Swedish Chemical Agency's pesticides register, from the paints' safety data sheet and technical data sheet.

Antifouling paint		Cu_2O (%)	ZnO (%)	Authorized usage
A	Mille Light	6.9	10 – 25	Boats> 200 kg with main mooring on the East or West coast of Sweden.
B	Biltema Baltic Sea	7.5	20 – 25	Boats> 200 kg with main mooring on the East coast of Sweden.
C	Cruiser One	8.5	10 – 25	Boats> 200 kg with main mooring on the East or West coast of Sweden.
D	Biltema West coast	13	15 – 20	Boats> 200 kg with main mooring on the West coast of Sweden.
E	Mille Xtra	34.6	10 – 25	Boats> 200 kg with main mooring on the West coast of Sweden.

Four different geographical areas (defined in Table 4 and shown in Fig. 6) were designated here to account for the regional differences in the antifouling paint market as well as the impact of salinity on the release rate of Cu and Zn. Release rates of Cu and Zn from five different coatings available on the Swedish market at two salinities (5 and 14 PSU) were obtained from Lagerström et al. (2018) as it is the only currently existing study with relevant release rates for the Baltic Sea. Information about the antifouling paints are shown in Table 3. A salinity of either 5 or 14 PSU was assumed for each area. The paint usage in "Western Baltic", "Southern Sweden" and "Northern Sweden" were based on the Swedish regional restrictions (Table 3). For area "Other", only paints available on the Finnish market (all but one) were considered. In Lagerström et al. 2018, the release of Cu and Zn was studied over a time period of 84 days at various time intervals (between day 0 and day 7, 14, 28, 56 and 84). Polynomial curves were fitted to the measured cumulative release of Cu and Zn, allowing the modelling of release rates with a daily resolution. For each geographical area, the average daily release rates of Cu and Zn from the paints was calculated (Fig 2). In Lagerström et al. (2018), the release of Cu and Zn were only studied for up to 84 days. In addition, very thin paint layers were used which could contribute to uncertainties in the prediction after day 56 at the higher salinity (14 PSU) as the measured release could have been affected by the paint becoming depleted in Cu and Zn, resulting

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

in an (erroneous) lower release rate. After day 56, a constant release rate was therefore assumed for all geographic areas to avoid any such potential error.

Table 4: Geographical areas and their assumed antifouling paint use. For each area, the release rates of the used paints were averaged. Release rate calculations were based on release rates from Lagerström et al. where these were derived for 5 and 14 PSU. The salinity assumption for each area is also listed here.

Area	Geographical extent	Paints used	Salinity
Western Baltic	Swedish West coast (Trelleborg to Norwegian border) and German coast (West of Stralsund)	D, E	14 PSU
Southern Sweden	Swedish East coast from Trelleborg to Öregrund	A, B, C	5 PSU
Northern Sweden	Swedish East coast from Öregrund to the Finnish border	None (prohibited)	None
Other	Coastlines of Finland, Estonia, Latvia, Lithuania, Poland and Germany (East of Stralsund)	A, B, D, E	5 PSU

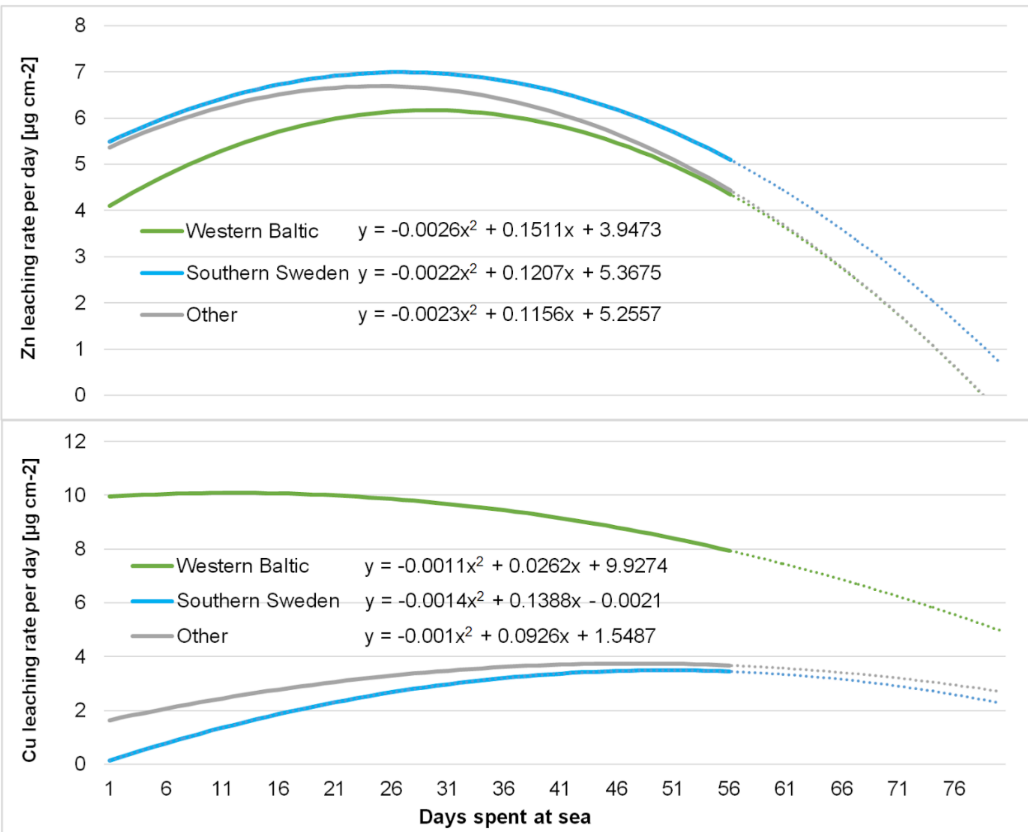

Figure 2: Cu and Zn contaminant leaching rates as a function of days spent at sea for different areas of the Baltic Sea, as described in Lagerström et al. 2018.

2.4 Temporal profile of activities

AIS-transmitters are mandatory for vessels larger than 300 gross tons. However while leisure boats in general are much smaller than 300gt, some boat owners (which probably represent a small subset of LMB and LMSB vessel owners) use AIS voluntarily, e.g., for safety reasons. As a consequence, while the AIS-data cannot facilitate reliable leisure boat modelling with full temporal and spatial coverage by itself, the data can still be used for the assessment of a generic temporal variation for the activities of leisure boats. In this study we have used the STEAM-model results based on AIS-data for the years 2014-2016 to identify vessels that exhibit leisure boat -like behavior. The AIS-data was given by Helcom, by the courtesy of the Baltic Sea riparian states. The identification criteria, which were designed based on the survey data for leisure boats, are as follows:

- **Seasonal activities:** The ship must be active only during the ice free season from 1st April – 30th October.
- **Low annual travel amounts:** Total travel distance for the ship must not exceed a selected threshold value of 1000 km per year.
- **Small and non-commercial:** The vessel is non-IMO-registered. In case the length has been specified in static AIS-data the length must be less than 15m.
- **Low utilization:** The relative monthly cruising time for the ship must not exceed a selected threshold of 5 %.

Using the selection criteria described above approximately 800-1500 vessels, depending on the year, were identified. It should be noted that the strict identification criteria may filter out some leisure boats, however, the goal is to extract a large representative dataset and not the largest possible dataset; the risk of false-positives (non-leisure boat vessel interpreted as one) is significantly reduced and the derived temporal profile does not require all leisure boats to be accounted for.

