SHIPPING EMISSIONS OVER EUROPE:

A STATE-OF-THE-ART AND COMPARATIVE ANALYSIS

M. A. Russo[1*], J. Leitão[1,2], C. Gama[1], J. Ferreira[1], A. Monteiro[1]

[1]CESAM & Department of Environment and Planning, University of Aveiro, Aveiro, Portugal

[2]Now at IASS – Institute for Advanced Sustainability Studies, Potsdam, Germany

*Corresponding author: M.A. Russo, e-mail: michaelarusso@ua.pt; Tel: +351 234 370220, Fax: +351 234 370309

Abstract

Several emission inventories exist for Europe, which include emissions originating from ship traffic in European sea areas. However, few comparisons of these inventories, in particular focusing on specific emission sectors like shipping, exist in literature. Therefore, the aim of this paper is to review and compare commonly used, and freely available, emission inventories available for the European domain, specifically for shipping and its main pollutants (NOx, SOx and PM10). Five different inventories were considered which include shipping activity: 1) EMEP; 2) TNO-MACC_III; 3) E-PRTR; 4) EDGAR and 5) STEAM. The inventories were initially compared in terms of total emission values and their spatial distribution. The total emission values are largely in agreement (with the exception of E-PRTR), however, the spatial representation shows significant differences in the emission distribution, in particular over the Mediterranean region. As for the contribution of shipping to overall emissions, this sector represent on average 16%, 11% and 5% of total NOx, SOx and PM10 emissions, respectively. Recommendations are given regarding the specific use of each available inventory.

Keywords: shipping; atmospheric pollutants; emissions; inventories; Europe.

1. INTRODUCTION

Due to its dependence on fossil fuel combustion and the fact that it is one of the least regulated anthropogenic emission sources, studies show that ships make a non-negligible contribution to air pollutant emissions (Corbet et al., 1997; Eyring et al., 2005a), specifically NOx, SOx and PM10. These pollutants have negative impacts on air quality, human health, and climate change problems at local, regional, and global levels (Isakson et al., 2001; Eyring et al., 2005b; Costa et al., 2014; Viana et al., 2014; Aksoyoglu et al., 2016). Accurate and up-to-date ship emission inventories are key inputs for air quality modelling, and are essential for a better understanding, and cost-effective control, of the impacts of air emissions from shipping activities on the environment and human health. One of the challenges in improving the accuracy of ship emission inventories is due to their mobility, poorly integrated models, and limited data (Matthias et al., 2010). Information on these types of emissions is limited due to a lack of dynamical features, such as the geographical or temporal variations of emissions. This information can be critically important for all transportation emissions, which present a substantial spatial and temporal variation (Jalkanen et al., 2016). For the maritime transport sector, characterization of shipping activity is a challenging task, and has large uncertainties in emission assessments (USEPA, 2004; Wang et al., 2008). Therefore, studies concerning ship emissions in Europe are mainly based on statistical analysis of cargo volumes (Schrooten et al., 2009), vessel arrivals and departures (Whall et al., 2002), voluntary weather reports from ships (Corbett et al., 2007) or search and rescue services (Endresen et al., 2003; Wang et al., 2008). Tools such as the Automatic Identification System (AIS) can significantly reduce the uncertainty concerning ship activities and their geographical distribution. However, these inventories are dependent on real-time information, full access to traffic activity and temporal changes (Jalkanen et al., 2016). Given the large number of ship movements and dynamic shipping routes, this type of data, for the entire European domain, is currently not freely accessible.

The aim of this study is to present a state-of-art of the most up-to-date and available emission inventories regarding ship exhaust emissions in European sea areas. The comparison is performed for the most critical pollutants: nitrogen oxides (NOx), sulphur oxides (SOx) and particulate matter (PM10), based on graphical and quantitative delta analysis.

