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Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution

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HIGHLIGHTS

- A model (STEAM3) for the assessment of global shipping emissions is presented.
- The modelling is based on ship activities given by AIS, for more than 300,000 ships.
- A route generation algorithm is used to handle large gaps in the AIS-data.
- Data-assimilation is used to assign physically realistic properties for each ship.
- Results for global shipping emissions have been analysed and presented for 2015.

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ABSTRACT

We present a comprehensive global shipping emission inventory and the global activities of ships for the year 2015. The emissions were evaluated using the Ship Traffic Emission Assessment Model (STEAM3), which uses Automatic Identification System data to describe the traffic activities of ships. We have improved the model regarding (i) the evaluation of the missing technical specifications of ships, and (ii) the treatment of shipping activities in case of sparse satellite AIS-data. We have developed a model for the collection and processing of available information on the technical specifications, using data assimilation techniques. We have also developed a path regeneration model that constructs, whenever necessary, the detailed geometry of the ship routes. The presented results for fuel consumption were qualitatively in agreement both with those in the 3rd Greenhouse Gas Study of the International Maritime Organisation and those reported by the International Energy Agency. We have also presented high-resolution global spatial distributions of the shipping emissions of NO_x, CO_2, SO_2 and $PM_{2.5}$. The emissions were also analysed in terms of selected sea areas, ship categories, the sizes of ships and flag states. The emission datasets provided by this study are available upon request; the datasets produced by the model can be utilized as input data for air quality modelling on a global scale, including the full temporal and spatial variation of shipping emissions for the first time. Dispersion modelling using this inventory as input can be used to assess the impacts of various emission abatement scenarios. The emission computation methods presented in this paper could also be used, e.g., to provide annual updates of the global ship emissions.

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1. Introduction

Reliable and detailed emission inventories are crucial for the accuracy of air quality modelling; such inventories should include all sectors of anthropogenic and non-anthropogenic pollution. Information on emissions should also include a sufficiently detailed treatment of their geographical and temporal variations. The introduction of an automatic vessel position reporting system, called the Automatic Identification System (AIS), has significantly reduced the uncertainties concerning ship activities. Currently, all vessels larger than 300 tons globally report their position with a few second intervals.

The use of Automatic Identification System (AIS) data for the assessment of shipping emissions has substantially increased during the last few years. Both the geographical coverage achieved via AIS satellite receivers and the amount of usable AIS-based shipping

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activity data have substantially increased while the financial costs for acquiring the relevant AIS data have significantly decreased. The availability of the new data has made it possible to use refined methods that can significantly improve the quality of bottom-up ship emission inventories. The main advantage of such bottom-up emission inventories, compared to the top-down ones, is that these can describe the emitters in a more realistic manner, while maintaining the connection between single emitters and large scale inventories. In addition, it is possible to construct sophisticated emission scenarios and analyse in detail the spatial-temporal variation of emissions.

The AIS system is useful for the evaluation of ship emissions, as it provides continuously automatic information on the vessel positions and instantaneous speeds of ships. If the required vessel characteristics are also known, the exhaust emissions can be modelled on very high temporal and spatial resolutions. The ship emission inventories based on the use of the AIS signals have several significant advantages over the previously developed approaches (e.g., Smith et al., 2015; Jalkanen et al., 2016). Such inventories are based on time-dependent, high-resolution dynamic traffic patterns, which can also allow, e.g., for the effects of changing weather conditions.

The function of AIS-data as a means to estimate shipping emissions is not new; AIS has been used previously for the assessment of emissions and air pollution originated from shipping. However, the scope of these studies has commonly been limited either to city-scale, for instance, regarding the influence of harbours and nearby ship traffic, or to selected sea regions (e.g., Jalkanen et al., 2012; Johansson et al., 2013; Liu et al., 2016; Marelle et al., 2016; Goldsworthy and Goldsworthy, 2015; Song, 2014; Ng et al., 2013; Matthias et al., 2016; Aulinger et al., 2016). There is one exception: in the Third Greenhouse Gas (GHG) Study of the International Maritime Organisation (IMO; Smith et al., 2015), AIS-data was used to assess global shipping emissions. Before the present study, the Third GHG Study therefore represented the most detailed and comprehensive global inventory of shipping emissions. The aim of that study was to provide IMO with both a multi-year inventory and future scenarios for green-house gases and other emissions from ships. Analysis in that study was carried out for each ship during each hour of each of the years 2007–2012, before aggregation to evaluate the total values. Since the focus of that study was on the evaluation of the total shipping emissions, the authors did consider neither the realistic pathing of individual ships nor the resulting spatial- and temporal variability of global shipping emissions. However, an accurate representation of the spatial and temporal variability the global shipping emissions is crucial for air quality modelling purposes.

