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A combined line-point-source model for ship emissions in the port of Hamburg, Germany

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1 INTRODUCTION

Pollutant exhaust from ships is an important factor influencing the air quality in cities with large ports like the city of Hamburg, Germany. Therefore, municipalities are concerned with measures aimed at mitigating air pollution by ships, in particular with $\mathrm{NO_x}$ and PM. For planning these measures and evaluating their effectiveness, it is essential to have an emission model that can be run in any temporal and spatial resolution, and above all, is able to simulate different emission scenarios.

At Helmholtz-Zentrum Geesthacht we developed a model that simulates the activities sailing, maneuvering and berthing of every single registered ship in the port of Hamburg and calculates their emissions of amongst others $\mathrm{NO_x}$, $\mathrm{SO_2}$ and black carbon. As different emission factors apply for the different activities, to calculate ship emissions it is at first necessary to reconstruct the activities of the ship during their stay within the port. This can be achieved by evaluating (Automatic Identification System (AIS) signals, that are broadcast by the ships every six seconds and contain at least the coordinates and time stamp. Alternatively, data gathered by the port authorities could be used. In our current development, we use such data in the form of arrival-departure data. This means that the least that must be known is time of entry into the port, arrival at the quay, departure from the quay and time of leaving the port. Emissions during sailing and maneuvering are represented as line sources while berthing emissions are point sources.

2 DATA

2.1 Port Calls

The model derives the activities of the ships in the port of Hamburg from so called arrival-departure tables. In these tables, Hamburg Port Authority makes a record when a ship enters and leaves the port area as well as when it arrives at a berthing place – this can be a quay, dock or a waiting position – and when it leaves this berthing place. A ship can arrive at or depart from the port or be hauled between two berthing locations. Each record comprises a time stamp, a code for the berthing place as well as the unique IMO number to identify a ship and some technical information. Most importantly, the ship type and grosstonnage are stored and can be used to derive the engine characteristics of the ships if no other information is available.

2.2 Engine Characteristics

The most important ship characteristics required to calculate emissions are the maximum continuous rating (MCR or maximum power in kW), maximum speed, revolutions per minute, engine type, and the total power of auxiliary engines. Helmholtz-Zentrum Geesthacht possesses a vessel data base purchased from the ship registration company IHS Fairplay with the technical specifications of about 10,000 vessels. Therein, the vessels are identified by their IMO number (International Maritime Organization). If a vessel's IMO number is not found in this data base, median values that are calculated for every ship type and size class are used instead.

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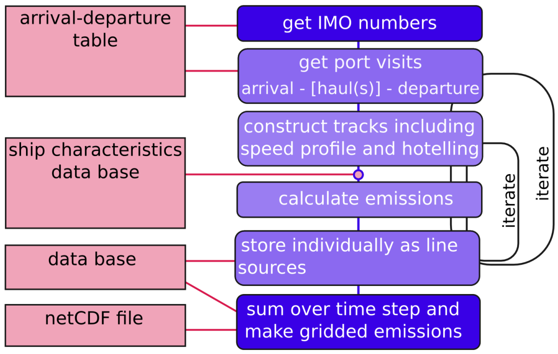

Figure 1: Model scheme.

3 MODEL

The model starts by extracting all IMO numbers from the arrival-departure table. While iterating over the IMO numbers the port calls of the respective ship are read from the table. Then the model iterates over the port visits which are defined as the period between entering and leaving the port area. During a visit, a ship can be hauled between quays frequent times. For each visit the routes sailed within the port and the berthing times are constructed, and the emissions during the activities sailing, maneuvering and berthing are calculated. Finally, the ship emissions are put into a grid by summing all emissions found in a grid cell during a given time step. Both the grid layout and the aggregation time step are freely definable. Alternatively, the ship routes and its emissions can be stored in a (e.g. SQLite) database and aggregated subsequently (figure 1).

3.1 Ship routes and activities

At first, route points (as lat-lon coordinates) between the entry point into the port and the various quays were defined with a GIS tool. These points were set in a way that allowed to construct the route a ship would take, knowing its start and end location that can be read from the arrival-departure table. Once a route for one ship movement is known, it is interpolated to a trace of points with a maximum distance, which can be set to any value. The distance between the route points is relevant for aggregating the line source emissions to gridded emissions as it is required to integrate them in SMOKE. Using the total time of the movement between two locations and assuming that a vessel accelerates and decelerates exponentially at the start and end points while traveling at constant speed in between, a time profile for each movement is created. This procedure results into a description of every movement of the recorded port calls with a time stamp and speed at any of the densely placed route points. At the berthing locations the speed is set to zero for the duration of the berthing. If the speed is less than or equal to 2 kn the activity is defined as maneuvering. If it is above 2 kn the activity is sailing.

