Estimation of shipping emissions using vessel Long Range Identification and Tracking data

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ABSTRACT

Shipping is a growing source of air pollutants and greenhouse gases, which are emitted mainly over an international territory, the seas, for which only shared responsibility by all countries is felt. The international community, in particular the International Maritime Organisation, is called to look for appropriate mitigation of these emissions. This starts with the reporting of emissions in an inventory and its mapping over the international territory to be able to then evaluate the effect of emission reduction policies on the environment. Under the European Monitoring and Evaluation Programme, Member States are required to provide gridded emissions for the different sectors but the spatial allocation of ship emissions requires a supranational setup to avoid transboundary inconsistencies. By using vessel density maps extracted from historical Long Range Identification and Tracking (LRIT) data, accurate high-resolution maps of emissions can be obtained in support of policy development, implementation and monitoring in the interrelated fields of air quality and climate.

1. Introduction

Under the 1979 Convention of Long-Range Transport of Air pollution (CLRTAP), extended with 8 protocols under which the latest Gothenburg Protocol, the European Commission has been playing an instrumental role in the establishment, functioning and revision of these protocols. These protocols were an important step in the European Union policy leading to the National Emission Ceiling Directives and their revision but also to the basic legislation for regulating sulphur emissions from ships, Directive 1999/32/EC. This directive was amended twice: by Directive 2005/33/EC, which designated the Baltic Sea, the North Sea and the English Channel as sulphur emission control areas and limited the maximum sulphur content of the fuels used by ships operating in these sea areas to 1.5%, and by the Directive 2012/33/EU reducing further the sulphur content of the fuel to 0.1% in the Baltic, the North Sea and the English Channel.

The estimation of emissions from anthropogenic activities is essential for policy development, implementation and monitoring. Under the CLRTAP, the Member States are annually reporting air pollutant inventories per sector with time series and grid maps, which are collected and analysed by the Task Force on Emission Inventories and Projections, established as part of the CLRTAP’s European Monitoring and Evaluation Programme (EMEP). Various well-established emission inventories are currently existing, with global coverage (e.g. HTAP_v2.2 emission inventory of 2008 and 2010; Janssens-Maenhout et al., 2015; the EDGARv4.3.1 historic emissions, Crippa et al., 2016) as well as regional coverage (e.g. TNO-MACC for European domain, Kuenen, Visschedijk, Jozwicka, & Denier van der Gon, 2014).

Emission quantities are typically evaluated over a given geographical territory (i.e. emissions of a county, province, state or country) following a so called ‘top-down’ approach or a ‘bottom-up’ one. In the case of shipping emissions, in the first case total emissions are calculated not considering the characteristics of the single boats while in the second one shipping activities are explicitly taken into account (Miola & Ciuffo, 2011). In the same way, the geographical characterisation of these emissions over the territory is based on either the geographical coordinates of the emission source (bottom-up approach; i.e. using point sources of the production facilities) or, in case of diffuse emissions, proxies which are nearing the potentially affected area (top-down approach, e.g. road network, population density and land use intensity).

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Whereas European countries can make use of road traffic statistics to grid the road transport emissions, the same maritime traffic information is not available over territorial and international waters along Europe. Reasons are multiple: (1) the low frequency for fuelling decreases the occasions for terrestrial checks in ports; (2) ships can travel under different nationalities changing their flag (allowing even a shift from the national fuel for inland waterways to international bunker fuel); (3) security control with radar monitoring of traffic on the sea is difficult, in particular in international waters and, for example, the deviation of shipping tracks from the prescribed ‘corridor’ due to piracy in the Arabian Sea was detected by Long Range Identification and Tracking [LRIT] data. Hence, surveillance needs to rely strongly on satellite-based and remote sensing techniques. As such, the high spatial resolution estimation of the distribution of maritime emissions has always been a challenging task, due to the difficulties in finding appropriate proxies of maritime traffic. Currently, national inventories provide shipping emission maps with very high spatial and thematic detail, but these cannot be used without creating border inconsistencies to build a larger spatial and thematic detail, but these cannot be used for representing shipping emission over the European or global domain. Global shipping maps have been published since the late nineties (Corbett & Fischbeck, 1997; Corbett, Fischbeck, & Pandis, 1999; Corbett & Köhler, 2003, 2004; Dalsoren et al., 2008; Eyring, Köhler, van Aardenne, & Lauer, 2005; Eyring et al., 2009; Wang, Corbett, & Firestone, 2008) and are the lead example for consistent geospatial distribution of shipping emission maps. Different methodologies for the gridding of ship emissions have been applied so far:

(1) At global scale: Corbett and Fischbeck (1997) proposed one of the first spatial maps of sea-shipping emissions at this scale, relying on a density proxy derived from the Comprehensive Ocean-Atmosphere Data Set (COADS, a dataset of shipping observations reported on a voluntary basis). Endresen et al. (2003) improved this approach adding the information about ship size in order to weight spatial information retrieved from the Automated Mutual-assistance Vessel Rescue system (AMVER) dataset. Wang et al. (2008) combined AMVER and COADS crossed with the fee-access Lloyds Register database that contains detailed ship movements data in order to improve the spatialisation of emission distribution. These approaches were also recently applied in the Second International Maritime Organization (IMO) GHG study (IMO, 2009).