Using the AIS-data from these identified vessels the STEAM model was used to assess the hourly temporal profile for leisure boat travel distances for the years of 2014, 2015 and 2016. This process has been done by modelling the travel kilometers of the unidentified vessels with STEAM and normalizing the resulting temporal profile to sum up to 1. Also, the three annual profiles were aligned (e.g., so that the days of week match), averaged and normalized into a single temporal profile, which has been presented in Fig. 3.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Ocean Science
Discussions

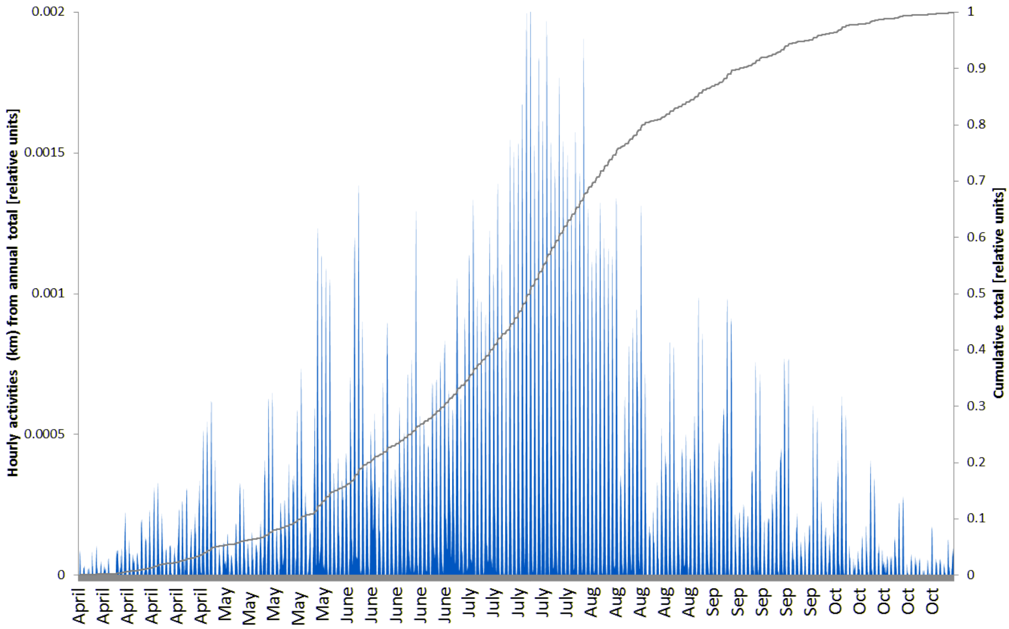

Figure 3: Estimated hourly temporal profile (blue bars) of leisure boat activities at the Baltic Sea based on AIS-data and modelled travel distances with the FMI-STEAM model. The secondary vertical axis (right) shows the cumulative temporal profile (gray line) as a function of time.

The Swedish national survey data also describes temporal patterns for leisure boat activities on a monthly basis. In Fig. 4a, a comparison of the derived temporal profile using AIS-data is compared against the reported monthly profile given by the survey data for all Swedish boats. The survey includes in-land use of boats, because the distinction was not made to boats along the Baltic Sea coastline and inland water areas. Regardless, the strong correlation of these two suggests that the temporal profile given by AIS-data can be used for the assessment of leisure boat activities. In Fig. 4b, it can be seen that the different leisure boat categories exhibit similar temporal patterns throughout the season, based on the survey data. Thus the derived AIS-pattern for temporal activities can be applied to each boat category without additional modifications.

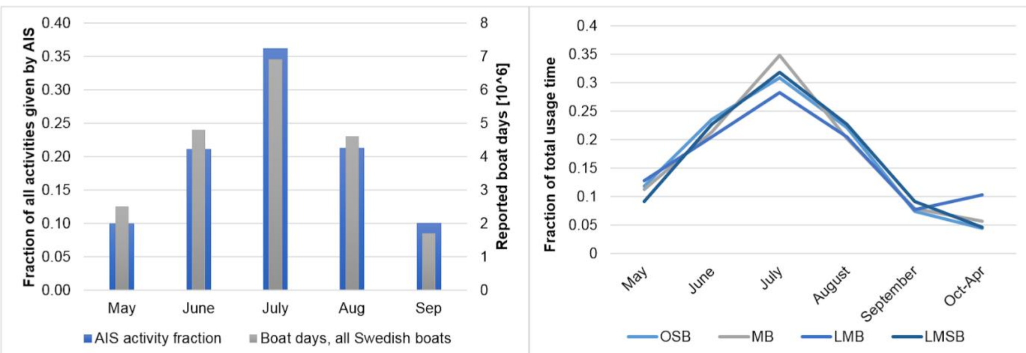

Figure 4a-b: In a), left, comparison of the temporal profile given by AIS versus reported boat day's for all Swedish leisure boats in 2010. In b), right, the reported temporal profiles for each leisure boat class separately is presented based on the reported boat days for all Swedish boats.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

2.4.1 Temporal profile adjustment

The temporal profile based on AIS describes the leisure boat activities at the Baltic Sea in general and can be used for the assessment of $f(t, c)$ used in Eqs. (1,4). However, this temporal profile still lacks the seasonal characteristics that occur for different parts of the Baltic Sea. In the northern parts of the sea the boating season is shorter and starts later during the early summer. In order to take this effect into account, a survey (interviews with marina representatives) was conducted to investigate the temporal patterns of marinas hosting leisure boats at varying latitudes. The survey was conducted by interviewing the marina captains of 11 marinas along the Swedish east and south coastline. The interviews were conducted on the 14th and 16th of March 2018. The marina captains were asked to give the number of boats in their marina and assign an approximate percentage of the marina occupancy during the boating season. This included the date when boat owners normally start to launch their boats in spring, dates for which the marina captains could assign the marina occupancy and the date when boat owners normally has taken up their boats from the marina. Instead of using a standardized questionnaire, where the marina captains should assign a specific occupancy to fixed dates, the marina captains were allowed to select dates for which they were confident to give a good estimate of the occupancy percentage. The survey results have been presented in Fig. 5 and locations of corresponding marinas are shown in Fig. 6.

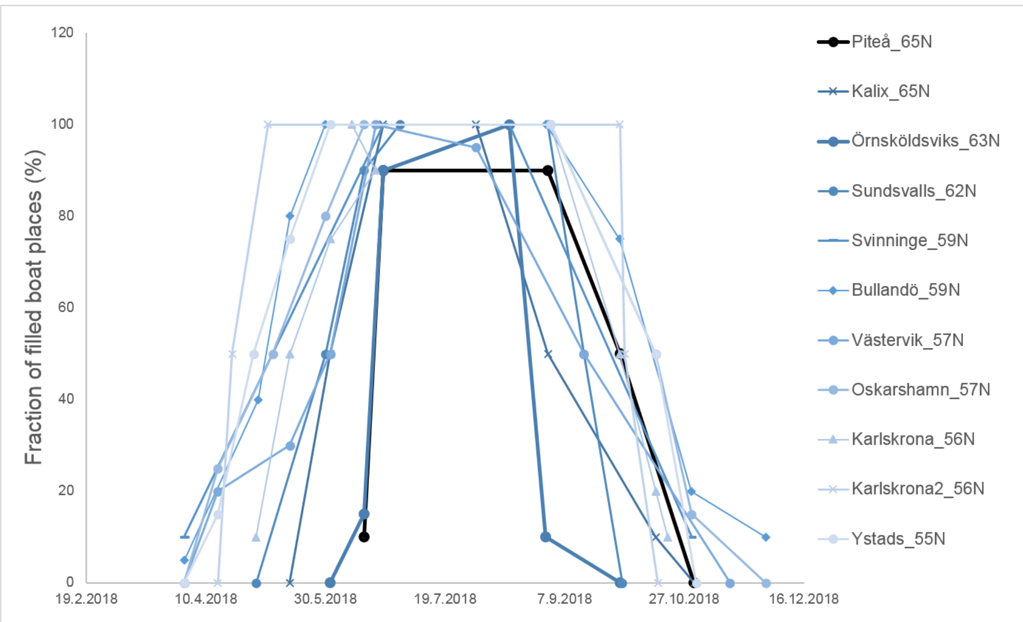

Figure 5: Seasonal patterns based on survey data for selected marinas at the Swedish coast, indicating the utilization rate of marinas as a function of time.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Ocean Science Discussions
Open Access

Figure 6: Location of the Swedish boat marinas which were used to determine the boating season length in the Baltic Sea area. Different antifouling paint zones have been illustrated with lines. Dark blue = "Northern Sweden". Cyan = "Southern Sweden". Green: "Western Baltic". Coastal areas for which the AFP-zone has not been defined belong to the zone "Other". Map provided by OpenStreetMap. © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License.

