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A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011

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Abstract

Emissions originated from ship traffic in European sea areas were modelled using the Ship Traffic Emission Assessment Model (STEAM), which uses Automatic Identification System data to describe ship traffic activity. We have estimated the emissions from ship traffic in the whole of Europe in 2011. We report the emission totals, the seasonal variation, the geographical distribution of emissions, and their disaggregation between various ship types and flag states. The total ship emissions of CO_2, NO_x, SO_x, CO and $PM_{2.5}$ in Europe for year 2011 were estimated to be 131, 2.9, 1.2, 0.2 and 0.3 million tons, respectively. The emissions of CO_2 from Baltic Sea were evaluated to be more than a half (58 %) of the emissions of the North Sea shipping; the combined contribution of these two sea regions was almost as high (96 %) as the total emissions from ships in the Mediterranean. As expected, the shipping emissions of SO_x were significantly lower in the SO_x Emission Control Areas, compared with the corresponding values in the Mediterranean. Shipping in the Mediterranean Sea is responsible for 39 and 49 % of the European ship emitted CO_2 and SO_x emissions, respectively. In particular, this study reported significantly smaller emissions of NO_x, SO_x and CO for shipping in the Mediterranean than the EMEP inventory; however, the reported $PM_{2.5}$ emissions were in a fairly good agreement with the corresponding values reported by EMEP. The vessels registered to all EU member states are responsible for 55 % of the total CO_2 emitted by ships in the study area. The vessels under the flags of convenience were responsible for 25 % of the total CO_2 emissions.

1 Introduction

The traffic activities of shipping in Europe are nowadays well known, as compared with vehicular traffic; this was not the case previously. The introduction of automatic vessel position reporting systems, such as the Automatic Identification System (AIS), have significantly reduced the uncertainty concerning ship activities and their geographical

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distribution. Nowadays, all vessels larger than the 300 ton size limit globally report their position with few second intervals; this has resulted to an availability of information on ship activities at an unprecedented level of detail. The ship emission inventories, which are based on such automated identification systems, have several significant advantages over the previously developed approaches. Such inventories are based on time-dependent, high-resolution dynamic traffic patterns, which can also allow for the effects of changing conditions, such as, e.g., marine and meteorological conditions (e.g., harsh winter conditions and sea ice cover) or weather routing.

Previous studies concerning the ship emissions in Europe have been based on statistics of cargo volumes (Schrooten et al., 2009), vessel arrival/departure times (Whall et al., 2002), voluntary weather reports from ships (ICOADS, Corbett et al., 2007) or search and rescue services (AMVER, Endresen et al., 2003; Wang et al., 2007). None of these data sources is able to reflect the total ship activity with full flexibility of traffic activity and temporal changes. Inconsistencies can exist between geographical emission inventories and satellite observations of pollutants (Vinken et al., 2014). Furthermore, important emission sources, like harbours have been often neglected from regional emission studies.

In this work, we have used the Ship Traffic Emission Assessment Model (Jalkanen et al., 2009, 2012; Johansson et al., 2013) which combines the vessel activity (AIS data) with vessel specific information of main and auxiliary engines. This allows the determination of vessel specific emissions, which are based on the detailed technical information of fuel consuming systems onboard. Fuel type used during harbour stays or open seas will be determined from actual vessel activity and engine characteristics taking possible sulphur restrictions in specific regions into account. The fuel type assignment (residuals/distillates) is determined from technical specifications of ships' engines which can provide a more realistic description of the use of various marine fuels than fleet wide adoption of residual fuels.

We present emissions for European sea regions, which are covered by the terrestrial network of AIS base stations. In general, European seas are relatively densely traf-

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ficked, especially in regions, in which intercontinental ship traffic intersects with busy short sea shipping routes. The vessel activity data from this area have been collected to operational Vessel Traffic Services center at the European Maritime Safety Agency. This centralized data archive allows one of the most comprehensive high resolution sources of vessel activity on a continental scale. The modelling approach of the present study can be largely automated, which facilitates annual updates of large-scale ship emissions. This allows, e.g, for the inclusion of the impacts of policy changes, such as sulphur reductions, to be included in the emission inventories used in air quality applications.

The aim of this study is to present a comprehensive inventory of ship traffic exhaust emissions for a number of contaminants (CO_2, NO_x, SO_x, $PM_{2.5}$, CO) in European sea areas, utilizing the STEAM ship emission model (Jalkanen et al., 2009, 2012; Johansson et al., 2013). A more specific aim is to geographically present and discuss the high-resolution spatial distributions of shipping emissions for selected species, and the shares of emissions in terms of the various ship types and flag states. We have also identified a few tens of the highest emission intensities in the European sea and harbour areas; these regions contain the highest amounts of predicted shipping emissions of CO_2 within a radius of 10 km. We aim also to compare the numerical values of this new emission inventory with the corresponding values presented in some previous inventories on the emissions originated from European shipping.

2 Materials and methods

2.1 Geographical domain and input datasets

This modelling approach uses as input values the position reports generated by the automatic identification system (AIS); this system is globally on-board in every vessel that weighs more than 300 tons. The AIS system provides automatic updates of the vessel positions and instantaneous speeds of ships at intervals of a few seconds. For

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this paper, we used the AIS messages received by the terrestrial AIS network and provided by the European Maritime Safety Agency (EMSA). We extracted the data that corresponded to the year 2011; the data contained more than 10^9 archived AIS messages. The data has been collected from the terrestrial AIS base station network of the EU member states. The coverage of this network is illustrated in Fig. 1.

Most of the European sea areas are well represented in this 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, especially near the northern African coastline. The data did not include position reports from any of the African countries; however, the ship activity in this area is significantly lower than in the northern parts of the Mediterranean. This was shown with an independent investigation of satellite AIS datasets obtained from the Norwegian Coastal Administration (detailed results not shown here). The data from inland waterways in Europe has been included, but cannot be taken to fully reflect the inland shipping, as the IMO SOLAS regulation does not require the use of AIS from these vessels.

The model requires as input also the detailed technical specifications of all fuel consuming systems on-board and other relevant technical details for all the ships considered. Such technical specifications were therefore collected and archived from various sources of information; the data from IHS Fairplay (IHS, 2012) was the most significant source. The technical data was supplemented with material from several other companies and agencies. These included the following: Det Norske Veritas, Nippon Kaiji Kyokai, Bureau Veritas, Germanischer Lloyd American Bureau of Shipping, publicly available ship registers (such as the Korean, Norwegian and Russian ship registers), ship owners and engine manufacturers. Fuel type was determined based on the properties of engines, such as power output, angular velocity and stroke type. The sulphur content was assigned based on the current regulations in European sea areas, such as the MARPOL Annex VI (IMO, 1998) and the EU Sulphur Directive.

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The technical specifications were collected and archived for more than 65 000 vessels that have an International Maritime Organization (IMO) number. This set of ships represents a majority of the global commercial fleet. In addition to these vessels, the AIS position reports were received from more than 35 500 vessels, for which the technical data could not be determined based on the information from classification societies, such as the Lloyds Register. In addition to the IMO number, the vessel Maritime Mobile Service Identity (MMSI) code was used as a secondary key in searching vessel data from ship databases.

However, the vessel data was not received for a vast majority of vessels that transmitted the MMSI code (and no IMO number) in AIS data. An additional attempt to identify these vessels with internet search engines using MMSI code was made for 5000 vessels, which had the largest fuel consumption. This revealed some potentially large vessels, but the impact of this step on overall CO_2 emissions was just over one percent. Clearly, the default method of assuming those vessels small, which do not transmit IMO registry number, introduces uncertainty to overall results, but the impact is negligible.

2.2 The STEAM model and its application

The emissions presented in this paper were evaluated using the Ship Traffic Emission Assessment Model (STEAM). A brief overview of this model is presented in the following; for a more detailed description, the reader is referred to Jalkanen et al. (2009, 2012) and Johansson et al. (2013). This study does not introduce any refinement of the model.