On the same track, Halpern et al. (2008) used data collected as part of the World Meteorological Organization Voluntary Observing Ships Scheme (http://www.vos.noaa.gov/vos_scheme.shtml) creating ship tracks under the assumption that ships travel in straight lines.

Automatic Identification System (AIS) data of ship activities are also used, for example in the third IMO GHG study (IMO, 2014) which compared it to analogous data from LRIT, for quality check of AIS data.

(2) At European scale: Many studies and projects (Jonson, Jalkanen, Johansson, Gauss, & Denier van der Gon, 2015; Theloke, Thiruchittampalam, Orlikova, Uzbasich, & Gauger, 2009; http://www.transphorm.eu; E-PRTR, The Diffuse Air Releases (Art 8) under the European Pollutant Release and Transfer Register – http://prtr.ec.europa.eu/www.vos.noaa.gov/vos_scheme.shtml) rely on the methodology developed by Wang et al. (2008), using the proxy data in the European region of interest. The EMEP derives the shipping movements from the ENTEC database (Whall et al., 2002). The ENTEC database relies on the Lloyds Marine Intelligence Unit (LMIU) providing detailed information for the registered vessels plus reporting of the port place details of departure/arrival/stop. The main assumption behind this database is that vessels take the shortest straight line route between two ports and the distribution of emissions is driven by the most probable shipping routes. This approach has been then refined by IIASA (Cofala et al., 2007) and adopted in several projects and studies such as the TREMOVE transport and emissions simulation models developed for the European Commission (De Ceuster, van Herbruggen, Logghe, Ivanova, & Carlier, 2006) and the TNO-MACC inventory (Denier van der Gon, Visschedijk, Van der Brugh, & Dröge, 2010). A limitation of this approach is that ENTEC (relying on the LMIU database) covers only ships greater than 500 gross tonnes (Whall et al., 2002). More recently, Jalkanen et al. (2009) proposed an emission assessment model (STEAM) which, for the geographical distribution of emissions in the Baltic Sea, relies on the usage of AIS data to interpolate shipping routes.

In this paper we provide a procedure for spatial gridding using also data from a system for space-borne monitoring of real ship tracks. In fact, during the past years, vessel tracking systems have improved safety and security of maritime traffic by providing vessel position information in real time. The continuous collection and storage of such data have contributed to build archives that can now be used with data mining tools to better understand the movements at sea. Frontrunners amongst them are the already mentioned Automatic Identification System (AIS) and the LRIT, which provide the basis for robust archives of data to extract main
AIS tracking data provide positioning and voyage related information. The data are broadcast by vessels to avoid collision under the Sea Safety Convention (SOLAS, 2004). The frequency of the messages communicating the vessel position varies from a few seconds to minutes depending on the vessel speed (IMO, 1998; ITU, 2014). AIS data are easily accessible, however, limited by the spatial coverage of ground receivers and spatial/temporal coverage of satellite-based receivers. For this reason, AIS data are particularly suitable for bottom-up approaches (e.g. IMO, 2014), since tracking data are collected from all vessels, irrespectively of their size, type (fishing, merchant, passenger, etc.) and flag. However, at regional scales, AIS-based estimations can be prone to coverage bias due to the spatial distribution of ground-based receivers. This can be improved by using satellite-based AIS receivers, although their use is limited in highly traffic-congested areas (such as the Mediterranean Sea) due to message collision and interference issues. The system was designed as a tool avoiding vessel collision and is not fully suited for satellite-based monitoring in specific areas.

On the contrary, LRIT in the European seas has virtually no spatial limitations, but is characterised by a temporal sampling at six-hour reporting interval (IMO, 2006). Although the message frequency is extremely lower than the one of AIS, by increasing the temporal range of the data, it is possible to reliably characterise vessel movements in wide areas since large merchant vessels do not change course at a high frequency rate, except in ports. Nevertheless, LRIT data are not broadcast and can only be accessed upon request. In this paper, access to global LRIT data was granted by the National Competent Authorities for LRIT of States participating in the EU LRIT CDC. This means that only merchant ships with flags of the states sharing their data are tracked, causing incomplete vessel coverage. In Europe, one can assume that the European vessels represent a significant portion of the traffic. Moreover, ships flying the flag of non-EU states follow similar patterns and adhere to the same ship routing systems of European vessels.