The most used emissions inventory is from the EMEP Centre on Emission Inventories and Projections (CEIP), which collects data from LRTAP Convention parties (WebDab). In addition, other inventories focused on the European domain, and used in this study, are: EDGAR (EDGARv4.3.1, 2016), TNO-MACC_III (Kuenen et al., 2014), E-PRTR (E-PRTR, 2011) and STEAM (Jalkanen et al., 2016). These inventories are independent from the EMEP database. EDGAR is an emission inventory with global annual emissions data, per country, for the most relevant air pollutants. E-PRTR (European Pollutant Release and Transfer Register database) and TNO have gridded emission data from officially submitted national emissions data, furthermore, TNO adds to the data with models and expert estimates. The Ship Traffic Emission Assessment Model (STEAM) provides estimates using AIS and vessel-specific information to model ship emissions.

The purpose of emission inventories is generally reflected in their overall dataset format, such as: mandatory international protocols, regulation purposes; research project/services; datasets for air quality modelling; etc. (Ferreira et al., 2013). The structure of the data is where these differences are most noticeable, in regards to how the sectors are presented (Reis et al., 2009).

According to Winiwarter et al., 2003, comparisons between emission inventories need to be easy to implement, efficient and accurate. The methods used in this paper are an analysis of emission totals, a graphical spatial distribution analysis of each inventory on the same grid, and a quantitative graphical analysis of the differences. These studies can provide useful insight into the structure inventories, allowing for a validation of the emissions and interesting conclusions regarding the distribution of emissions. In addition, an idea of the uncertainty of shipping emissions can be achieved when comparing different inventories with similar methodologies.

The overview of the atmospheric emission inventories proposed in this paper will be important for the characterization and assessment of the differences between available inventories, to estimate uncertainty and to infer their potential impacts on its use for air quality modelling applications.

The paper is organised as follows: in Section 2, the emission inventories analysed are described in detail. Section 3 focuses on the comparison of the shipping emission data inventories, per pollutant. Finally, in Section 4, the main conclusions are summarized.

2. THE EMISSION INVENTORIES

Five emission inventories with data freely available for the European domain were compared in this review study: EMEP; E-PRTR; EDGAR; TNO-MACC_III and STEAM. Following, they are described in more detail with further information regarding domain, resolution and pollutants being shown in Table 1. Due to availability of data, and in order to minimize inconsistencies in this comparison, the year 2008 was used for EMEP, TNO and E-PRTR. For EDGAR, 2010 is considered, as there is only data available for this year. Although STEAM emissions are available for 2011 and updated for 2015, 2011 was chosen, as it is closer to the studied year of 2008.

<u>EDGAR</u>

The Emissions Database for Global Atmospheric Research is a global emission inventory developed jointly at JRC (European Commission Joint Research Centre) and PBL (the Netherlands Environmental Assessment Agency). One of the main advantages of EDGAR is that it provides emissions data, for all countries, determined from a consistent method to breakdown each sector, i.e., technology and activity, applied to all countries. This, whenever possible, accounts for the emission factors recommended by the EMEP/EEA air pollutant emission inventory guidebook. Data is available by country but also on a spatial grid (0.1° x 0.1º) for several greenhouse gases and air pollutants emitted by anthropogenic sources. The latest version available, version 4.3.1, provides gridded data by sector only for 2010 although long time series (from 1970 to 2010) are available for country totals. Here, data for the shipping sector (1A3d+1C2) was the one considered. More details on the assumptions in this inventory can be found at Crippa et al. (2016). Regarding emissions from shipping activities, the EDGAR approach is a combination of bottom-up and top-down methods. Emission factors and fuel statistics from the IEA (International Energy Agency), taking into account fuel usage of different vessel types, port activities and ship types are used to determine overall ship emissions. While the spatial distribution of the international maritime transport is based on the calculated emissions, using the 6 min x 6 min resolved global shipping proxies from Wang et al. (2008), the domestic shipping is spatially resolved using population density maps. For more details, see http://edgar.jrc.ec.europa.eu/factsheet_1a3d-1c2.php (EDGARv4.3.1, 2016).