The STEAM model was used to combine the AIS based information with the detailed technical knowledge of the ships. This combined information is used to predict vessel water resistance and instantaneous engine power of main and auxiliary engines. The model predicts as output both the instantaneous fuel consumption and the emissions of selected pollutants. The fuel consumption and emissions are computed separately for each vessel, by using archived regional scale AIS data results in a regional emission

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inventory. The STEAM emission model allows for the influences of the high-resolution travel routes and ship speeds, engine load, fuel sulfur content, multiengine set-ups, abatement methods and the effects of waves (Jalkanen et al., 2012; Johansson et al., 2013).

The STEAM model includes a possibility to model some environmental effects on ships, such as the effects of waves and the influence of sea currents. However, for simplicity these factors were not taken into account in this study. The waves increase fuel consumption and emissions, whereas the direct effects of the wind and sea currents can be negative or positive. In considering long time scales and extensive regions, the net influences of direct wind effects and sea currents are expected to be fairly small. It would be possible also to use satellite-based AIS messages as input values of the model; however, for simplicity these were not used in this study, except for the above mentioned confirmation of lack of significant vessel activity in southern Mediterranean Sea.

The emissions of NO_x were modelled as a function of crankshaft angular velocity (revolutions per minute, rpm), according to the IMO Tier I and II rules (IMO, 2008). Tier I rule was applied also to those ships, which were built before 2000; this assumption can result in a slight underestimation of emissions originated from these vessels. The effects of emission abatement techniques were also modeled, and certified emission factors have been used whenever possible. The emission certificates were provided by a group of ship owners, the emissions of these vessels had been measured by an accredited laboratory, in order to obtain a discount in the system of Swedish fairway dues. However, the vessels that were equipped with emission abatement techniques or had been subject to certified emissions represented less than 1 % of the ships included in this study.

We have included in the modelling most of the various engine setups, such as gas turbines, diesel electric and mechanical power transmission, nuclear vessels and sailboats. We allowed for the fact that the operation of a shaft generator is possible for vessels, which have been indicated to have geared drives or power take-off systems.

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The modelled values of engine loads also take into account multi-engine setups and load balancing of operational engines.

The STEAM model simulates the required power of the main and auxiliary engines, by determining the required power level set up that corresponds to the speed value in the AIS messages. All ships are modelled individually, and the modelling takes into account the differences in hull form, propeller efficiency, shaft generators and auxiliary engine usage. The sulphur content of the fuel has been modelled explicitly for each vessel and its engines. We have allowed for the sulphur reduction techniques and the influences of the regulations regarding fuel sulphur content in various regions and during various time periods (Johansson et al., 2013).

In cases, in which more detailed information could not be obtained from engine manufacturers, the Specific Fuel Oil Consumption (SFOC) has been modeled based on the methods in the second IMO GHG report (Buhaug et al., 2009). The SFOC is modelled as a function of engine load. In the model, low engine load levels can increase SFOC up to 25 %. Operating engines outside their optimal working range (without de-rating) will lead to increased SFOC and emission factors. The emissions of particulate matter, sulphate and water are modeled as a function of the fuel sulphur content. All vessels have been treated as single displacement hulls; catamarans and hydrofoil vessels were not separately modeled. The currently modelled pollutants are NO_x, SO_x, CO, CO_2, EC, OC, ash and hydrated SO_4. The model can also be used to generate vessel-specific emission inventories, and to predict the amount of consumed fuel. The transport work (cargo payload) is described as the product of the weight of cargo transported and the distance travelled (commonly in units of ton km). In this work we adopted the scheme reported by the second IMO GHG study (Buhaug et al., 2009).

2.2.1 Detection of locations with the highest shipping emissions of CO2

We have evaluated in more detail the emissions from locations with an especially high emission intensity, which we refer to as shipping emission "hotspots". The STEAM model has been executed on a resolution of approximately 2.5 km × 2.5 km in the EU-

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region. For the evaluation of hotspots the resulting CO_2 emission grid has subsequently been evaluated using the following rules:

1. The sum of emissions in the vicinity of each grid cell has been calculated within a radius of 10 km (such a domain contains approximately 44 closest grid cells).
2. The sum (if high enough) along with center coordinates are placed in the list of top 30 highest ranking CO_2 hotspots.
3. The first and second steps are repeated until each cell in the emission grid has been once the candidate emission hotspot.

This analysis also indicates the areas with the highest ship fuel consumption, whether this occurs in harbour areas or along shipping lanes.

3 Results and discussion

3.1 Summaries of total emissions and their geographical distribution in Europe

A compilation of computed emissions, payloads, numbers of ships and distances travelled has been presented in Table 1. The geographical distribution of ship CO_2 emissions and hotpots and are illustrated in Figs. 2 and 3. The results have been presented in terms of (i) IMO registered and unidentified ships, (ii) sea regions, (iii) top flag states, and (iv) ship types. The percentages of the total ship emissions in each of the sea regions for the selected pollutants have also been presented graphically in Fig. 4. The region denoted as "other" (that refers to other European sea areas) includes the western parts of the Black Sea, Canary Islands, Celtic Sea, Barents Sea and North-East Atlantic Ocean (see Fig. 1).

The highest CO_2 emissions are located along the busiest shipping lines near the coast of the Netherlands and in the English Channel, in the straits of Gibraltar, Sicily

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and Bosporus, and in the Danish Straits. In addition, there are localized high amounts of CO_2 emissions near several major ports. These ports include, in particular, the ones in the Netherlands (e.g. Antwerp, Rotterdam and Amsterdam), Gibraltar, St. Petersburg and some ports in the UK, Germany, Italy and Spain. The relative geographical distribution of the shipping emissions is similar also for the other modelled compounds, and those results have therefore not been presented here.

The international cargo traffic contributes significantly to the emissions at the most densely trafficked shipping lanes; a prominent example is the ship route in the Mediterranean Sea that extends from Suez Canal to Gibraltar. The route patterns of passenger traffic are different; these occur more frequently via shorter routes. For example, there are a lot of routes between the islands in Greece and the mainland, and between Italy and the islands of Sardinia, Corsica and Sicily. There is a dense network of shorter passenger vessel routes in numerous sea regions in the Mediterranean. The routes of cargo and passenger traffic intersect also in several regions of the Baltic Sea and the North Sea. For example, in the English Channel passenger traffic takes mainly place across the channel, whereas most of the cargo routes are aligned along the Channel.

We have also analysed the areas that have the highest CO_2 shipping emissions in Europe. These areas were defined as circular domains with a radius of 10 km. We have presented the results for 30 areas that had the highest estimated emissions. These domains are called in the following as the emission hot spots. The results have been presented in Table 2 and in Fig. 3. The combined CO_2 emissions of these 30 hotspot areas correspond to approximately 7 % of total CO_2 emitted by ships in Europe.

The area including the Netherlands and the English Channel has the highest density of these hot spots; there are in total ten domains in these regions amongst the top 30 shipping CO_2 hotspots in Europe. There are also hot spots at numerous locations in the Mediterranean, some in Germany, and a few in the Baltic Sea region. Harbour areas dominate the list of highest CO_2 hotspots. Besides harbour locations, some shipping lanes and some major coastal cities are associated with very high CO_2 emissions. Clearly, a major part of emissions in these coastal cities are also due to harbour activi-

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ties. Several of the largest harbours in Europe reside in the Netherlands and along the English Channel.

In some sea regions, busy shipping traffic is focused in geographical bottlenecks with high CO_2 emissions; prominent examples of these in southern Europe are the strait of Gibraltar, the channel between Malta and Sicily, and the Bosporus Strait. However, the emissions originated in the Bosporus Strait are not well represented in the data, as the data from the Turkish national AIS network were not available for this study. The data from Greece and Romania include part of vessel activity from this area, but not a sufficient coverage.

Emissions of CO_2 originated from Mediterranean shipping were found to be about 36 % of the total CO_2 emissions from shipping. Emissions from ships in the North Sea and the Baltic Sea constituted approximately one quarter and one seventh of the total emissions of CO_2 from shipping, respectively. The emissions of NO_x from the ships in the Mediterranean Sea (1 186 000 tons, calculated as NO_2) are almost as high as those in the Baltic Sea (359 000 tons) and the North Sea (664 000 tons) combined. Emissions of NO_x from other areas considered in this study are of the same magnitude as contribution from the North Sea shipping. The share of the Mediterranean sea traffic is even larger in case of the SO_x emissions, compared with the corresponding emissions for CO_2 and NO_x.