Based on this survey data a simple statistical model was set up to estimate the season properties, which includes the length (L) and the mid-season day (D_M) of the season as a function of latitude coordinate in WGS84-projection (c). In addition, a "ramp-up" (L_U) and "ramp-down" (L_D) length measured in days were also evaluated which describe the amount of days the boat counts increase to 100 % and decreases down to 0 % respectively. The simple linear statistical model, which is valid at the Baltic Sea only (53ºN < c < 66ºN), has been defined as follows:

$$D_M = 1.8c + 102,$$
$$L = 720 - 9.1c,$$
$$L_U = 0.2L,\ L_D = 0.33L \qquad \text{(7a-c)}$$

The temporal profile adjustment has the following implications: in the northern marinas the season is shorter and starts later, which will affect the distribution of emissions. Secondly, all activities given by the general temporal profile when no boats

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

are present at the marina are ignored; however we still assume the same amount of total activities regardless of latitude and therefore normalize the marina-specific profile to sum up to 1. According to the survey data and Eqs. (7), when the boat season begins ($D_M - L/2$) the marina capacity utilization reaches 100 % rapidly in 3-4 weeks; when the season ends ($D_M + L/2$) this utilization rate has decreased to 0 % in 4 -6 weeks' time. For a more concrete example, let us consider a marina near Stockholm ($c = 59.0ºN$). According to Eqs. (7) the length of the season is 180 days, starting around 28th of April and ending around the 27th of October. The "ramp-up" amount of days is estimated to be 36 days and therefore by 3rd of July the marina is expected to have reached 100 % capacity. After the beginning of September the capacity gradually starts to decrease and after approx. 60 days the marina is expected to be empty until the season starts again next year.

2.5 Geographical distribution of boats and activities

The modelled geographical distribution of leisure boat activities is a product of two separate processes: first, the list of marina locations with boat count estimates will outline the general geographical distribution at the Baltic Sea. Secondly, at the vicinity of each marina location the boat activities are allocated on a higher resolution, taking into account land cover information. A list of leisure boat harbours (boat place counts, location) for each riparian state was collected based on survey data, existing national studies and satellite image analysis. The satellite image analysis for marina locations and sizes was performed manually (Fig. 7a). However, for the Swedish coastline a digital mapping of the marinas provided by the Swedish EPA was used that described the geographic areas of the marinas; these areas were converted into boat count estimates, which were manually verified with satellite image analysis.

The full list of marinas includes more than 3000 locations for leisure boats at the Baltic and accounts for more than 250 000 boats in total. Based on the Swedish survey data 37 % of boat owners report using offshore facilities and trailers to harbor their boats. Additionally, a significant fraction of the boats are located on private shores outside of marinas. To take this into account in the modelling we assume that the listed marina locations are expected to harbour only 50 % of the total fleet and we therefore multiply each marina boat count with a factor of 2; in other words, we assume that for each boat in a marina there is another boat not accounted for and its activities can be associated to the area near the marina location. This assumption is consistent, for example with the estimates of Daehne et al, (2017), who report 43 000 German boats for the Baltic Sea coastline. Our boat count based on satellite images yields 19 900 boats for the German Baltic Sea area, but become consistent with Daehne et al (2017) estimate if offshore locations are considered.

In Table 5 the amount of boats in marinas, private shores and offshore facilities for all Riparian states are shown. Also the fleet composition has been shown in the table, which has been assessed based on survey data. For the Finnish fleet it should be noted that total surveyed boat count (195000) is for fuel consuming boats without distinction between the Baltic Sea and inland waters. In another study by the Finnish authorities[1] it has been estimated that there are over 90000 boats at the Finnish coast, which is consistent with our estimates based on satellite analysis – once the multiplication with a factor of 2 is done.

[1] A report "Antifouling valmisteiden ympäristöriskinhallinta ja kestävä käyttö" by TUKES written in Finnish is available at: https://tukes.fi/tietoa-tukesista/materiaalit/biosidit/

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Table 5: National leisure boat counts based on survey data (Appendix A) and coastal satellite image analysis. Total modelled amount of boats equals the preliminary boat count (marina) added with the estimates for boats at private shores and in trailers. The described fleet composition corresponds to the percentages used for SB, MB, LMB and LMSB types.

Riparian State	Boats, marina	Boats, private shore	Boats, offshore/trailer	Total Modelled	Total survey	Fleet type composition [%]
Sweden	113900	84286	29614	227800	231900	11,53,22,15
Finland	50600	37444	13156	101200	195000,90000	11,53,22,15
Denmark	59600	44104	15496	119200	-	10,34,22,34
Germany	20000	14800	5200	40000	42700	10,15,20,55
Russia	2450	1813	637	4900	-	11,53,22,15
Estonia	2330	1724	606	4660	-	11,53,22,15
Poland	1720	1273	447	3440	-	11,53,22,15
Latvia	1080	799	281	2160	-	11,53,22,15
Lithuania	685	507	178	1370	-	11,53,22,15

2.5.1 Local geographical distribution

The Swedish surveys (Båtlivsundersökningen, 2010 and 2015) indicate that the clear majority of leisure boats regardless of type operate very locally near their marinas. Based on this information it is sufficient for the scope of this study to allocate all leisure boat activities in the vicinity of marinas, although some marina-to-marina activities for the larger boat classes will be misallocated in this estimation. The overall process of analyzing the coastline for marina locations with boat counts and deriving local distributions of activities is described in Fig. 7.

For each marina we form a list of local discrete locations for possible boating activities defined with a selected resolution of 0.2 km x 0.2 km. The maximum range for this mapping has been set to (50 km) and land-use data has been used to omit all discrete locations that are not located at the Baltic Sea. For each of these locations the distances to the marina (r_m) and to the nearest coastline (r_c) is evaluated. For r_c in particular, land-use information (OpenStreetMap) has been used in the assessment also taking into account islands.

For each listed discrete location for possible boating activities, we compute an activity probability $p(r_m, r_c)$. In this study we have opted for a simple exponential function to express $p(r_m, r_c)$, given by

$$p(r_m, r_c) = e^{-a(r_m + br_c)} \tag{8}$$

where the term $r_m + br_c$ can be regarded as the "effective" distance from the marina that also considers the distance to the nearest coastline, and the factor a defines how strongly the probability decreases as a function of this distance. Presumably the factors a and b depend on the leisure boat class, for example, the larger boats are used for longer travels and can safely be operated farther away from the coastline. However, due to lack of usable data we have settled for generalized empirical values for a and b that are the same for each boat class. Finally we normalize the probabilities so that they sum up to 1.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

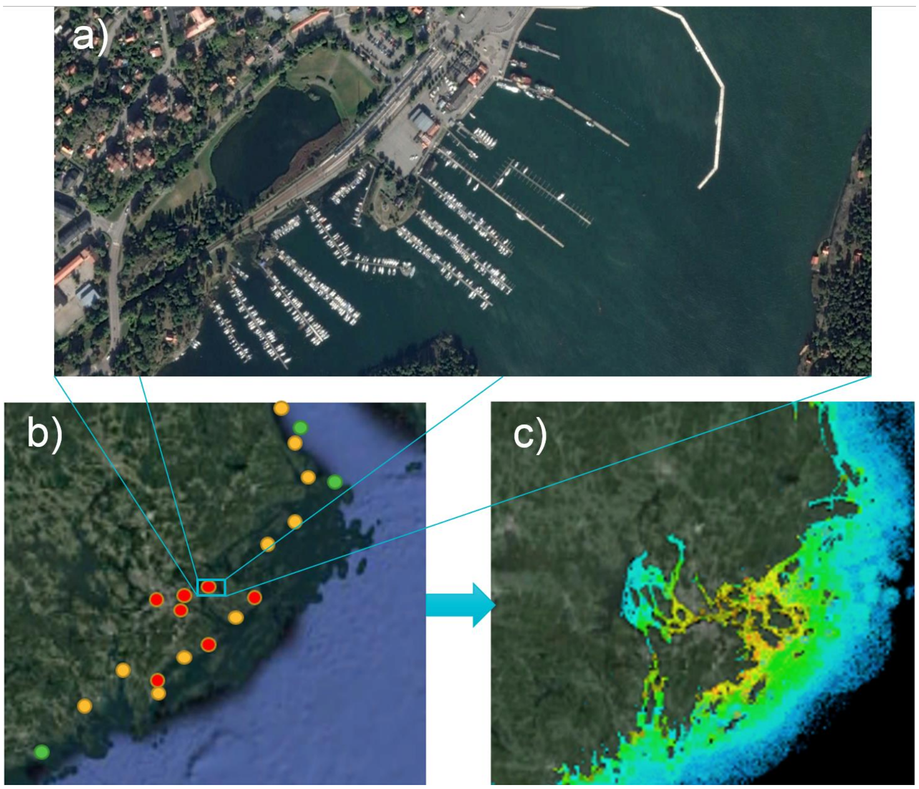

Figure 7a-c: The overall process for geographical distribution of activities. In a), an example of satellite imagery used to calculate the number of boat places in a small boat marina (58.9 N,17.95 E, Sweden). Iterating over the analysis of a) a complete mapping of marinas and boat counts is formed (b). In c) an example is given when emissions of selected marinas have been allocated according to Eq. 8. Image produced with ©Google Earth.