EMEP

The EMEP programme collects qualified scientific information necessary to fulfil the goals of the LRTAP Convention, focusing on three main activities: collection of emission data, atmospheric and precipitation measurements and air quality modelling. One of the Tasks Forces of this programme is specifically dedicated to emission inventories and projections, the TFEIP. Reported emissions and projections of acidifying air pollutants, heavy metals, particulate matter and photochemical oxidants are collected by the CEIP (http://www.ceip.at). For this study, 0.5º x 0.5º gridded emissions were used. As for shipping activities, both national and international shipping are included in sector 8 (SNAP nomenclature) of the EMEP inventory. However, this sector is not exclusively shipping, as it also includes aviation and other off-road vehicles, and EMEP does not distinguish one subsector from another within the inventory. Therefore, only international shipping activities were considered, by selecting the grid cells classified as water land use.

E-PRTR

The European Pollutant Release and Transfer Register (E-PRTR) is a web-based register that includes values for annual emissions of several pollutants released in the 28 EU Member States, as well as Iceland, Liechtenstein, Norway, Serbia and Switzerland. This dataset includes not only air pollutants but also information on, for example, releases to water and land, in a 5km x 5 km grid, approximately (0.047º - 0.183º) x 0.045º. The diffuse emissions of air pollutants are based on data reported by countries under the LRTAP Convention and the United Nations Framework Convention on Climate Change (UNFCCC) requisitions. The information is collected from several industries (according to the E-PRTR list of economic activities) across nine sectors. The E-PRTR includes typical diffuse sources (like transport and/or agricultural activities) but also small industrial point sources. The diffuse emissions are allocated using GIS overlay techniques for distribution into grid cell. A complete and detailed methodology report covering each pollutant and sector is available in the E-PRTR methodology documentation (E-PRTR, 2011). National totals are available and the shipping sector includes both international maritime transportation and circulation in inland waterways, derived from the following source categories: 1A3di(i) and 1A3di(ii) (NFR sectors) and 1C1b (CRF sectors). More details on applied methodology for this and remaining sectors can be found on http://prtr.ec.europa.eu/ and Theloke et al. (2011).

STEAM

Jalkanen, et al. (2016) created an emissions inventory for ship traffic in European sea areas, named hereinafter as STEAM, by the application of the Ship Traffic Emission Assessment Model (STEAM). The STEAM model uses as input values the position reports generated by the automatic identification system (AIS) and the detailed technical knowledge of the ships. The AIS system is global, on-board every vessel that weighs more than 300 t and provides automatic updates of the vessel position and instantaneous speed of ships. AIS data from the terrestrial AIS network are provided by the European Maritime Safety Agency (EMSA). Most of the European sea areas are well represented in these data. However, the Arctic Ocean has not been included. Extensive open-sea areas, such as the Atlantic Ocean, are also not completely represented, due to the limited reception range of the terrestrial AIS base station network. There are also spatial gaps of the data in the southernmost parts of the Mediterranean, particularly near the northern African coastline. The data did not include position reports from any of the African countries; however, shipping activity in this area is significantly lower than in the northern parts of the Mediterranean (Jalkanen, et al., 2016). The gridded emissions have a resolution of 0.0487º x 0.0335º (approximately 2.5 km x 2.5 km).

TNO

The TNO-MACC_III (hereinafter TNO) is a 0.125º x 0.0625º gridded anthropogenic emission database that was primarily developed to support air quality model studies from several European projects, such the EU FP7 MACC (Monitoring Atmospheric Composition and Climate) project or the FAIRMODE (The Forum for Air quality Modelling) framework. It provides consistent anthropogenic emission data by country by source category for 2000-2011 years. The emission inventory combines the emission data officially reported by the countries to EMEP (selected after a quality check), information at country level from the IIASA GAINS model and expert estimates. The latest version available is a result of constant improvement of spatial allocation of emissions, possible by the addition and update of, for example, point sources. Data for international shipping emissions are included according to EMEP inventory. Further information on the development and assumptions in this dataset can be found in Kuenen et al., 2014. To avoid inconsistencies and especially because countries may treat international inland navigation differently in their inventories, in TNO emissions considered here, only international coastal shipping emissions have been included.