The emissions originated from the other sea areas except for the three specifically mentioned three sea regions (Baltic Sea, North Sea and Mediterranean Sea) have also been reported in Table 1 and Fig. 4. These areas include the western parts of the Black Sea, Canary Islands, Celtic Sea, Barents Sea and North-East Atlantic Ocean. The emissions from shipping in these other regions were estimated to produce almost one quarter of CO_2; however, this value is probably an underestimation, as the coverage of AIS reception in remote sea areas, such as the Atlantic Ocean, is incomplete.

These results have obvious policy implications. Reductions of ship exhaust emissions in areas with high emission levels and a surrounding dense population is likely to yield major health benefits (e.g., Corbett et al., 2007). However, policy changes for

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reducing shipping emissions may have significant cost impacts (e.g., Johansson et al., 2013; Kalli et al., 2013), which necessitates thorough assessments of both the costs and the benefits. The identified emission hot spots, especially those which are in the vicinity of major cities, are prime candidates for enhanced emission control measures. The low fuel sulphur requirement of the EU directive has already addressed some aspects of this issue.

3.2 Analysis of emissions in terms of the flag state and the ship type

The AIS signals include a Maritime Mobile Service Identity (MMSI) code that contains information that specifies the flag state of the ship. We have selected 20 flag states that had the highest total fuel consumption in Europe in 2011, and evaluated their annual statistics of the numbers of ships, payload, and the emissions of three pollutants. The results of this analysis are included in Table 1 and in Fig. 5. The emissions have been presented as fractions (%) of the total emissions in the European sea areas in Fig. 5.

The total fuel consumption was largest for the Liberian and second largest for the Italian fleet. The UK, Malta, Bahamas, Norway and the Netherlands also have had major fleets. In addition to major European states, such as Italy, UK, Norway, the Netherlands, Greece, Germany, etc., major fleets have also sailed under the flags of relatively smaller states, such as Liberia, Malta, Bahamas, Marshall Islands, etc. The flags of convenience allow open vessel registration regardless of the owner's nationality (ITF, 2014), which is in contrast with national ship registries. The states among the top 20 fuel consumers with the flags of convenience are Panama, Cyprus, Antigua and Barbuda, Marshall Islands, Bahamas, Malta and Liberia. The CO_2 emission shares of vessels in open registries are responsible for 25 %, European vessels contribute 55 % and vessels with some other flag contribute 20 % of the total CO_2 emissions. The emissions under flags of convenience are distributed throughout the all EU sea regions, whereas the emissions of vessels of some countries (for example Sweden, France and Finland) mostly occur close to the national coastlines or in the nearby sea areas.

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We have allocated the emissions to IMO registered (referred here also as "large") and unidentified (referred to as "small") ships in Table 1, as the IMO registered ships constitute most of the commercial marine traffic. According to the values in Table 1, the contribution of unidentified vessels is only 2.2 % of the total CO_2 emissions, although the number of such small vessels is 43 % of all vessels. The significance of the contribution of unidentified ships to total emissions varies in terms of pollutants; for CO it is the largest (4 %). The unidentified ships travel 7 % of the distances travelled by all vessels. For some countries, such as the Netherlands, Germany, France and Sweden, the share of large vessels is less than one third of the total number of ships. This may indicate the different practices in including the small vessel movements in overall traffic image of various countries. It is very likely that small vessel traffic is underestimated by AIS, because for these vessels AIS voluntary, in contrast to the requirements for large vessels. In this context, the Dutch fleet is an extreme case, in which only 13 % of 7530 vessels are considered large. In the Dutch case, the share of CO_2 emitted by small vessels is 43 %, which is the largest fraction for all of the studied fleets. Already in Finland, there are over 190 000 boats (Trafi, 2014) and 525 Finnish vessels were picked up by AIS in Europe. Clearly, the representation of small vessel traffic activity is incomplete in AIS.

The descriptions of the technical details for small vessels in the emission inventory are limited. These are significantly less accurate than the corresponding descriptions for large vessels, for which the engine setup and technical data are readily available. Model results for the fuel consumption of small vessels are further complicated by an incomplete inclusion of the activities of small vessels; a fraction of the small vessels do not carry AIS equipment on board.

The shares of emissions and payload (i.e., transport work) for various ship types have been presented in Fig. 6. A comparison of CO_2 emissions and payload reflects the energy efficiency of various ship types. We used the approach described by Buhaug et al. (2009). The unit emissions (the mass of CO_2 emitted, divided by transport work) are lowest for the tanker class (7.3 $g\,ton^{-1}\,km^{-1}$), slightly higher for con-

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tainer (10.2 $g\,ton^{-1}\,km^{-1}$) and cargo vessels (10 $g\,ton^{-1}\,km^{-1}$), and significantly higher for passenger traffic (175 $g\,ton^{-1}\,km^{-1}$). However, the values for passenger traffic are not directly comparable, as the above mentioned transport work of passenger traffic has been calculated as a function of cargo capacity, which does not take the number of passengers into account. There are large variations of unit emissions between various vessels in the cargo class, as this class includes both dry bulk and palletized cargo vessels, for which there are large differences in the use of their cargo carrying capacity.

3.3 Seasonal variation of the emissions

There were clear seasonal variations in the emissions of all pollutants; the variations in case of CO2 have been presented in Fig. 7. For example, the emissions of CO2 in June are 30 % larger than the corresponding values in January. During the summer months (June, July and August), both the numbers of passenger vessels and small vessels is the largest, especially in the Mediterranean Sea. This is mainly caused by the increased recreational travel; in summer the number of small vessels is at maximum in all sea areas. The emissions of container ships are also higher in the summer than winter, but the activities of tankers and cargo ships exhibit no substantial seasonal dependency. Recently, Ialongo et al. (2014) used satellite based OMI NO_x observations to track the annual variability of NO_x emissions from Baltic Sea shipping. Ialongo et al. demonstrated decrease in satellite observed NO_x similar to Jalkanen et al. (2014). Although the emissions cannot be directly compared with observations of atmospheric columns of NO_x, decrease of NO_x was observed in both datasets which coincide with the economic downturn during 2008–2009.

A disaggregated compilation of vessel types and their operational features has been presented in Table 3. The five more general level categories (cargo, container, tanker, passenger and other) have been divided to more detailed categories. The division of vessel activity to operational modes (cruising, maneuvering and hoteling) has not been predetermined; it has been defined by vessel activity data. Based on AIS data, it is

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possible to determine these explicitly, which will significantly decrease the large uncertainties that habe previously been associated with vessel activities.

The shares of fuel used by the main engines have also been presented in Table 3, these have also been evaluated by the model. The amounts of fuel used in main and auxiliary engines depend not only on vessel specifics, but also its operational profile. However, there is a major uncertainty in the predictions of the fuel consumption of the auxiliary engine, as the use of an auxiliary engine varies greatly, even for ships of the same type. The use of auxiliary power cannot be determined from tank tests of ship resistance, unlike the power needed for propulsion, for which various theories exist for performance prediction. In this study, we have used the methodology presented previously (Jalkanen et al., 2009, 2012; Johansson et al., 2013). This method combines the information on cargo capacity and auxiliary engine power profiles. However, there are also other modelling approaches, which are based on extensive vessel boarding programs (Starcrest, 2013), local knowledge and pre-assigned contributions (Dalsoren, 2009).

3.4 Comparison of the predictions of various emission inventories

The comparison of the numerical results of various European-scale emission inventories can be challenging, as pointed out, e.g., by EEA et al. (2013). The main reasons for this are that the methodologies and various modelling selections used for evaluating shipping emissions vary substantially in various published studies. E.g., the various studies may define differently the geographical domain, and some studies address only international ship traffic.