Therefore, in the opinion of the authors, LRIT data are more appropriate to spatially distribute emission inventory data. Figure 1 shows the different spatial coverage performance between LRIT and terrestrial AIS data and illustrates that historic LRIT data are overlaid by real time, intermittent AIS tracks, especially in open seas and generally away from the presence of ground receivers. As mentioned, satellite-based reception of AIS messages is not yet reliable in maritime areas with high traffic volume, whereas LRIT represents the most complete source of data from a spatial coverage point of view, in particular for the Mediterranean basin with busy shipping activities.

In this paper, we will apply LRIT data for emissions gridding over the sea, presenting two different applications of these data. In a first example, LRIT will provide proxies for an emission inventory in which no data were previously available. In a second example, we will present a case where large improvements on a realistic preview have been made compared to the emission gridding methodology previously applied. Section 2 addresses the LRIT data and methodology for gridding ship emissions and Section 3 describes the results of the
applied data and methodology. Conclusions are summarised in Section 4.

2. Data and methodology for gridding ship emissions

2.1. Dataset

The data used in this analysis originated from LRIT. The dataset covers ships flying the flag of States contributing to the EU LRIT Cooperative Data Centre (CDC): all EU Member States, Iceland, Norway, and Overseas Territories of EU Member States. Nominally, the LRIT vessel positions are refreshed every six hours although vessel positions can be polled over delimited areas by operational authorities in specific circumstances such as for Search and Rescue. Every LRIT message is transmitted using satellite communications and includes, among other fields, vessel identification and position as extracted by on-board GPS measurements. Figure 2 shows the density used as input to the next stage of gridding shipping emissions.

3. Methods

As already explained, this paper describes two applications of the LRIT proxies on emissions data from two different data sources:

- The first application at the European scale uses the ship emission values retrieved from the EMEP database. This database provides emissions data from international shipping activities and the data are provided per sea for several pollutants covering the whole European continent (EMEP, 2015). Emissions from all the other economic activities, for the EU 28 member states over sea and land, are extracted from the Greenhouse Gas and Air Pollution Interactions and Synergies Model (GAINS, Amann et al., 2011). This application is linked to the possibility to create future emission scenarios (using detailed emission categories) with the final aim of exploring possible air quality optimal policies at regional/local scale (Trombetti, Pisoni, & Lavalle, 2017).

- The second application at global scale uses the Emissions Database for Global Atmospheric Research (EDGAR), version 4.3.1 (European Commission – Joint Research Centre/Netherlands Environmental Assessment Agency [EC–JRC/PBL], 2015). EDGAR aims at informing about global anthropogenic emissions of greenhouse gases and air pollutants with historic country-specific time-series to policymakers and with grid maps to the scientific global modelling community. EDGAR tries to provide consistently calculated emissions, applying the same methodology worldwide, in order to obtain intercomparable emissions for all world countries. Shipping emissions are calculated using fuel statistics of the International Energy Agency (IEA, 2009) combined with emission factors in the Guidelines for GHG emissions of Intergovernmental Panel for Climate Change (IPCC) (2006) and emission factors in the Air pollutants guidebook of EMEP/European Environmental Agency (EMEP/EEA, 2013) for 12 different vessel
types (bulk ship, container ship, chemical tanker, fishing vessel, general cargo, liquefied gas tanker, offshore supply vessel, oil tanker, passenger vessel, reefer, Ro-Ro vessel, Tugs) characterised for either in-port or at-sea status as defined in Dalsøren et al. (2008). EDGARv4.3.1 is a global annual inventory and global international ship emissions have been allocated to annual gridded maps with 0.1 degree x 0.1 degree resolution and with global coverage, using the spatial proxy of Wang et al. (2008).

The gridding methodology of this paper is based on estimates of the vessel density. The density of LRIT messages is computed assuming a uniform subsampling of the vessel trajectories every six hours. Even though the relative low message frequency excludes very short transfers from the analysis, the data are considered to be sufficient for mapping the vessel densities over a relatively long time period and seems to depict the traffic at European scale realistically. One year of LRIT data are used for the gridding of the annual emission inventories. The ship density is calculated as a number of messages received throughout the year for each 1 km x 1 km cell. The gridding proxy needs only a density map with relative levels of the different cells and not the actual number of ships in a cell.