Table 1. Summary of the main characteristics of the European emission inventories used in this work

Inventory	References/link	Resolution	Pollutants	Methodology
EMEP (European Monitoring and Evaluation Programme)	http://www.ceip.at/ms/ceip_home1/ceip_home/webdab_emepdatabase/emissions_emepmodels/	European 0.5º x 0.5º	NOx, SOx, CO, NMVOC, NH_3, PM10, PM2.5, PMcoarse, Heavy metals and POPs	International shipping routes, reported emissions by Member States
E-PRTR (European Pollutant Release and Transfer Register)	http://prtr.ec.europa.eu https://www.eea.europa.eu/data-and-maps/data/european-pollutant-release-and-transfer-register-e-prtr-regulation-art-8-diffuse-air-data	European (0.047º - 0.183º) x 0.045º; 5 km x 5 km	NOx, PM10, SO_2, CO, NH_3 and CO_2	Proxy data on worldwide international shipping from Wang et al. (2008). International emissions on inland waterways gridded using traffic volume data Domestic sea shipping based on EUROSTAT statistics on freight and passenger transport
EDGAR (Emission Database for Global Atmospheric Research)	http://edgar.jrc.ec.europa.eu/overview.php?v=431	Global 0.1º x 0.1º	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, CF_6, NF_3, CO, NOx, NMVOC, SO_2, NH_3, PM10, PM2.5, BC and OC	Global shipping proxies from Wang et al. (2008) and population density maps for domestic shipping
TNO (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek - Netherlands Organisation for Applied Scientific Research)	Kuenen et al., 2014	European 0.125º x 0.0625º	CH_4, CO, NH_3, NMVOC, NOx, PM10, PM2.5 and SO_2	EMEP gridded emissions disaggregated using shipping ANVER – ICOADS grid
STEAM (Ship Traffic Emission Assessment Model)	Jalkanen, et al., 2016 and references therein	European 0.0487º x 0.0335º; 2.5 km x 2.5 km	CO_2, NOx, SOx, CO, PM2.5	Emissions calculated by the STEAM model based on AIS (real-time) data and vessel characteristics

3. SHIPPING EMISSIONS OVER EUROPE

3.1. Contribution of shipping sector

In Figure 1, the contribution of shipping activities to the total anthropogenic emission data over the European domain is presented for TNO, E-PRTR, EMEP and EDGAR. The STEAM inventory is not included in this section, as it does not have other sectors besides shipping. Emission data reports to 2008, selected based on available years for the inventories, with the exception of EDGAR, for which the only available inventory is the year 2010.

Figure 1. Contribution of the shipping sector to the total emissions for Europe domain, for different pollutants, considering the inventories, clockwise from the top: TNO, E-PRTR, EDGAR and EMEP

Regarding NOx, almost all the inventories are consistent with the total annual values – approximately 1.6 tonnes – with a contribution of 16-17% to total emissions. However, the total annual value of E-PRTR is much lower (0.6 t) which, in part, can be attributed to the fact that E-PRTR does not include all emission sources (Theloke et al., 2011).

The same is observed for SOx: three emission inventories – TNO, EMEP and EDGAR – total a value of 1.2-1.4 t of SOx emitted from anthropogenic sources, which correspond to a relative contribution of 11-13% from shipping activities, while E-PRTR estimates a much lower total amount (0.2 t), with a much higher shipping contribution (31%).

There is only consistency between the four inventories in PM10 values: a total amount of 0.4 t of PM10 emitted from anthropogenic sources is foreseen (E-PRTR estimates 0.2 t), with a contribution of around 4-5% from shipping activities.