The current work reports emissions for the year 2011. Significant reductions were therefore in force regarding the sulphur content of marine fuel in the North Sea and the Baltic Sea area, as well as the requirement for low sulphur fuel in EU harbour areas. The effects of these regulations were included in the current work, and it is therefore not possible to directly compare the predicted SO_x and $PM_{2.5}$ emissions with the corresponding values during previous years. Changes in international regulations

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also concern NO_x, but to a lesser extent, as the IMO Tier II NO_x limits for marine diesel engines affect all engines built since 1 January 2011. The ships constructed after this date will have to conform to Tier II NO_x requirements (15 % less NO_x produced when compared with Tier I engines), but such new ships constitute only 3 % of the fleet of IMO registered vessels in this study. Significant policy changes are expected to be implemented in 2015, regarding the sulphur content of marine fuel.

The emissions of NO_x for the Mediterranean Sea reported in this work are lower than in the EMEP inventory, qualitatively the same result was reported by Marmer et al. (2009). Marmer et al. also concluded that their methodology yielded lower SO_x emissions than the corresponding EMEP values. The prediction of the STEAM inventory for the Mediterranean shipping in the case of NO_x is about 40 % of the corresponding value in the EMEP inventory. Vinken et al. (2014) used satellite observations of NO_x from the OMI instrument to constrain top-down emissions from ships. The study area of this study (defined by AIS coverage illustrated in Fig. 1) and Vinken et al. (2014) are the same (N,W,S boundaries are same), except that the domain used by Vinken et al. (2014) extends further to the East (50E); neither of these assessments includes the trans-Atlantic ship traffic. Vinken et al. (2014) reported up to 60 % smaller emissions for the Mediterranean shipping than the EMEP inventory.

The emissions of NO_x for the Baltic Sea are similar in the STEAM and EMEP inventories, whereas Vinken et al. (2014) reported significantly higher emissions of NO_x than either of the above mentioned two inventories. The reported total NO_x emission for all European sea areas in this study is 2.94 million tons, which corresponds to 0.9 million tons of reduced nitrogen (N). This is close to the corresponding value reported by Vinken et al. (2014), their estimate for European shipping emissions was 1.0 million tons of reduced nitrogen for the year 2006. Unfortunately, AIS data from 2005–2006 for all European sea areas is not available since at the time AIS had just been deployed as a navigational aid and fleet wide adoption of AIS was in progress. Despite the difference of study periods (this study 2011; Vinken et al., 2006) the magnitude of satellite constrained NO_x emission dataset of Vinken et al. is very similar to our results.

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For the Baltic Sea, the direct comparison of 2006 NO_x emission dataset (Jalkanen et al., 2014) with Vinken et al. (2014) is possible. The modeled emissions of NO_x in the Baltic Sea area using STEAM in 2011 and 2006 are fairly similar to each other; the difference is less than 10 %. The results of our work partially agree (NO_x emission reduction of Mediterranean shipping) with Vinken et al. (2014), but disagree with the conclusions reported for the Baltic Sea ship emissions. The difference between STEAM and EMEP in the Baltic Sea shipping NO_x emissions are less than 6 %.

The annual SO_x emissions reported in this study for various sea regions are 88, 154 and 613 thousand tons for the Baltic Sea, North Sea and the Mediterranean, respectively. The corresponding SO_x emissions of the EMEP inventory for the above mentioned sea areas are 82, 192 and 1367 thousand tons. For the Baltic Sea, the inventories are approximately in agreement; there is a larger difference (20 %) between the inventories in the North Sea. However, the predicted emissions of SO_x in the Mediterranean Sea by the two inventories are drastically different. The SO_x emissions predicted in this study for the Mediterranean are less than a half of the corresponding values in the EMEP inventory. As discussed above, this was also the case for the NO_x emissions.

The reasons for such major differences in the predictions of these two inventories could be caused, for example, by the neglect of the impacts of relevant legislation, such as the EU sulphur directive (2012/33/EC). This directive limits the sulphur content of marine fuels to 0.1 % (by mass) in harbour areas and to 1.5 % (by mass) for passenger vessels on a regular schedule. It is possible that not all passenger ships comply with the requirement of 1.5 % fuel sulphur content, as assumed in the STEAM model. However, a possible non-compliance by a fairly small fraction of ships would explain only a minor portion of the differences between the STEAM and EMEP inventories. More information on the compliance with EU regulations can be obtained either during Port State Control checks, or via relevant compliance monitoring schemes (Balzani et al., 2014; Berg et al., 2012; Beecken et al., 2014a, b; Pirjola et al., 2014).

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It is not possible to perform a similar satellite-based comparison for SO_x, due to the technical limitations of currently available satellite instruments; these cannot accurately determine ship emitted SO_x near the sea surface. Such instruments can detect stationary SO_2 sources that have an emission higher than approximately 70 kilotons (Fioletov et al., 2013); however, this value is too high for the shipping lanes in Europe.

The inventory of Cofala et al. (2007) includes an estimate for ship CO_2 emissions, which is based on the same methodology as the EMEP inventories. According to Cofala et al. (2007), the predicted CO_2 emission in 2010 from ships in the Mediterranean is approximately 76 million tons (obtained by a linear interpolation between the values in 2000 and 2020), which corresponds to 24 million tons of fuel burned. In this work, the Mediterranean shipping was responsible for 51 million tons of CO_2 emitted.

The differences in $PM_{2.5}$ emissions between this work and Cofala et al. (2007) in all sea areas are less than 20 %. A large variation could be expected in the $PM_{2.5}$ emissions predicted by the various methods, due to the substantial variability of experimentally determined emission factors and the differences in $PM_{2.5}$ sampling methods (e.g., Jalkanen et al., 2012). Clearly, the $PM_{2.5}$ emissions are associated with the SO_x emissions and the sulphur content of the fuel, as SO_4 is one of the main constituents of atmospheric $PM_{2.5}$.

The range of European shipping emissions of CO_2 reported in the review by EEA et al. (2013) is 71–153 million tons (for various years between 2000–2009), based on the work of EEA et al. (2012), Cofala et al. (2007), Whall et al. (2002), Schrooten et al. (2009) and Campling et al. (2012), the estimate of the present study is at the higher end of this range. Similarly, in case of NO_x emissions, the range of values in various inventories reviewed by EEA et al. (2013) is 1.7–3.6 million tons whereas this study evaluated the European emissions from shipping in 2011 to be 2.94 million tons, calculated as NO_2. However, in case of NO_x the inclusion of variability in assumptions of technology development (Tier I, II, inclusion of NO_x abatement, NO_x emission factor rpm dependency) of marine engines can have a large impact on overall NO_x results of various inventories, especially if ship emissions from different years are compared.

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4 Conclusions

The comparison of emitted pollutants with existing ship emission inventories revealed that there are major differences between the estimates of the various inventories for the emissions of ships sailing the Mediterranean Sea, whereas the results were better in agreement for the North Sea and the Baltic Sea regions. The NO_x, SO_x and CO emissions evaluated in this study for the Mediterranean Sea were roughly half of the corresponding values in EMEP and IIASA inventories, whereas differences in $PM_{2.5}$ emissions were less than 20 % between these different inventories. Satellite observations using the OMI instrument also indicated smaller annual emissions of NO_x in the Mediterranean, compared with the EMEP inventory (EMEP, 2014). The reasons for these deviations should be investigated further and confirmed with independent experimental datasets, as these can have significant policy implications concerning health and environmental impact assessments.

Despite the wide geographical extent, the ship emission data can also be segmented in terms of the various properties of vessel categories or individual vessels. This makes it possible to classify the emissions using several criteria. The disaggregation of ship emissions into individual vessels on a fine temporal resolution also allows fine resolution air quality and health impact assessment studies. A specific advantage of an inventory based on individual vessel data is that it facilitates comparisons with experimental stack measurements.

According to this study, the vessels carrying an EU flag were responsible for 55 % of CO_2 emissions in the EU, whereas the states with flags of convenience and other states constitute the remaining share. The CO_2 hotspot mapping indicate that the English Channel constitutes a large source of ship emitted CO_2, both from harbour areas and densely trafficked shipping lanes.