3.2 Emissions During Sailing and Maneuvering

The emission factors for moving ships are energy specific (denoted in $\frac{\mathrm{g}}{\mathrm{kWh}}$) and defined as a function of the engine load. We used different functions for different engine types and ship sizes (denoted in grosstonnage). It is a good approximation to assume that a ship's grosstonnage is proportional to its engine power. The emission factor functions are described in detail in Aulinger et al. (2016). The actual load while sailing is calculated from the actual speed s and the maximum speed s_{max} of the vessel using the cube law (see equation 1) whereas for the activity maneuvering fixed loads are assumed per ship type. The energy consumption per line segment is calculated by multiplying the load by the MCR (in kW) and the duration needed for sailing from one route point to the next one Δt (in h). The energy consumption multiplied by the emission factor EF yields the emissions (in g) in a line segment from the main engine. The emissions of the auxiliary engines E_{aux} are calculated the same way assuming, however, fixed loads for these engines (equation 1).

$$E = (\frac{s}{s_{max}})^3 \cdot MCR \cdot \Delta t \cdot EF + E_{aux} \qquad (1)$$

3.3 Emissions at Berth

Ship emissions at berth are calculated with fuel specific emission factors (denoted in $\frac{\mathrm{g}}{\mathrm{kg}}$). At first, the fuel consumption during the ship's berthing was calculated. The fuel factors ff in $\frac{\mathrm{kg}}{\mathrm{h}}$ were derived from an on board survey comprising 175 ships (Clean North Sea Shipping Project Consortium, 2014). It was assumed that part of the energy needed for berthing activities was produced with the auxiliary engines (e.g. pumping and cooling) and

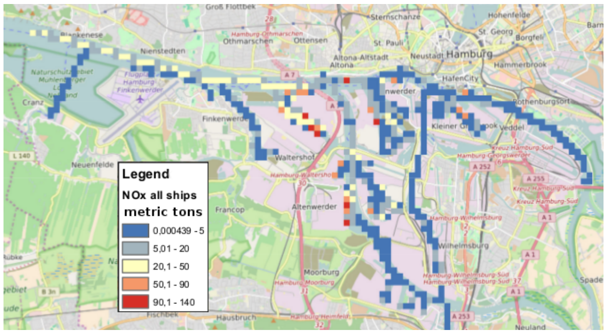

Figure 2: NO_x emissions by ships in the port of Hamburg in 2013.

part of the energy – for heating fuel and water – was produced with boilers, for which different emission factors apply (EF_b and EF_{aux}). The rate of boiler usage r distinguished by ship type was also derived from the on board survey (equation 2). For a detailed description of the method and the emission factors refer to (Hulskotte and van der Gon, 2010).

$$E = (r \cdot EF_b + (1 - r) \cdot EF_{aux}) \cdot ff \cdot \Delta t \qquad (2)$$

4 RESULTS AND DISCUSSION

Based on a simple arrival-departure table, the model is able to quickly calculate ship emissions in any desired spatial and temporal resolution. Due to its bottom-up nature it is simple to set up a different ship traffic scheme and calculate scenario emissions. Storing the emissions as line sources in a data base before aggregating them to gridded emissions would even further simplify the scenario creation. If the routes and activities of the ships in ports were reconstructed from AIS signals – a module for this is in preparation – the model would be easily portable to other port areas. Currently, the model calculates emissions of NO_x, SO_2, sulfuric acid, CO, VOC, PM_{10}, black carbon and primary organic carbon. After conversion of the line emissions to gridded emissions they can be used in air quality models like CMAQ.

Showing the emissions as raster maps allows for identifying hot spots (figure 2), which are in the case of the port of Hamburg the cruise terminals at the northern banks of the River Elbe and, most of all, the container terminals. Container ships have by far the largest share in the total ship emissions because they are both the most abundant ship type in Hamburg and they belong to the largest ships with the highest engine power. As an example, container and general cargo ships emitted about 3500 tons NO_x in the year 2013 in contrast to less than 500 tons NO_x emitted by all the other vessels.

Emissions at berth that account for about half of the total emissions have to be used cautiously because the assumptions about fuel usage and boiler ratio are derived from only a few ships that took part in an on-board survey. This introduces an uncertainty into the model results which is difficult to quantify. Further studies about emissions of ships at berth are required.

The emissions from ships constitute 20-36% of the total NO_x emissions in the city of Hamburg, which underlines the importance of port emissions for the air quality in Hamburg.

References

Aulinger, A., V. Matthias, J. B. M. Zeretzke, M. Quante, and A. Backes, 2016: The impact of shipping emissions on air pollution in the greater north sea region – part 1: Current emissions and concentrations. *Atmos. Chem. Phys.*, **16**, 739–758, doi:doi:10.5194/acp-16-739-2016.

Clean North Sea Shipping Project Consortium, 2014: Clean north sea shipping (CNSS): Final report – key findings and recommendations. Tech. rep. URL http://www.cnss.no.

Hulskotte, J. H. J., and H. A. C. D. van der Gon, 2010: Fuel consumption and associated emissions from seagoing ships at berth derived from an on-board survey. *Atmos. Environ.*, **44**, 1229–1236.