In the study by (Montes at al, 2018) the distribution and intensity of recreational boating in the South-East US has been presented. The findings of the study performed in Florida are not fully applicable to leisure boats at the Baltic, however, the observed boating patterns do exhibit clear dependencies to both the coastline distance and the marina distance. Due to the lack of data we assume the effects of r_m and r_c to be equal and set value for b to 1 and use a value of 0.2 for a, which we estimate to lead to similar distributions than was obtained with the generalized additive model (GAM) in (Montes at al, 2018).

3. Results

The BEAM model was used to estimate the hourly emissions of leisure boats at the Baltic Sea starting from 1st of March until the end of November. It should be noted that in the production of input datasets a heterogeneous collection of survey material, AIS-data, and satellite imagery was utilized dating between 2010 and 2017. Therefore the presented results do not represent any specific year in particular. The modelled annual total emissions, fuel consumption and travel amounts have been presented in Table 6.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Table 6: Modelled leisure boat fuel consumption, emissions and travel distances at the Baltic Sea, for different flag states and boat types. Flag state category "Other" includes Russia, Estonia, Latvia, Lithuania and Poland.

	Gasoline [ton]	Diesel [ton]	CO [ton]	NMVOC [ton]	NOx [ton]	$PM_{2.5}$ [ton]	AFP_{Cu} [ton]	AFP_{Zn} [ton]	Travel [km^6]
All boats	37800	21800	13200	3930	1220	400	57	49	162
Sweden	19300	8920	6750	2030	520	198	15.9	18.6	67
Finland	8620	3990	3010	904	232	88	5.5	8.4	30
Denmark	6890	5600	2410	694	298	78	23.8	13.7	41
Germany	1610	2620	577	159	128	23	10.3	6.3	19
Other	1390	634	487	146	37	14	1.1	1.6	4.8
OSB	739	0	468	102	3	8	2.6	2.3	2.9
MB	23700	2040	8560	2910	239	234	15.7	15.7	51
LMB	12900	11600	3860	801	582	121	12.2	10.9	34
LMSB	569	8150	349	120	392	39	26.3	19.6	74

According to the results, almost half of the gasoline fuel consumption, CO-, NMVOC- and $PM_{2.5}$ emissions comes from the Swedish leisure boat fleet. For exhaust emissions and fuel consumptions Denmark and Finland have the second and third largest contribution, in changing order depending on the pollutant species; Germany has the 4th largest contribution for these estimates. Together these 4 flag states contribute 96 % - 99 % of exhaust emissions from all leisure boats at the Baltic Sea. The combined fuel consumption is estimated to be approximately 60 ktons of which the clear majority of this is gasoline fuel.

Quantitative estimates for Swedish leisure boat fuel consumption for all boat classes can be derived from the Swedish leisure boat survey. Based on these survey material estimates, the modelled fuel consumption for both gasoline and diesel are in fair agreement with modelled values (Appendix B). This agreement gives an indication that the used average speeds, engine loads and engine power ratings can be considered realistic at least for the Swedish fleet. Emissions of NO_X, $PM_{2.5}$ and CO for the whole Swedish leisure boat fleet (also comprising boats in inland waters) have been determined by the Swedish EPA for the year 2018 and was 1273 tons (NO_x), 148 tons ($PM_{2.5}$), 2744 tons (NMVOC) and 18854 tons (CO) (Swedish EPA, 2018). Based on the Swedish survey data, clear majority of MB and LMSB boats and half of the LMB boats operate at the Baltic Sea for the Swedish fleet; based on this, the emission totals given by Swedish EPA seem higher for NO_x and CO while $PM_{2.5}$ is lower than the presented BEAM predictions would suggest.

The boat class –specific emission totals shown in Table 6 show that the motorboats (MB) are responsible for 74 % of released NMVOC emissions, mainly due to high amount of gasoline used with old 2-stroke gasoline engines. The motorboats are also modelled to be responsible for 65 % of CO emissions and 58 % of $PM_{2.5}$ emissions. Together, LMB and LMSB release 80 % of NO_x emissions due to the higher use of diesel fuel. For all modelled emission species the smallest boat category OSB has very low shares in general.

The loads of Cu and Zn from antifouling paint are affected by sea salinity as well as the types of paint allowed and used in the different parts of the Baltic Sea. As a consequence, 58 % of the Cu emissions and 42 % of Zn originate from the relatively short combined coastline of Denmark and Germany due to the combination of the higher ambient salinity (resulting in higher leaching rates) and types of paints allowed. In contrast, the much longer combined coastline of Finland,

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Ocean Science
Discussions
Open Access

Russia, the Baltic States and Poland produces only 11 % of Cu and 20 % of Zn emissions. For antifouling paint contaminants the contribution from LMSB boats is the largest (26.3 tons), due to the large water surface area (26 m^2) for this boat type.

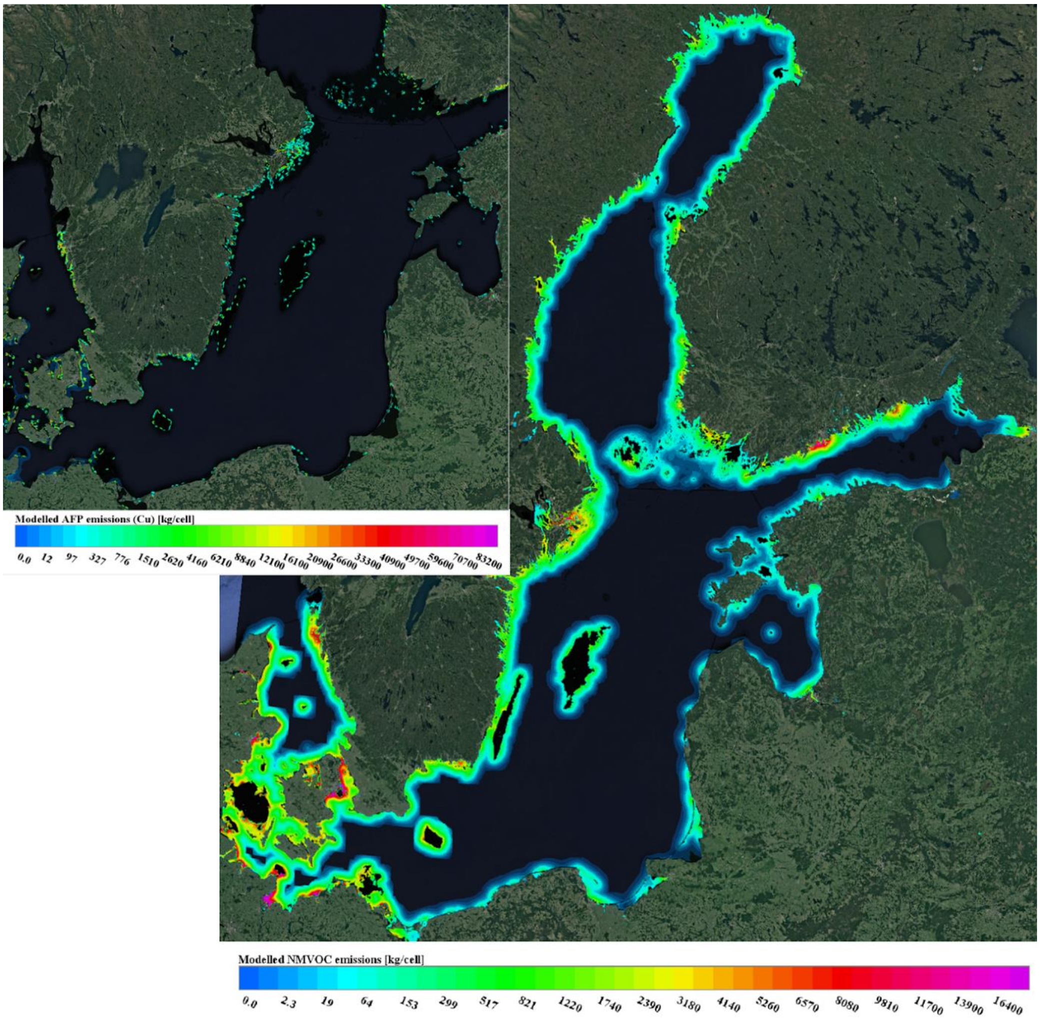

Figure 8: Estimated geographical distribution of NMVOC exhaust emissions and the copper emissions from antifouling paints for a selected area. Satellite image provided by ©Google Earth.