The emissions from ships have a clear seasonal variation; the emission maximum occurs during the summer months. This concerns especially passenger traffic, but also containerships have the same seasonal pattern. However, the emissions originated

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from oil tankers and other cargo ships do not have a clear seasonality. Temporal variation of ship emissions has mostly been neglected in previous emission inventories, due to inherent limitations of the activity data used as a basis for these inventories. Seasonal variations can be of the order of 30 %; these features should therefore be included in emission and health impact assessments.

The current work also facilitates studies of ship energy efficiency, as all emissions and fuel data are generated on the ship level. There were substantial differences between fuel burned and transport work carried out by various ship types. The unit emissions were the lowest for the oil tankers and largest for passenger vessels. However, the description of transport work of passenger vessels currently considers cargo operations and does not completely cover passenger cargoes.

The availability of the shipping activity data for research can be a challenging task; however, there are several options for data acquisition. Data collected by maritime authorities are rarely available for research purposes. However, there are networks of volunteers maintaining AIS base stations; activity data can therefore either be shared or is commercially available. Most satellite AIS datasets are available from commercial service providers, but also national space programs may provide access to these. Automatic AIS data collection facilitates annually updated ship emissions in the EU waters; however, the coverage area should be expanded to the North-East Atlantic Ocean. This could be done with the inclusion of other activity data sources, such as, e.g., the satellite AIS data, which could be used to extend the AIS coverage, e.g., to fully cover the EMEP modelling domain.

Acknowledgements. This study was made possible as a result of cooperation with the European Maritime Safety Agency and the Norwegian Coastal Administration. We would like to thank both agencies for making the relevant AIS datasets available for this work. We are also grateful for financial support of the European Space Agency (Samba project), FP7 project TRANSPHORM and the Academy of Finland (APTA project). This work is partly based on the material supplied by IHS Fairplay.

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Balzani Lööv, J. M., Alfoldy, B., Gast, L. F. L., Hjorth, J., Lagler, F., Mellqvist, J., Beecken, J., Berg, N., Duyzer, J., Westrate, H., Swart, D. P. J., Berkhout, A. J. C., Jalkanen, J.-P., Prata, A. J., van der Hoff, G. R., and Borowiak, A.: Field test of available methods to measure remotely SO_x and NO_x emissions from ships, Atmos. Meas. Tech., 7, 2597–2613, doi:10.5194/amt-7-2597-2014, 2014.

Beecken, J., Mellqvist, J., Salo, K., Ekholm, J., and Jalkanen, J.-P.: Airborne emission measurements of SO_2, NO_x and particles from individual ships using a sniffer technique, Atmos. Meas. Tech., 7, 1957–1968, doi:10.5194/amt-7-1957-2014, 2014a.

Beecken, J., Mellqvist, J., Salo, K., Ekholm, J., Jalkanen, J.-P., Johansson, L., Litvinenko, V., Volodin, K., and Frank-Kamenetsky, D. A.: Emission factors of SO_2, NO_x and particles from ships in Neva Bay from ground-based and helicopter-borne measurements and AIS-based modeling, Atmos. Chem. Phys. Discuss., 14, 25931–25965, doi:10.5194/acpd-14-25931-2014, 2014b.

Berg, N., Mellqvist, J., Jalkanen, J.-P., and Balzani, J.: Ship emissions of SO_2 and NO_2: DOAS measurements from airborne platforms, Atmos. Meas. Tech., 5, 1085–1098, doi:10.5194/amt-5-1085-2012, 2012.

Buhaug, Ø., Corbett, J. J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D. S., Lee, D., Lindstad, H., Markowska, A. Z., Mjelde, A., Nelissen, D., Nilsen, J., Palsson, C., Winebrake, J. J., Wu, W.-Q., and Yoshida, K.: Second IMO GHG Study, International Maritime Organization (IMO), London, UK, 2009.

Campling, P., Janssen, L., and Vanherle, K.: Specific Evaluation of Emissions from Shipping Including Assessment for the Establishment of Possible New Emission Control Areas in European Seas, VITO, Mol, Belgium, 2012.

Cofala, J., Amann, M., Heyes, C., Wagner, F., Klimont, Z., Posch, M., Schöpp, W., Tarasson, L, Jonson, J. E., Whall, and C., Stavrakaki: Analysis of Policy Measures to Reduce Ship Emissionsin the Context of the Revision of the National Emissions Ceilings Directive Final Report, International Institute for Applied Systems Analysis, Austria, 2007.

Corbett, J. J., Winebrake, J. J., Green, E. H., Kasiblathe, P., Eyring, V., and Lauer, A.: Mortality from ship emissions: a global assessment, Environ. Sci. Technol., 41, 8512–8518, 2007.

Dalsøren, S. B., Eide, M. S., Endresen, Ø., Mjelde, A., Gravir, G., and Isaksen, I. S. A.: Update on emissions and environmental impacts from the international fleet of ships: the contribution

from major ship types and ports, Atmos. Chem. Phys., 9, 2171–2194, doi:10.5194/acp-9-2171-2009, 2009.
EEA: The Impact of International Shipping on European Air Quality and Climate Forcing, EEA Technical report No 4/2013, Copenhagen, 2013.
EMEP: available at: http://www.ceip.at/ms/ceip_home1/ceip_home/webdab_emepdatabase/emissions_emepmodels/, last access: 24 November 2014, 2014.
Endresen, Ø., Sørgård, E., Sundet, J. K., Dalsøren, S. B., Isaksen, I. S. A., Berglen, T. F., and Gravir, G.: Emission from international sea transportation and environmental impact, J. Geophys. Res., 108, 4560, doi:10.1029/2002JD002898, 2003.
EU: Directive EU: Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels,Brussels, 2012.
Fioletov, V. E., McLinden, C. A., Krotkov, N., Yang, K., Loyola, D. G., Valks, P., Theys, N., Van Roozendael, M., Nowlan, C. R., Chance, K., Liu, X., Lee, C., and Martin, R. V.: Application of OMI, SCIAMACHY, and GOME-2 satellite SO_2 retrievals for detection of large emission sources, J. Geophys. Res.-Atmos., 118, 11399–11418, 2013.
Ialongo, I., Hakkarainen, J., Hyttinen, N., Jalkanen, J.-P., Johansson, L., Boersma, K. F., Krotkov, N., and Tamminen, J.: Characterization of OMI tropospheric NO_2 over the Baltic Sea region, Atmos. Chem. Phys., 14, 7795–7805, doi:10.5194/acp-14-7795-2014, 2014.
IHS Global: Chemin de la Mairie, Perly, Geneva, Switzerland, 2014.
International Maritime Organization (IMO): Regulations for the Prevention of Air Pollution from Ships and NO_x Technical Code, Annex VI of the MARPOL convention 73/78, London, 1998.
ITF: International Transporter Workers' Federation, available at: http://www.itfglobal.org/en/transport-sectors/seafarers/in-focus/flags-of-convenience-campaign/, last access: 21 November 2014, 2014.
Jalkanen, J.-P., Brink, A., Kalli, J., Pettersson, H., Kukkonen, J., and Stipa, T.: A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area, Atmos. Chem. Phys., 9, 9209–9223, doi:10.5194/acp-9-9209-2009, 2009.
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, Atmos. Chem. Phys., 12, 2641–2659, doi:10.5194/acp-12-2641-2012, 2012.
Jalkanen, J.-P., Johansson, L., and Kukkonen, J.: A comprehensive inventory of the ship traffic exhaust emissions in the Baltic Sea from 2006 to 2009, Ambio, 43, 311–324, 2014.

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A comprehensive inventory of ship traffic exhaust emission

J.-P. Jalkanen et al.

Johansson, L., Jalkanen, J.-P., Kalli, J., and Kukkonen, J.: The evolution of shipping emissions and the costs of regulation changes in the northern EU area, Atmos. Chem. Phys., 13, 11375–11389, doi:10.5194/acp-13-11375-2013, 2013.

Kalli, J., Jalkanen, J.-P., Johansson, L., and Repka, S.: Atmospheric emissions of European SECA shipping: long-term projections, WMU J. Marit. Affairs, 12, 129–145, 2013.