In the case of the EMEP emissions data gridding, the downscaling process was implemented for each of the considered marine areas, because of the details in the emissions data. The input vessel density map was then split into five smaller maps and, for each one, a surrogate layer was computed. A spatial surrogate is a value between zero and one which represents the fraction over the area total to be assigned to the considered pixel (Eyth & Hanisak, 2003). In this way, multiplying the total value of emission for each marine area with the corresponding spatial surrogate, a fraction of the total emission value is assigned to each pixel according to the corresponding density of vessels. The analysis is implemented at 100 m x 100 m resolution and then resampled at 1 km x 1 km resolution.

In the case of the EDGARv4.3.1 emissions data gridding, a similar approach was used for the relative closed marine areas of the Mediterranean Sea, the Black Sea and the Baltic Sea, because the LRIT was only recommended for the European area. The spatial proxy data of Wang et al. (2008) were replaced by the LRIT proxy data for the relative closed sea areas without problems in continuity to the other sea areas (which would not have been the case for open sea areas). As such, in

![Figure 3. NOx emissions estimated for the year 2010.](image-url)
the Baltic, Black and Mediterranean Seas the representativeness of European vessel tracks enhanced and the quality of shipping grid maps improved considerably.

4. Resulting emissions grid maps

In this section we show the results obtained with the proposed methodology, focusing on the results obtained with the EMEP and the EDGAR data.

4.1. EMEP shipping grid maps

Figure 3 and Main Map 1 show the results obtained gridding the EMEP data. The map shows NOx emissions (an air quality pollutant per-se, but also precursor of ozone and particulate matter) in 2010, merging both shipping (from EMEP) and land1 (from GAINS) emissions. The map underlines the importance, from an air quality point of view, of shipping emissions over sea that heavily contribute to total NOx emissions in some specific areas (as e.g. close to the Netherlands and Denmark). The same type of reasoning (not shown here) holds also for SOx emissions. Thanks to the implementation of this approach, it will be possible to analyse alternative future policies for air quality improvement over land, considering also in a consistent way the contribution of shipping emissions.

4.2. EDGARv4.3.1 emissions grid maps

The original emissions grid maps, using for the entire marine area the spatial proxy of Wang et al. (2008), were improved in the Mediterranean, Black and Baltic basins by replacing them with the LRIT distribution for these closed sea areas while keeping the percentage of emissions in the total basin the same as in the original grid map. Figure 4 and Main Map 2 show the results of the SO2 emissions grid maps obtained with the new spatial proxy data zooming in on the European area covering the Mediterranean, Black and the Baltic basins. The new grid maps show a smoother and broader distribution of the ship tracks in these areas and in particular more shipping traffic in the Ionic and Adriatic Sea, which represents better the activity of the Italian ports from Brindisi to Ancona, Venice and Trieste. Figure 5 shows the difference in CO2 emissions between the original grid maps of EDGARv4.3.1 (using only Wang et al., 2008) and the new grid maps published here (upgrading the Mediterranean, Black and Baltic seas with LRIT) and highlights also a decrease in shipping traffic in the Ligurian, Balearic and

![Figure 4. SO2 emissions estimated by EDGARv4.3.1 for the year 2010 distributed with LRIT proxy for the Mediterranean, Black and Baltic Seas and with Wang et al. (2008) proxy for the rest.](image)
Tyrrhenian Seas. This better represents the shorter route chosen for shipping goods via the Suez Canal to the European mainland via the ports of Trieste, Venice, Ravenna, Koper and Rijeka as top 5 amongst others. Also the Black Sea shows the shipping traffic to mainland Europe via Constanța and Varna. In addition, many passengers are travelling via Split, Ancona and Bari. In the Baltic Sea we see less change, even though the analysis shows a higher volume of transport into the Gulf of Finland.

5. Conclusions

In this paper we showed how LRIT data can be used to spatially grid shipping emissions over Europe with a realistic preview of the shipping routes, especially in the European domain. LRIT data were retrieved and converted in ship density, which was then used to distribute emissions from two different sources: EMEP and EDGAR. Maps resulting from this analysis show how this approach can be integrated with land-based proxies, to improve the quality of emission inventories for air quality and greenhouse gases.

Further work will deal with a possible integration of LRIT and AIS to overcome the respective vessel and spatial coverage limitations of each individual datasets. This would be the basis for robust bottom-up approaches towards the estimation of shipping emissions at EU scale.

Software

We employ different software packages for the preparation of the map. LRIT were ingested into PostgreSQL database. For the density analysis part, the model was written in Python 2.7 and run on ArcGIS 10.3.1. The final results data were then converted into vector and raster data files and consequently mapped using ArcGIS.

Notes

1. Note that land emissions are gridded using proxies based on the LUISA modeling platform (Lavalle et al., 2013; Trombetti et al., 2017).
2. AIS data obtained from MSSIS, courtesy of the Volpe Center of the US Department of Transportation and the US Navy.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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