In Fig. 8 the estimated NMVOC emissions have been presented. It can be seen from the figure that there are several hotspots, including the archipelago near Stockholm, Helsinki area, Copenhagen, Gothenburg and Lubeck area. It should be noted that the modelled geographic distribution of emissions on a local level is only indicative due to the lack of usable data to parametrize Eq. 8. The copper emission from antifouling paints have also been presented in the figure (upper left) for the South-Western part of the Baltic Sea and in contrast to NMVOC, the copper emissions are heavily concentrated on marina locations. The reason for this is that all boat classes are expected to have very low amount of active hours per year, which in turn causes the main source of releases to be stationary boats at the marina locations. As an example, consider OSB's that have an average annual travel amount of only 57 km which is reached with less than 5 hours of activity during the year.

The geographical distribution of exhaust emissions is difficult to predict due to the lack of activity data available for leisure boats. As was discussed in Sect. 2.4 we used AIS-data for 2014-2016 and the STEAM model to isolate a small subset of leisure boats, which were used to assess the temporal distribution of activities. Presumably, this set of boats is a subset of the larger boat classes (LMB, LMSB) and the geographical distribution of modelled fuel consumption for these boats should be comparable to BEAM predictions for the largest boat classes. We used this AIS-data to model the fuel consumption of these small number of boats for 2014-2016 and the averaged results of this modelling have been presented in Fig. 9. For comparison, the BEAM modelled fuel consumption for LMSB-boats have been presented in the figure. To be able to compare these modelled distributions, the modelling resolution has been set identical and the grid cell values have been scaled to be in proportion to the average grid cell content. It can be seen from the figure that the AIS-driven approach show marina-to-marina boat activities which have not been considered in BEAM. In both approaches the clear majority of activities (travelling amount and thereby fuel consumption) coincide near coastal areas and are heavily concentrated on the same hot-spots - the area near Lubeck being an exception.

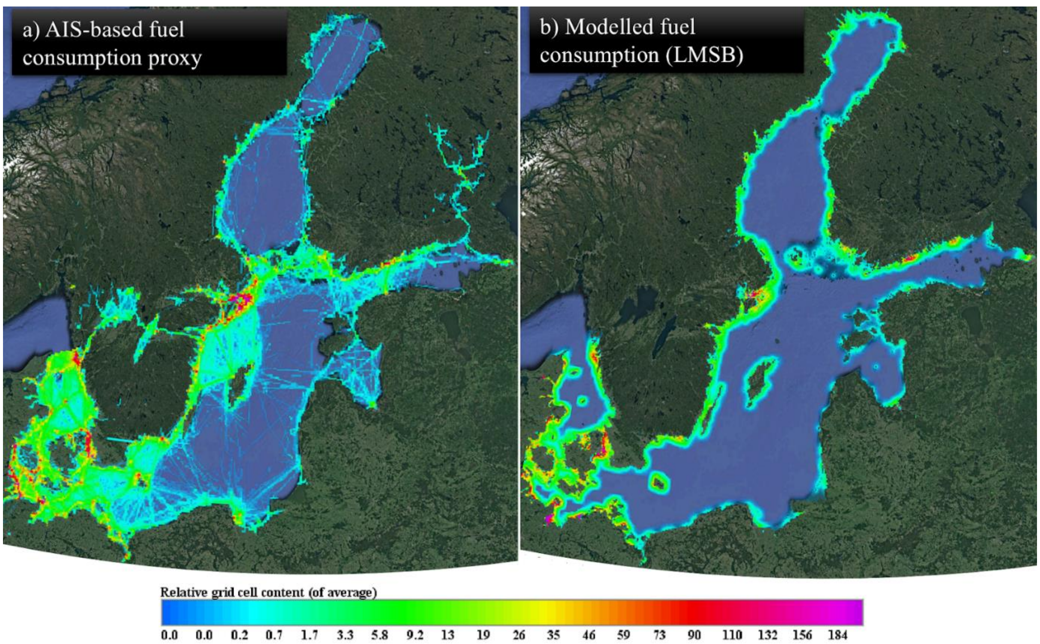

Figure 9: Estimated distribution of leisure boat fuel consumption in terms of grid cell average. In a) the predictions based on AIS (STEAM) are shown. In b) BEAM predictions for LMSB fuel consumption has been shown. Satellite image provided by ©Google Earth.

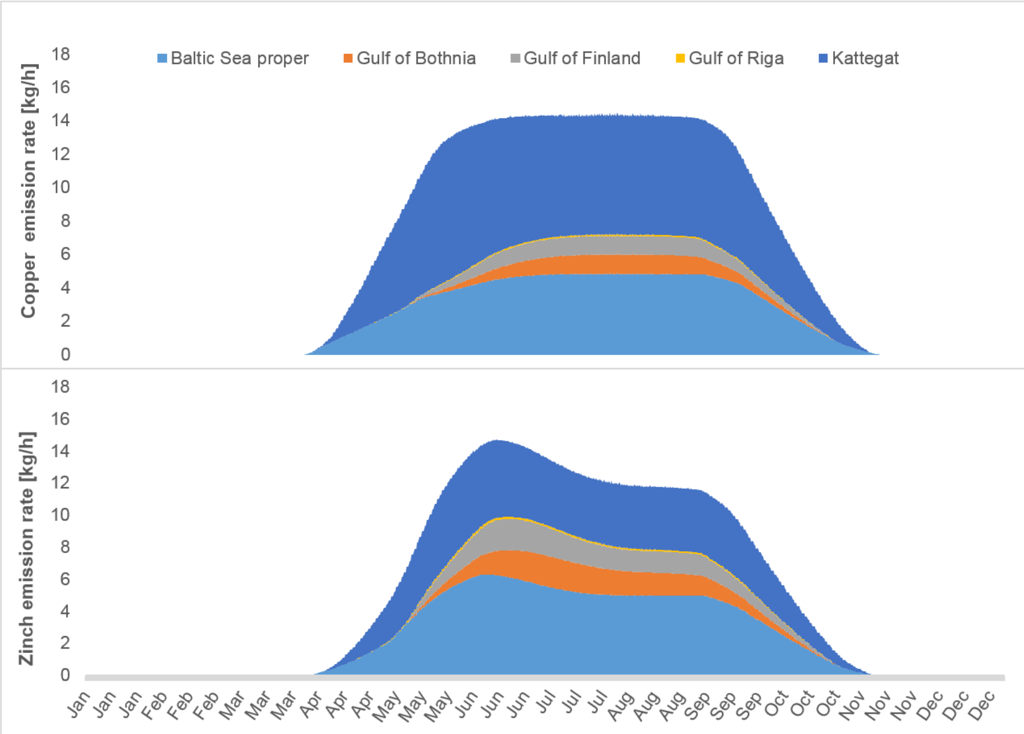

Figure 10: Modelled antifouling paint contaminant leaching rates for different parts of the Baltic Sea.

The modelled emissions have a clear seasonal patterns and this is especially evident for the modelled antifouling paints. The hourly emission rates for copper and zinc contaminant is presented in Fig. 10 for different parts of the Baltic Sea. As it can be seen from the figure, copper and zinc emissions have different temporal patterns which are caused by the dynamic emission factors shown in Fig. 2 (Lagerström et al., 2018). According to the model, the total zinc emission release rate peaks at the beginning of June whereas the releases of copper are more evenly distributed during the season. The two dominant regions for copper and zinc emissions are clearly Kattegat and the Baltic Sea proper.

3.1 Leisure boat emissions versus commercial shipping

The emissions and impacts of registered shipping at the Baltic have been studied thoroughly, and these known emissions have been compared against the leisure boat emissions to gain a better perspective on the presented total emissions. In Fig. 11, the total emissions of registered shipping in 2014 using the STEAM-model have been presented. For commercial shipping, the activities and emissions are somewhat evenly distributed during the year whereas leisure boat emissions are heavily concentrated on the summer months. To highlight this contrast, the leisure boat emissions have also been compared against the commercial emissions in July.