Corbett et al. (2007) analysed the global premature mortality caused by ship emissions. They evaluated that shipping-related PM emissions were annually responsible for a considerable amount, approximately 60,000, cardiopulmonary and lung cancer deaths. The impacts were focused in coastal regions on major trade routes; most premature deaths occurred near coastlines in Europe, East Asia and South Asia. Liu et al. (2016) evaluated the health and climate impacts of vessels in East Asia, using a detailed bottom-up AIS-based shipping emission model. They reported that shipping emissions in East Asia had rapidly increased since the beginning of this century. According to that study, East Asia accounted for 16% of global shipping CO_2 emissions in 2013, compared to only 4–7% in 2002–2005. Further, the emissions from shipping in East Asia resulted in substantial adverse health impacts, with 14,500–37,500 premature deaths per year according to Liu et al. Since the data regarding the technical characteristics of vessels can be difficult to obtain, especially for smaller vessels, Liu et al. adopted Gradient Boosting Regression Trees (GBRT) to refine their technical vessel database. Despite the adopted GBRT technique, the amount of identified and technically specified vessels was limited to 18,300 ships; the clear majority of AIS-messages (3.7 billion of 5.7 billion) originated from ships that could not be identified and were omitted from the modelling.

The present authors have previously introduced the Ship Traffic Emission Assessment Model (STEAM), which uses AIS data to describe ship traffic activity. The previous model versions have been described in detail by Jalkanen et al. (2009, 2012, 2014 and 2016) and Johansson et al. (2013). The model has previously been applied to evaluate the shipping emissions in the Baltic Sea (Jalkanen et al., 2009), in the Danish Straits (Jalkanen et al., 2012), in the Baltic and North Seas (Johansson et al., 2013; Jonson et al., 2015), and in the whole of Europe (Jalkanen et al., 2016).

In this study, we present for the first time a global, entirely bottom-up, physically realistic AIS-based assessment of shipping emissions on very high spatial and temporal resolutions. Our modelling approach is based on the vessel water resistance method (Hollenbach, 1998). We model the shipping activities of each vessel that send AIS-data and consider the activities of ships between the consecutive AIS-messages on a minute by minute basis. We have constructed a route generation algorithm to handle the challenges related to the sparsity and heterogeneous distribution of AIS-data. Further, we use data-assimilation techniques to assign physically realistic properties for ships, for which the technical information is incomplete or missing. We included non-IMO registered traffic in our modelling; for each ship we included also the temporally resolved effects related to emission control areas and emission abatement equipment installed on-board. The final results can readily be used as input values for atmospheric dispersion models.

The first aim of this study is to describe the latest improvements of the applied mathematical emission model (called STEAM3), especially focusing on two key improvements that were required to perform the global assessments. The second aim is to intercompare the numerical results on the fuel consumption to the values reported in the corresponding previous inventories. The third aim is to present new selected numerical results on the activities and atmospheric emissions of global shipping. We have not presented an evaluation of the STEAM3 model against measured emission or concentration data in this paper; that has been addressed extensively in several previous studies (e.g., Jalkanen et al., 2009, 2012, 2014; 2016; Johansson et al., 2013; Marelle et al., 2016).

2. Methods

The STEAM model combines the AIS-based information and the detailed technical knowledge of the world fleet with principles of naval architecture. This input information is used to predict the resistance of vessels in water and the instantaneous engine power of the main and auxiliary engines on a minute-by-minute basis, for each vessel that has sent AIS messages. The model then predicts as output both the instantaneous fuel consumption and the emissions of selected pollutants (Jalkanen et al., 2012; Johansson et al., 2013).

In the following, we introduce a refined version of the Ship Traffic Emission Assessment Model (STEAM3) and describe the improvements of the model that were required for the global assessments. These include the methods that compensate for (i) the missing information on the technical specifications of a fraction of the ships and (ii) the scarcity of satellite data in some regions. In addition, we address (iii) the model refinements that allow for the

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