Marmer, E., Dentener, F., Aardenne, J. v., Cavalli, F., Vignati, E., Velchev, K., Hjorth, J., Boersma, F., Vinken, G., Mihalopoulos, N., and Raes, F.: What can we learn about ship emission inventories from measurements of air pollutants over the Mediterranean Sea?, Atmos. Chem. Phys., 9, 6815–6831, doi:10.5194/acp-9-6815-2009, 2009.

Pirjola, L., Pajunoja, A., Walden, J., Jalkanen, J.-P., Rönkkö, T., Kousa, A., and Koskentalo, T.: Mobile measurements of ship emissions in two harbour areas in Finland, Atmos. Meas. Tech., 7, 149–161, doi:10.5194/amt-7-149-2014, 2014.

Schrooten, L., De Vlieger, I., Int Panis, L., Chiffi, C., and Pastori, E.: Emissions of maritime transport: a European reference system, Sci. Total Environ., 408, 318–323, 2009.

Starcrest: Port of Los Angeles Inventory of Air Emissions 2012, Los Angeles, USA, 2013.

Trafi: Finnish Transport Safety Agency, National small boat register, available at: http://www.veneily.fi/venerekisteri, last access: 24 November 2014, 2014.

Vinken, G. C. M., Boersma, K. F., van Donkelaar, A., and Zhang, L.: Constraints on ship NO_x emissions in Europe using GEOS-Chem and OMI satellite NO_2 observations, Atmos. Chem. Phys., 14, 1353–1369, doi:10.5194/acp-14-1353-2014, 2014.

Wang, C., Corbett, J. J., and Firestone, J.: Improving spatial representation of global ship emissions inventories, Environ. Sci. Technol., 42, 193–199, 2008.

Whall, C., Cooper, D., Archer, K., Twigger, L., Thurston, N., Ockwell, D., McIntyre, A., andRitchie, A.: Quantification of Emissions from Ships Associated with Ship Movements Between Ports in the European Community, Final Report for European Commission, ENTEC UK Limited, London, 2002.

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Table 1. Emissions and shipping statistics in the SafeSeaNet area in 2011. The section "All ships" includes also emissions from unidentified vessels. "IMO registered" refer to commercial ships with specified IMO number. In the section "top flags", twenty countried are presented that have the largest contributions to emitted CO_2. Together these flag states represent over 76 % of the total CO_2 emitted. The NO_x emissions have been calculated as NO_2. The details of ship type aggregation is further explained in Annex II.

EU – 2011		CO_2 [ton]	NO_x [ton]	SO_x [ton]	$PM_{2.5}$ [ton]	CO [ton]	Payload [10^9 ton · km]	Ships	Travel [10^6 km]
All ships		130 798 034	2 941 469	1 242 341	260 521	209 481	10 597	48 783	887
	IMO registered	127 853 532	2 894 117	1 232 398	257 010	201 022	10 597	27 580	822
	Unidentified	2 944 502	47 352	9 943	3 512	8 459	0	21 203	65
Region	Baltic Sea	17 744 133	358 993	88 046	23 398	26 965	897	–	–
	North Sea	30 753 487	663 884	154 237	41 148	53 080	2 131	–	–
	Medit. Sea	50 720 901	1 185 902	613 204	120 286	78 239	4 419	–	–
	Other	31 131 819	727 365	386 387	75 405	50 551	3 149	–	–
Top flag states	Liberia	11 150 027	284 274	137 703	27 058	19 027	1 457	1 811	47
	Italy	8 715 284	189 631	82 215	17 207	12 716	371	2 022	46
	UK	8 256 851	180 919	72 237	15 511	13 708	566	2 715	52
	Malta	7 667 022	174 299	73 162	15 266	11 418	727	1 896	58
	Bahamas	6 020 361	135 291	57 290	11 956	8 816	491	980	32
	Norway	5 767 792	114 667	35 162	8 505	9 677	232	2 178	53
	Netherlands	5 742 984	109 772	33 092	8 257	9 751	220	7 530	72
	Marshall Isl.	5 699 343	142 695	73 457	14 272	8 810	764	1 176	27
	Greece	5 062 098	122 448	55 204	11 155	7 461	567	969	25
	Germany	4 746 092	107 309	43 091	9 238	9 252	353	2 911	31
	Antigua and B.	4 715 428	96 828	35 848	7 990	6 953	265	1 086	54
	Denmark	4 673 877	103 689	41 400	8 970	9 037	365	1 191	30
	Cyprus	3 815 263	84 179	31 448	6 854	6 287	299	721	27
	Hong Kong	3 539 554	92 450	46 537	9 044	6 402	520	679	14
	Sweden	3 096 531	55 345	18 388	4 560	4 260	84	951	20
	Panama	2 960 001	77 088	38 091	7 420	4 881	357	628	13
	France	2 162 569	47 827	19 703	4 220	3 855	110	1 763	18
	Finland	2 144 776	39 887	12 422	3 099	3 245	70	525	14
	Turkey	2 056 285	45 138	22 278	4 473	3 182	172	805	22
	Spain	1 925 528	36 568	15 098	3 307	3 032	65	690	12
Ship types	Passenger ships	21 570 658	424 776	155 087	35 273	32 953	123	2 078	104
	Cargo ships	33 353 076	755 964	316 002	65 991	47 718	3 332	10 813	336
	Container ships	35 866 083	897 086	443 584	87 321	67 622	3 527	2 880	133
	Tankers	26 262 775	626 577	281 192	56 995	37 075	3 615	5 198	160
	Other	10 800 940	189 713	36 533	11 430	15 654	0	6 611	90

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Table 2. The locations in European sea areas that contain the highest CO_2 emissions within a circular area that has a radius of 10 km.

Rank	Description	Latitude [° N]	Longitude [° E]	CO_2 (r = 10 km) [10^6 ton]	Fraction of total CO_2 [%]
1	Antwerpen harbour	51.3172	4.3066	786	0.61 %
2	Gibraltar harbour	36.1037	−5.3687	668	0.51 %
3	West of Rotterdam	51.9735	4.1022	604	0.47 %
4	Hamburg	53.5441	9.8937	471	0.36 %
5	St. Petersburg	59.9202	30.1643	367	0.28 %
6	Shipping lane, Gulf of Gibraltar	35.9396	−5.5390	367	0.28 %
7	South-West of Rotterdam	51.8563	4.3406	352	0.27 %
8	North-West of Bremerhaven	53.5910	8.4629	348	0.27 %
9	Shipping lane, English channel	51.0593	1.5470	304	0.23 %
10	Las Palmas de Gran Canaria harbour	28.1571	−15.3507	292	0.22 %
11	Genoa harbour	44.3551	8.8717	289	0.22 %
12	East of Vlissingen, harbour	51.4109	3.6933	281	0.22 %
13	Zeebrugge harbour	51.3875	3.1142	261	0.20 %
14	Barcelona harbour	41.3077	2.2284	242	0.19 %
15	Valencia harbour	39.4089	−0.2585	236	0.18 %
16	Eastern Malta	35.8693	14.5951	233	0.18 %
17	Shipping lane, West of Gibraltar	35.9162	−5.7775	209	0.16 %
18	Shipping lane, South of Gibraltar	36.0803	−5.1302	205	0.16 %
19	Napoli habour	40.7920	14.1863	201	0.16 %
20	Ijmuiden harbour	52.4658	4.7495	201	0.15 %
21	West of Zeebrugge	51.4344	2.6372	200	0.15 %
22	North-West of Rotterdam	52.0907	3.8296	196	0.15 %
23	Aberdeen harbout	57.2010	−1.9959	195	0.15 %
24	Gulf of Fehmarn	54.5990	11.2905	193	0.15 %
25	Shipping lane, English channel	51.0593	1.78557	193	0.15 %
26	Constanta harbour	44.1207	28.7334	191	0.15 %
27	Shipping lane, West of Gibraltar	35.9162	−6.0160	187	0.14 %
28	Livorno harbour	43.5346	10.2004	183	0.14 %
29	Tallinn harbour	59.5217	24.7134	181	0.14 %
30	Harwich-Felixstowe harbour	51.9266	1.3426	179	0.14 %

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Table 3. Summary of average operational features of some selected ship types. The first column indicates the aggregated ship type, whereas the second column contains a more detailed description of vessel type. The time spent in each operation mode (cruising, maneuvering, hoteling) is indicated by the next three columns as percentages. "ME of Fuel" refers to the fraction of fuel used in main engines from total fuel consumption.