From this annual comparison it can be seen that while the total travel kilometers of leisure boats are comparable to the total of the registered fleet, the fuel consumption, NO_x and $PM_{2.5}$ is significantly lower (1.2 %, 0.4 % and 2.7 % respectively) for leisure boats. However, the zinc contaminants from the antifouling paints and CO are lower but comparable to those of the

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Ocean Science
Discussions

registered fleet and copper contaminants are 19 % from the respective total. Since NMVOC emission factors for leisure boat engines are 1-2 orders of magnitude larger than for the large well-optimized marine diesel engines, the NMVOC-emissions from the leisure boats is estimated to be significantly larger than the emissions from registered vessels. In July the relative importance of leisure boat emissions with respect to the commercial fleet is greatly emphasized in this comparison. In particular NMVOC's are 500 % larger, CO emissions are 140 % larger and zinc emissions are 80 % larger for leisure boats than the emissions from registered traffic during July. It should also be noted that the emissions released by leisure boats are heavily concentrated near populated coastal areas, for which Fig. 8 gives an indication.

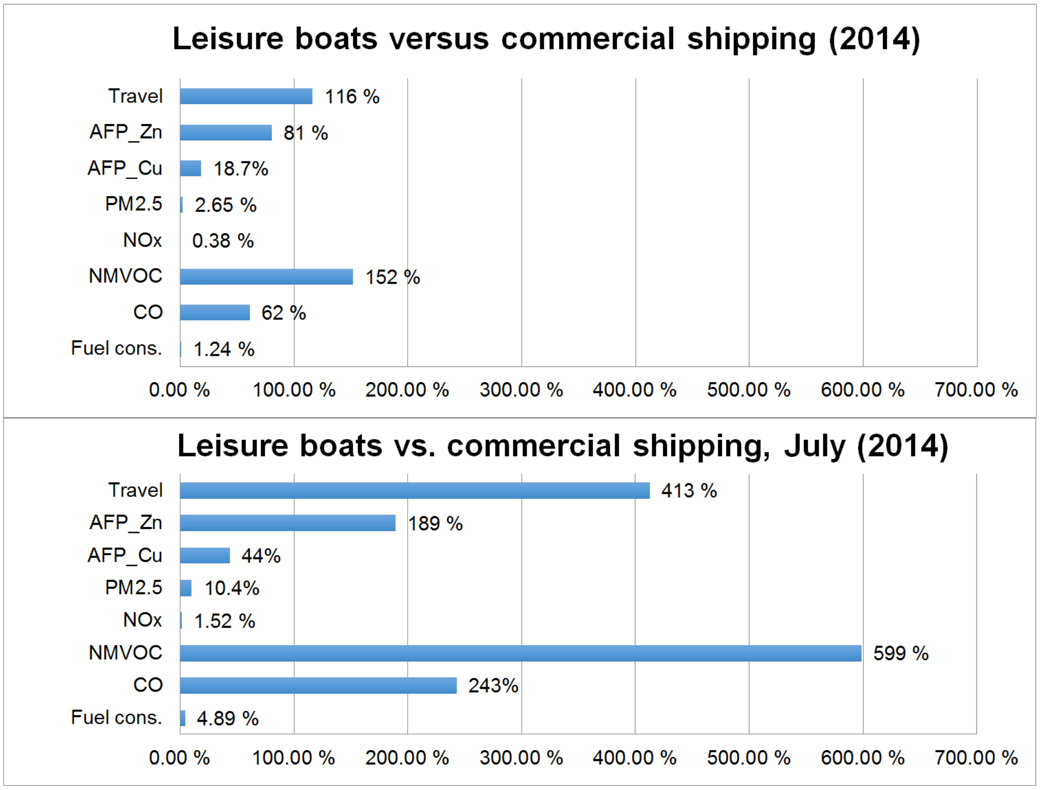

Figure 11: Modelled leisure boat emissions, fuel consumption [kg] and travel kilometers with respect to those of the commercial fleet in 2014, and separately for July 2014. Value of 100 % indicates equal contribution from small boats and commercial shipping.

4. Conclusions

A new simulation model for the assessment of leisure boat activities and emissions at the Baltic Sea (BEAM) has been presented. In the model both the temporal and spatial distribution of emissions is considered and leisure boat fleet characteristics can be customized, e.g., according to available survey material. For this study at the Baltic Sea we have utilized a wide range of information sources and data processing techniques in our modelling, including AIS-data, coastline satellite imagery, survey material, data on marina locations with boat counts as well as land-use information.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Ocean Science Discussions
Open Access
EGU

The leisure boat emissions have previously been largely unknown at the Baltic Sea and the results given by the presented model improves this situation. Leisure boat emissions, being heavily concentrated on the populated urban areas during the summer months, are rarely used – and most often neglected - in dispersion modelling or other impact assessment modelling work such as marine ecosystem modelling (e.g. Raudsepp et al., 2019). The presented model can be used to produce dynamic emission datasets for selected exhaust pollutants and water contaminants, which could be utilized in the above-mentioned studies in the future.

According to our results some of the pollutants emitted by leisure boats are very substantial when compared against the emissions originating from registered, commercial shipping activities at the Baltic Sea. CO emissions equal 70 % of the registered shipping emissions and NMVOC emissions equal 160 % with respect to commercial shipping. However, modelled NO_x and $PM_{2.5}$ from leisure boats are clearly less significant with respect to the registered shipping emissions. In absolute terms the modelled emissions are 13 ktons for CO, 3.9 ktons for NMVOC, 0.4 ktons for $PM_{2.5}$, 1.2 ktons for NO_x, 57 tons for copper- and 49 tons for zinc water contaminants. It should be noted that most of the modelled emissions occur during the summer months, during which their relevance nearby marina areas are further increased. Given the relatively large emission estimates for leisure boats, especially for NMVOC, this commonly overlooked source of emissions deserves to be further investigated in greater detail. Also the impact on air quality should be studied further with measurements and dispersion modeling. It should be noted that while the leisure boat emissions are significant with respect the commercial fleet, the modelled exhaust emissions are still fairly small when compared against, e.g., national total anthropogenic emissions. For example, the reported NMVOC emissions for Finland are reported[2] to be 88 ktons in 2016.

Clear majority of the emissions can be attributed to Swedish, Finnish and Danish boats, of which the main contribution originates from motor boats (MB, LMB), but the leisure boat fleets have the potential to become larger in Russia, Estonia, Latvia, Lithuania and Poland in the future. The motorboats are especially dominant in the emissions of NMVOC, CO emissions, largely due to the large amount of motorboats with old 2-stroke gasoline engines. Therefore, an effective approach to reduce leisure boat impacts on marina areas could be to reduce the amount of these engine setups, however, a more thorough impact analysis should be conducted first. As older engines are replaced by newer combustion engines or electrical engines the situation will naturally improve. For anti-fouling paint leach the largest boat category has the highest impact. The smallest contribution in terms of exhaust and water emissions comes from the smallest boat type, OSB.

The uncertainty margin for the presented results is fairly high, which should be narrowed down with further development and research. The most notable sources for error in this study are arguably the national total boat counts. The used satellite analysis is difficult to conduct and is subject to interpretation. Also, the boats on private shores and the use of offshore trailers is a matter of concern for the modelling and the survey material gives only an indication on the amount of boats that are outside marinas. As a second source of error, the fleet composition and the split of engine setups are difficult to customize for other Riparian states of the Baltic Sea besides Sweden, which has by far the highest quality survey material available. Third, the used emission factors for different engines are based on averaged Swedish data compiled several years, which introduces uncertainties. Fourth source of error is that our treatment of temporal and spatial patterns for boats does not consider the different boat classes independently, but a generalized profile is used. Finally, the geographical distribution

[2] Reported Finnish emissions can be seen from: https://www.ymparisto.fi/fi-FI/Kartat_ja_tilastot/Ilman_epapuhtauksien_paastot, visited 18.12.2019.

of activities on a local scale is based on model that was set up with very low amount of evaluation data and marina-to-marina activities could not considered. Arguably the highest confidence can be given to the temporal profile of activities based on AIS-data analysis. Even for the temporal profile further model development is required so that a specific year can targeted and, e.g., take into account the impact of weather.