These results in terms of total amount of emitted pollutants show that there is agreement between the different European emission inventories, with the exception of the E-PRTR inventory, in particular NOx and SOx. Shipping activities are an important source (with relative contributions of 11-17%) of NOx and SOx pollutant emissions, with a less significant contribution to PM10 (below 6%).

3.2. Analysis of spatial distribution

For this section, the emissions grid of the EMEP, E-PRTR, EDGAR and STEAM inventories were converted to the 0.125º x 0.0625º grid of the TNO inventory (a compromise between the different grid resolutions) in order to compare the emission values in terms of spatial distribution. Figures 2 - 4 show the maps of the annual emissions data for the inventories, for NOx, SOx and PM10, respectively.

Figure 2. NOx emissions ($t.yr^{-1}$) from shipping estimated for Europe domain, considering the inventories: a) TNO (2008), b) E-PRTR(2010), c) EMEP(2008), d) EDGAR (2008) and e) STEAM (2011)

The routes of the international shipping are visible in all five inventories, which is explained by the use of shipping traffic and/or AIS data, depending on the inventory (see Table 1). TNO and EDGAR exhibit the highest NOx emission values over the international routes. Available emissions data for domestic shipping is included in E-PRTR, and to some extent in EDGAR, while this is not the case for the other inventories (see section 2 for more details).

STEAM, TNO and EDGAR show higher similarities in terms of spatial distribution of emissions, which can be explained by the high resolution used by these inventories. Nevertheless, several differences exist in the magnitude of the values. STEAM exhibits the highest spatially detail in shipping routes and their emissions, with a large number of secondary routes that do not appear in other inventories. Lower emission values of STEAM, in particular over the Mediterranean and North Atlantic routes, where hotspots exist in the TNO and EDGAR inventory, can be explained by the emissions being allocated to other (secondary) routes.

Figure 3. SOx emissions ($t.yr^{-1}$) from shipping estimated for Europe domain, considering the inventories: a) TNO (2008), b) E-PRTR(2010), c) EMEP(2008), d) EDGAR (2008) and e) STEAM (2011)

For SOx, E-PRTR and STEAM show the lowest emission values along the international routes. The other inventories – TNO, EMEP and EDGAR - show similarities in terms of spatial distribution, especially TNO and EMEP, with both of them highlighting the SOx emissions associated to the Mediterranean routes. As previously shown, the STEAM inventory presents higher detail in terms of spatially distribution of shipping emissions when compared to other inventories.

Figure 4. PM10 emissions (t.yr^{-1}) from shipping estimated for Europe domain, considering the inventories: a) TNO (2008), b) E-PRTR(2010), c) EMEP(2008), d) EDGAR (2008) and PM2.5 (t.yr^{-1}) from e) STEAM (2011).

For PM10 there is higher consistency between the spatial distributions of the different emission inventories, which was already observed during the analysis of the total annual values. Once more, TNO and EDGAR show more similarities regarding the definition of the routes and the magnitude and distribution of shipping emission values. The E-PRTR inventory exhibits large differences compared to other inventories, with overall lower values along international shipping routes. In addition to represented values being a fraction of PM10, the lower values of PM2.5 for STEAM follow what was observed for the other pollutants, with high detail in their spatial distribution.

3.3. Quantitative (delta) analysis

In order to quantify the differences found between the emission inventories, deltas between TNO and EMEP (inventory with coarse resolution), as well as TNO and E-PRTR (inventory with lowest overall values) and finally TNO and STEAM (inventory with fine resolution detail), are shown in Figures 5 - 7. As STEAM does not have values for PM10, the differences for this pollutant are not included for this inventory.