Ship type	Disaggregated ship type	cruising [%]	maneuv. [%]	hoteling [%]	Build year	ME of Fuel [%]	design speed	Ships
Passenger	Cruise Ship	54	3	44	1988	81	19	248
Passenger	RoRo/Passenger	40	4	56	1991	73	19	1294
Containerships	Container ship	56	3	41	2001	66	21	2312
Cargo	RoRo Cargo	52	2	46	1992	76	17	494
Cargo	General Cargo	50	3	47	1991	57	12	5956
Cargo	Bulk Cargo	54	2	43	1996	72	14	3443
Cargo	Vehicles (PCTC)	64	3	33	2000	77	19	459
Cargo	Reefers	49	3	48	1991	60	18	482
Tankers	Chemical Tanker	49	3	48	2002	64	14	2371
Tankers	Product Tanker	36	4	60	1995	67	13	862
Tankers	Crude Oil Tanker	46	5	49	2002	79	14	1094
Tankers	LNG Tanker	63	5	33	2001	91	19	191
Other ships	Supply (AHTS)	21	15	64	1997	47	13	851
Other ships	Dredger	22	11	67	1984	51	10	376
Other ships	Tugboats	14	7	79	1993	38	12	1603
Other ships	Fishing Vessel	23	13	64	1988	37	12	984

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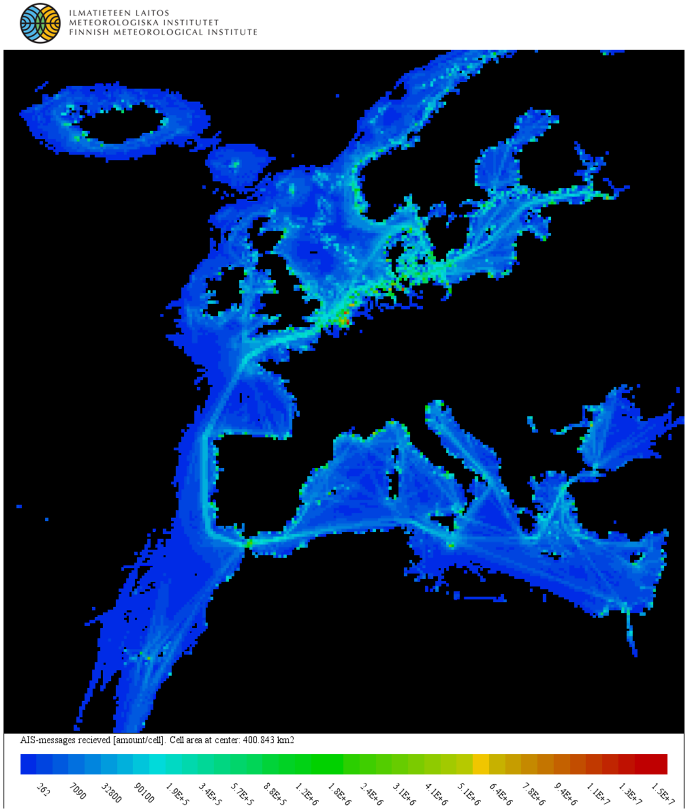

Figure 1. The geographical coverage of the terrestrial AIS network in Europe. The color scale illustrates the number of position reports per unit area, received in the EU sea areas in 2011.

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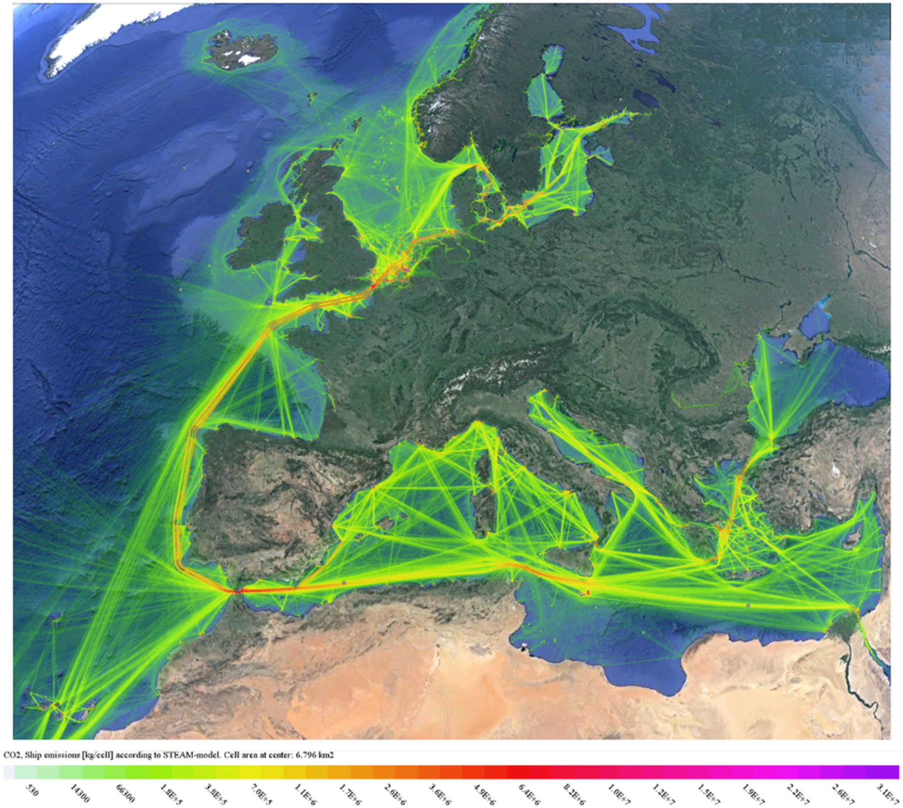

Figure 2. Predicted geographic distribution of shipping emissions of CO_2 in Europe in 2011. The colour code indicates emissions in relative mass units per unit area.

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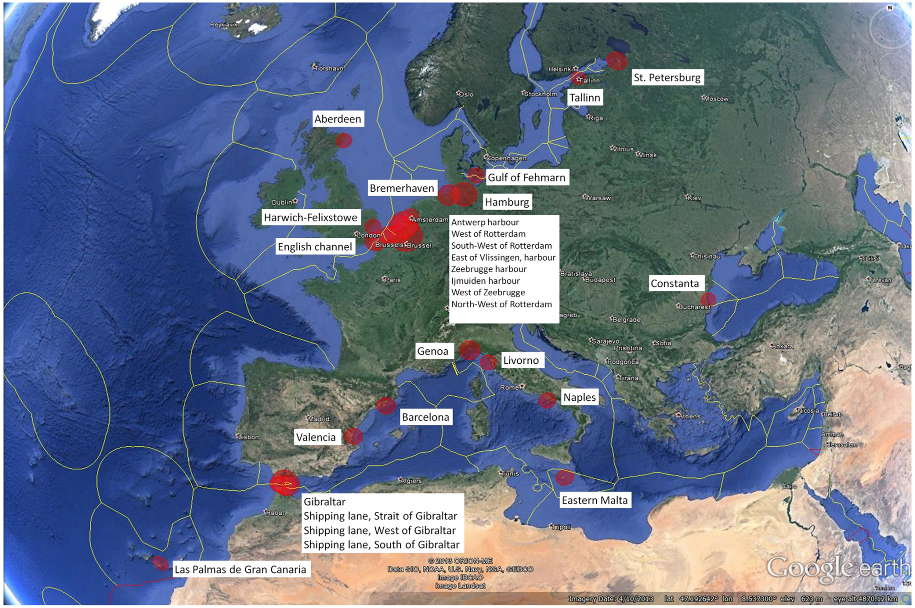

Figure 3. The 30 locations, in which there were highest ship emissions of CO_2 in Europe in 2011. The area of each circle is proportional to the annual CO_2 emission.