5. Appendices

Appendix A: Fleet description for Riparian states other than Sweden

Fleet characteristics for Finland

Study conducted by VTT (Finnish Maritime Administration, 2005) concluded that in Finland, there was about 390 000 small boats with a motor. The national small boat registry (Finnish Transport Safety Agency, 2015) lists over 195 000 small boats powered by an engine, which is about half of the previous assessment. The discrepancy of boat numbers may be partly because new boat registry requires an active registration of all boats with an engine. If a boat is not actively used, it may not be included in the small boat registry. The information contained in the small boat registry is only an indication of the total fleet of boats, because it does not distinguish between boats used in Baltic Sea coastline and those used in inland waters. For this reason, the satellite imagery from the Finnish coastline was searched for small boat marina locations. Vessel counting was done based on available places for boats, not the actual boats themselves, because it was likely that some of the boats were in use during the time satellite image was taken. On the other hand, counting the boat places automatically assumes 100 % usage of available capacity. Regardless, 475 boat marinas were found in the Finnish coastline, Turku archipelago area and Ahvenanmaa islands. These marinas had space for over 50 600 vessels. The vessel characteristics for the Finnish fleet are based on the Swedish survey. No official records exist for fuel sold to small boats in Finland.

Fleet characteristics for Denmark

The Danish Maritime Authority registers leisure boats over 20GT (type of boat, type of propellant or homeport is not available), but no register of all Danish leisure boats was seen to be available. Based on the information found from http://www.sejlnet.dk/havneguide it was possible to locate 338 marinas in the Danish part of the Baltic Sea. This information included the geo-reference of the marina, the number of mooring places as well as contact details for further contact to individual harbours. The largest of the harbours were contacted by telephone and email to inquire whether the marina had a separate fuel station, so that an estimation of fuel consumption could be made. 15 of the biggest marinas fit the conditions and were able to inform the fuel consumption in their marina, although the fuel consumption statistics were not ultimately utilized in this study. It was estimated that the listed marinas had space for over 59 600 vessels according to satellite image analysis. The fleet composition was observed to be different than the one reported for the Swedish fleet.

Fleet characteristics for Germany

A telephone survey formed the basis of the bottom-up statistic, which was used to obtain information on the annual fuel sales in liters (diesel and petrol) from the German water petrol stations in the Baltic Sea. All 39 petrol stations on the German Baltic Sea coast were contacted and information from 35 stations was received and recorded. Research was conducted prior to the survey on the number of water petrol stations and their connected berth.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

The number of berths is relevant to the research, since the study examined whether the revenue per berth is similar in different regions on the German Baltic Sea coast and can therefore be transferred to other regions. Since there are no exact statistics on how many German leisure boats exist in the Baltic Sea, this study relates to a previous study which equates the number of berths to the number of existing vessels.

An online questionnaire formed the basis of the top-down statistics. The survey was conducted by 265 German leisure boat owners who sail the Baltic Sea. The survey asked technical questions regarding the characteristics of their vessel, such as motor and fuel consumption, as well as information on their activities. Activities were divided into two categories: popular short trips and popular long trips. The boats in the survey were classified into three sub-types: sailing boats with engines, sailing boats without engines, and motorboats.

It was estimated that the listed marinas had space for approx. 20 000 vessels according to satellite image analysis, which was approximately half of the amount of vessels according to survey material. The fleet composition was observed to be different than the one reported for the Swedish fleet.

Fleet characteristics for Poland, the Baltic states and Russia

Local authorities were contacted for existing inventories and surveys for leisure boat activities. Unfortunately, inventories were not available and leisure boat activity in the Baltic Sea for Poland, Lithuania, Latvia, Estonia and Russia were estimated based on marina locations (listed port areas, satellite images) and supporting information. The mix of gasoline and diesel use was taken from the Swedish survey data.

Small harbours along the eastern coast of the Baltic Sea were positioned based on reference locations in http://en.seaclub.lv/ports/estonia/ [link accessed 2018-04] and their size was estimated by satellite images. The total number of crafts for Estonian leisure boats were estimated to be 1075 crafts, which compares well to national registry database (700 yachts + small ships which include 134 motorboats and 206 workboats).

Appendix B: Fuel consumption estimates for the Swedish fleet and survey data processing

A large part of the used fleet characteristics originate from the Swedish survey studies (2015), such as the average travel distances and fractions for different engine setups. The survey data is by its nature, qualitative and does not easily provide quantitative information. To overcome this, the survey data has been processed so that it is more usable for the modelling.

The first step in this process was the removal of "blank" answers such as ("Not sure"), which were selected quite often by the users. We simply assumed that the users with blank answers would follow the same distribution as the other users did with their answers. In other words, we scale the amount of non-blank answers so that they in total sum up to 100 % of all questionnaire users. Such a blank-removed questionnaire summary for fuel consumption habits has been shown in Table B1.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Table B1: Swedish leisure boat survey material (fuel consumption and boat counts) and derivatives processed based on the data. "L" corresponds to litre.

		OSB	MB	LMB	LMSB
Boats total (Sweden)	**uses gasoline**	58002	181195	71164	12517
	uses diesel	24929	17788	31556	35886
of which at the Baltic		29.4 %	61.6 %	48.5 %	70.2 %
Specified gasoline usage	**Quantitative (L)**	**OSB**	**MB**	**LMB**	**LMSB**
0 – 25 L	12.5	75.1 %	32.0 %	13.2 %	70.5 %
25.1 – 75 L	50	19.2 %	32.0 %	25.6 %	27.7 %
75.1 – 250 L	162.5	5.6 %	26.4 %	48.9 %	1.8 %
250.1 -1000 L	625	0.1 %	9.7 %	9.6 %	0.0 %
>1000 L	1500	0.0 %	0.0 %	2.9 %	0.0 %
Boats (Baltic, gasoline)		24417	111631	34547	8787
Specified Diesel usage	**Quantitative (L)**	**OSB**	**MB**	**LMB**	**LMSB**
0 – 25 L	12.5	100.0 %	48.0 %	21.7 %	42.3 %
25.1 – 75 L	50	0.0 %	22.3 %	26.6 %	34.7 %
75.1 – 250 L	162.5	0.0 %	7.5 %	20.2 %	17.2 %
250.1 -1000 L	625	0.0 %	10.4 %	16.3 %	5.7 %
>1000 L	1500	0.0 %	11.9 %	15.3 %	0.0 %
Boats (Baltic, Diesel)		0	10959	15319	25192

We transform the qualitative answer possibilities (e.g., 0-25L) into quantitative using the average value of the specified range (e.g., 12.5L). For the last fuel consumption range (>1000L) the averaging is not possible, and we have assumed a value of 1500 liters as the quantitative value. For other statistics such as travel distances we have assumed a 150% value for the last answer option in case the range has been left open in a similar fashion.

Based on the survey material the total amount of gasoline and diesel boats have been specified for each boat class. In addition, the fraction of boats at the Baltic Sea has also been specified, which in turn yields the amount of gasoline- and diesel powered boats at the Baltic. Finally, the total fuel consumption estimates for each boat class can be computed by combining a) the boat counts, b) the quantitative fuel consumption thresholds and c) the distribution of boat owner answers. These totals has been shown in Fig. B1 and for comparison the BEAM model predictions has been also shown in the

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Ocean Science Discussions

figure. For the comparison the fuel consumption totals have been presented in metric tons, which we have obtained by from the quantities in litres by using a density of 0.8kg/litre for both Diesel and gasoline.

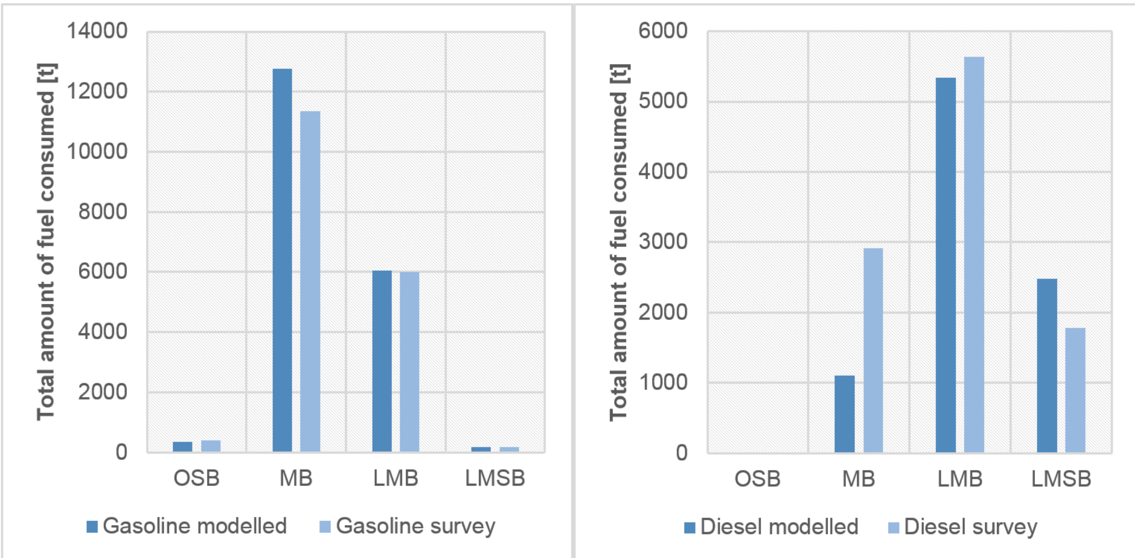

Figure B1: Comparison of fuel consumption statistics for the Swedish fleet at the Baltic Sea against BEAM model predictions. Comparison has been made for each both class and separately for gasoline and diesel setups.