Figure 5. Differences (t.yr^{-1}) in emissions between TNO and EMEP, TNO and E-PRTR and TNO and STEAM for NOx

Figure 6. Differences (t.yr^{-1}) in emissions between TNO and EMEP, TNO and E-PRTR and TNO and STEAM for SOx

Figure 7. Differences (t.yr^{-1}) in emissions between TNO and EMEP, TNO and E-PRTR for PM10

Although TNO and EMEP are based on the same approach for shipping emissions values (see Table 1), the maximum deltas (located mainly over the international routes) are found between TNO and EMEP. This is explained by the large coarse resolution of EMEP when converted to the TNO grid, which is particularly evident in the deltas surrounding shipping routes. The differences are higher than 3000 t for NOx, 2000 t for SOx and 240 t for PM10. These maximum deltas represent more than 95% of the average emission data over the shipping route lines, for all pollutants considered.

The differences found between TNO and E-PRTR are always positive, contrarily to the deltas found between TNO and STEAM, where negative values are found in several secondary routes that are only included in the STEAM inventory. The use of AIS data by STEAM model, while the others inventories are based on shipping traffic proxy data, explains these results. These negative deltas (STEAM > TNO) reaches more than 60 t for NOx and 150 for SOx.

4. SUMMARY AND CONCLUSIONS

This work intends to review, compile and compare the emission inventories available for the European domain, specifically for the international shipping sector and its main pollutants (NOx, SOx and PM10). Five different inventories that include shipping activities for this domain were studied: 1) EMEP; 2) TNO-MACC_III; 3) E-PRTR; 4) EDGAR and 5) STEAM.

Data compiled from the five inventories was gathered, processed and compared, at the same temporal and spatial scale. Emissions were converted to the TNO grid (TNO: 0.125º x 0.0625º) to spatially compare the emission datasets, evaluate the differences and calculate the associated delta/range. The inventories were initially compared in terms of total emission values and the relative contribution of shipping activity was estimated (except the STEAM inventory, which only includes shipping activity), together with their geographical representation. The total emission values show an overall agreement, with the exception of the E-PRTR inventory that presents lower values, in particular for NOx and SOx. In general, the contribution of shipping activities are approximately 16%, 11% and 5% of total NOx, SOx and PM10 emissions, respectively.

The spatial representation shows significant differences in the emission distribution, in particular over, and close to, international shipping routes, the Mediterranean and Atlantic North regions. The differences found between the values of EMEP and TNO, which are based on the same approach (officially data reported by Member States), are mainly due to the grid resolution. The lower values of E-PRTR when compared to TNO and EDGAR can be justified by the absence of routes and sources. STEAM appears as the most reliable and detailed emissions inventory since it is based on AIS data and specific vessel information, with a resolution of 2.5 km x 2.5 km. The delta found between STEAM and TNO indicate that TNO emissions are overestimated, in particular over hotspot the Mediterranean shipping routes, and underestimated in secondary routes.

In summary, we recommend that the STEAM inventory should be used in studies that require high-resolution shipping emissions data. However, as this inventory only includes shipping activity data, for other applications, where all emission sectors are relevant and need consistency, TNO and E-PRTR (this inventory has domestic shipping, which can be relevant for specific inland case studies) are recommended. EDGAR has the advantage of being a global database, which can be applied outside of Europe. Finally, only when fine grid resolution is not essential (and/or other pollutants like POPs and metals are important), should the EMEP emissions inventory be considered as a good option. These facts, focused on shipping activities, can be important when applying regional atmospheric chemical transport models, since air quality model results will benefit from the availability of appropriate resolution, consistency and reliability of emission values.

ACKNOWLEDGEMENTS

Thanks are due for the financial support to FCT/MEC through national funds, the co-funding by FEDER, within the PT2020 Partnership Agreement and Compete 2020, for the AIRSHIP project (PTDC/AAG-MAA/2569/2014 - POCI-01-0145-FEDER-016752). And for the post doc and doc grants of J. Ferreira (SFRH/BPD/100346/2014) and C. Gama (SFRH/BD/87468/2012) . To TNO for access to the TNO-MACC_III emission inventory, and Hugo Denier van der Gon and Jeroen J. P. Kuenen for their support regarding the TNO emission inventory. Finally, to Jukka-Pekka Jalkanen et al. for access to their emissions inventory, STEAM.

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