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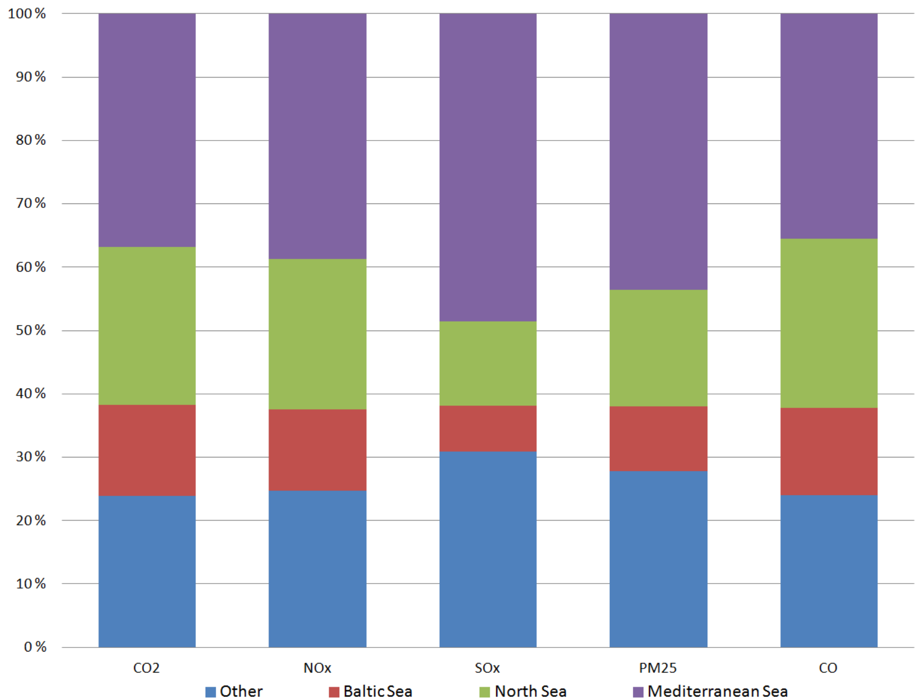

Figure 4. The fractions of shipping emissions for European sea regions in 2011.

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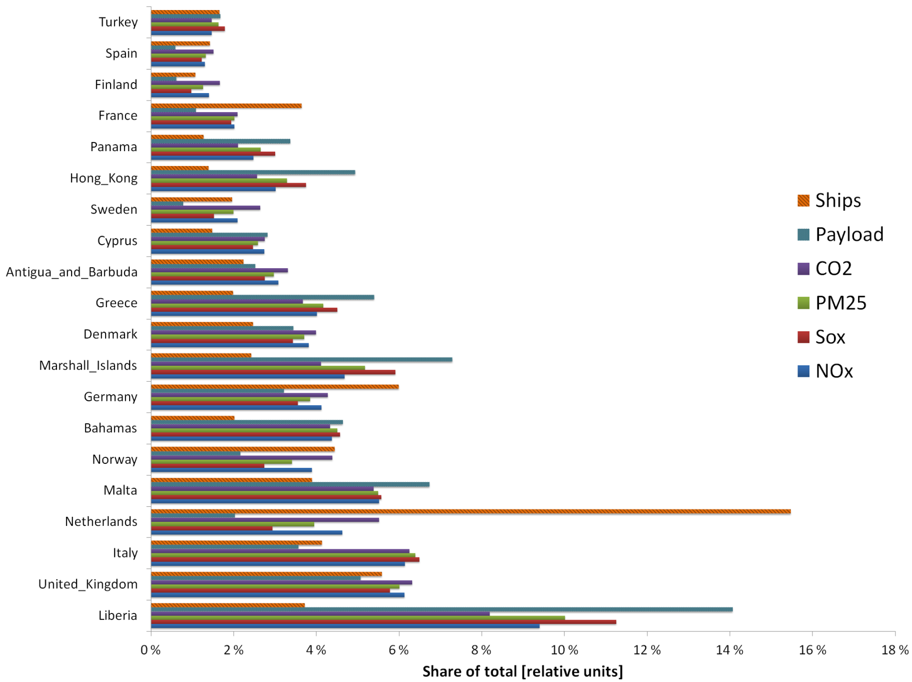

Figure 5. Relative contributions of various flag states to selected emissions, the numbers of ships and cargo payload in Europe in 2011. We have selected 20 states that had the highest emissions of CO_2. These states have been presented in terms of the emissions of CO_2; the lowest entry (Liberia) in the figure had the highest emissions.

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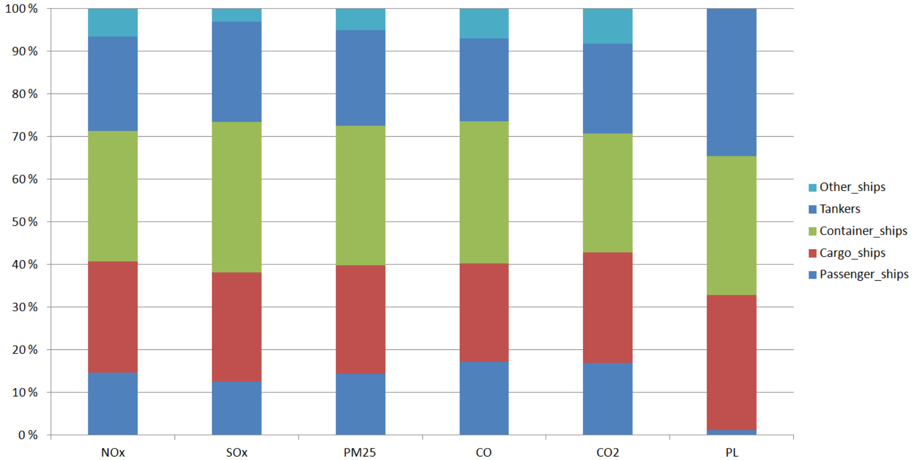

Figure 6. The fractions of European shipping emissions and payload, classified in terms of the ship types, in 2011.

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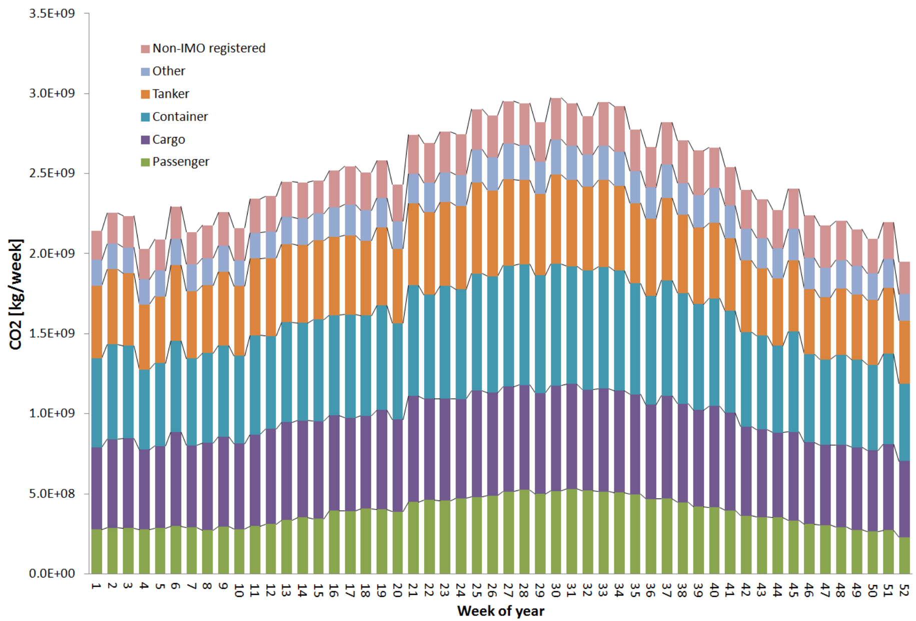

Figure 7. Seasonal variation of the shipping emissions of CO2 in the European sea regions in 2011, classified in terms of various vessel categories.

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