6. Code and data availability

BEAM model source-code has been written in Java as an extension module under the STEAM model software since they share common operations and methods to function. STEAM is an intellectual property of the Finnish Meteorological Institute and it is not freely available due to copyright reasons. The dissemination of input datasets, such as the vessel activity and the ship technical data, are governed by bilateral contracts with data providers and as such cannot be made available. As such, the BEAM model is not available as a stand-alone, open source version.

The output data presented in this paper, such as the gridded annual total emissions in netCDF format, are available upon request from the corresponding author.

7. Author contribution

L. Johansson designed and carried out the technical BEAM model development described in the paper and processed the input data required for the shipping emissions modelling. He is also responsible for the shipping emissions modelling work, results preparation and figures presented in the paper. He prepared the manuscript with contributions from all co-authors. **E. Ytreberg** was responsible for antifouling sections, including the work required to define emission factors for antifouling paints. He also contributed to manuscript preparation, the Swedish fleet survey material analysis and in the preparation of marina location data sets. **J.-P. Jalkanen** contributed to manuscript preparation and was responsible for the review and analysis of the Finnish leisure boat fleet characteristics. **E. Fridell** contributed to manuscript preparation and in the processing of fleet characteristics that were used in the modelling, especially with regards to emission factors, engine setups and fuel consumption.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

K. M. Eriksson was responsible for the Swedish marina survey that was conducted as a part of this study for Section 2.4.1. He also contributed to manuscript preparation. **M. Lagerström** contributed to manuscript preparation and antifouling emission factors used in the study. **I. Maljutenko** was responsible for the marina location analysis and fleet composition research for Russia, Estonia, Latvia, Lithuania and Poland. He also contributed in manuscript preparation. **U. Raudsepp** contributed in manuscript preparation. **V. Fischer** was responsible for the fleet characteristics of the German leisure boat fleet based on a survey that was conducted and analyzed as a part of this study. **E. Roth** was responsible for the research on fleet characteristics of the Danish leisure boat fleet.

8. Acknowledgements

This work resulted from the BONUS SHEBA project and it was supported by BONUS (Art 185). We are grateful to the Helcom member states for allowing the use of Helcom AIS data in this research.

9. References

Almeida, E., Diamantino, T. C. and De Sousa, O.: Marine paints: the particular case of antifouling paints, Progress in Organic coatings, 59(1), 2-20, 2007.

Daehne, D., Fürle, C., Thomsen, A., Watermann, B., and Feibicke, M.: Antifouling biocides in German marinas: Exposure assessment and calculation of national consumption and emission, Integrated Environmental Assessment and Management, 13(5), 892–905, https://doi.org/10.1002/ieam.1896, 2017.

EU: Directive 2013/53/EU of the European Parliament and of the Council of 20 November 2013 - On recreational craft and personal watercraft and repealing Directive 94/25/EC, Official Journal of the European Union, L354/90, 2013.

Dafforn, K. A., Lewis, J. A. and Johnston, E. L.: Antifouling strategies: History and regulation, ecological impacts and mitigation, Marine Pollution Bulletin 62:453-465, 2011.

European Environment Agency (EEA): EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016: technical guidance to prepare national emission inventories, EEA-Report, 21, 2016.

Ferry, J.D. and Carritt, D.E.: Action of antifouling paints, Ind. Eng. Chem. 38 (6), 612–617, http://dx.doi.org/10.1021/ie50438a021, 1946.

Gray, D. L., Canessa, R. R., Keller, C. P., Dearden, P., and Rollins, R. B.: Spatial characterization of marine recreational boating: Exploring the use of an on-the-water questionnaire for a case study in the Pacific Northwest, Marine Policy, 35(3), 286-298, 2011.

HELCOM: State of the Baltic Sea–Second HELCOM holistic assessment 2011-2016 In Baltic Sea Environment Proceedings (p. 155), 2018.

Jalkanen, J. P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J. and Stipa, T.: Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide, Atmospheric Chemistry and Physics, 12(5), 2641-2659, 2012.

Johansson, L., Jalkanen, J. P., and Kukkonen, J.: Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution, Atmospheric environment, 167, 403-415, 2017.

Lagerström, M., Lindgren, J. F., Holmqvist, A., Dahlström, M. and Ytreberg, E.: In situ release rates of Cu and Zn from commercial antifouling paints at different salinities, Marine pollution bulletin, 127, 289-296, 2018.

Lepeule, J., Laden, F., Dockery, D. and Schwartz, J.: Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009, Environ. Health Perspect. 120, 965, 2012.

https://doi.org/10.5194/os-2020-5
Preprint. Discussion started: 29 January 2020

Montes, N., Swett, R., and Ahrens, R.: Modeling the spatial and seasonal distribution of offshore recreational vessels in the southeast United States, PloS one, 13(11), e0208126, 2018.

Raudsepp, U., Maljutenko, I., Kõuts, M., Granhag, L., Wilewska-Bien, M., Hassellöv, I. M. and Matthias, V.: Shipborne nutrient dynamics and impact on the eutrophication in the Baltic Sea. Science of The Total Environment, 671, 189-207, 2019.

Sidman, C. F., and Fik, T. J.: "Modeling spatial patterns of recreational boaters: vessel, behavioral, and geographic considerations", Leisure Sciences, 27(2), 175-189, 2005.

Swedish EPA, Utsläpp av växthusgaser från inrikes transporter efter växthusgas och transportslag. Available at: http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__MI__MI0107/MI0107InTransp/?rxid=3b565bcc-1933-4a0a-92ac-d751673e13d6, Accessed 2019-12-19, 2018.

Tedengren, M., and Kautsky, N: Comparative stress response to diesel oil and salinity changes of the blue mussel, Mytilus edulis from the Baltic and North Seas, Ophelia, 28(1), 1-9, 1987.

The Swedish Transport Agency, 2010: Båtlivsundersökningen 2010 - En Undersökning Om Svenska Fritidsbåtar Och Hur de Används (in Swedish), 2010.

The Swedish Transport Agency, 2015: Båtlivsundersökningen 2015 - En Undersökning Om Svenska Fritidsbåtar Och Hur de Används (in Swedish), 2015.

Trozzi, C., and Lauretis, R. D.: EMEP/EEA air pollutant emission inventory guidebook 2016. European Environment Agency, 2016. Available at www.eea.europa.se/publications/emep-eea-guidebook-2019.

Yebra, D. M., Kiil, S., Weinell, C. E., and Dam-Johansen, K.: Dissolution rate measurements of sea water soluble pigments for antifouling paints: ZnO. Progress in organic coatings, 56(4), 327-337, 2006.

Ytreberg, E., Lagerström M, Holmqvist, A., Eklund, B., Elwing, H., Dahlström, M., Dahl, P. and Dahlström M.: A novel XRF method to measure environmental release of copper and zinc from antifouling paints, Environmental Pollution 225:490-496, 2017.

Ytreberg, E., M. A. Bighiu, L. Lundgren, and B. Eklund.: XRF measurements of tin, copper and zinc in antifouling paints coated on leisure boats, Environmental Pollution 213:594-599, 2016.

Zheng, X. Y., Ding, H., Jiang, L. N., Chen, S. W., Zheng, J. P., Qiu, M., ... and Guan, W. J.: Association between air pollutants and asthma emergency room visits and hospital admissions in time series studies: a systematic review and meta-analysis, PloS one, 10(9), e0138146, 2015.