Author response to critique concerning the manuscript “A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011” by Jalkanen et al.

General remarks from the authors

We thank the referees for their comments. The results of this paper have been rerun with the most recent STEAM version. This has lead to some numerical changes; tables and figures now reflect these changes. Further, some additions were included, which were not addressed in the referee comments. In our opinion these additions will make the content of this paper more relevant to a wider audience. For example, in Table 1 there is an entry for inland shipping as well as emissions as a function of vessel size categories. Table 3 now includes average cruising speed of vessels found in AIS as well as their overall contribution to total CO2 emissions.

These additions can have important implications, because official statistics of ship emissions usually distinguish between inland and other shipping. Also, the size categories help to assess the significance of the exclusion of vessels under 5000 tons from EU MRV initiative (vessel specific reporting of CO2 emissions; the Monitoring, Reporting and Verification regulation 2015/757/EC). Inclusion of actual vessel cruising speeds is now consistent with the results reported in the 3rd IMO GHG study. This helps the reader to assess the extent slow steaming is practiced with ships sailing the study area.

Detailed responses to referee comments

Response to Referee 3

Referee3:

What I am missing, however, is a clear explanation and motivation, how these things connect to atmospheric science. (Remember, you submitted to ACP!) In its presentversion, the article could well appear in a journal for transport science, with no connection to the atmosphere at all. I therefore suggest to expand particularly the introductory part of the manuscript, providing more motivation why this work is so important, and how it connects to research activities in the atmospheric domain (modelling, climate studies, health studies?).

Authors' response

While it is true that that it is possible to publish the manuscript in one of the transport journals, we would like to stress the significance of this work to the air quality community. This work will help to decrease the uncertainty regarding the evaluation of emissions from the transport sectors, which is a major challenge to air quality modeling. The publication of this work in ACP will have at least the following implications:

a) Clear improvement of ship emission inventory concerning the temporal and spatial description as well as the variation of emissions. Emission inventories are no longer static maps with constant geographical distribution, but fully dynamic reflecting the underlying true ship activity.

b) Possibility for evaluation of uncertainty of emissions by conducting vessel specific emission modeling and measurements. Stack measurements can be directly compared with the modeling work reported in this paper.

c) Large scale validation of regional ship emissions using satellite data. The comparison between the work of Vinken et al and this work are already discussed in the paper. Both of these approaches are independent of each other and they both indicate that existing ship emission inventories for the Mediterranean Sea are too large with regard to NOx emissions. This warrants further work which is urgently needed at the policy side, because the environmental legislation of the maritime sector is in turmoil.

e) The starting point of many air quality studies are the emissions provided by EMEP. If the accuracy of ship emission inventories of EMEP can be improved with the current work, it may help to reduce the uncertainty of air quality modeling studies and consecutive impact assessments.

With these points in mind, we have modified the Introduction -section and added the following text to the beginning:

"The cornerstone of air quality modelling research is an up-to-date description of emissions from all sectors of anthropogenic (i.e. industry, agriculture, transport) and non-anthropogenic (i.e biogenic, desert dust, wildland fires) activities. However, information on emissions may have limited dynamical features, such as the geographical or temporal variations of emissions. This is especially important for transport emissions, which vary substantially both spatially and temporally."

We also restructured the Introduction –section to respond other comments of the referees.

Reviewer3:

"Why are ship emissions so important for atmospheric effects, for atmospheric modelling and/or science in general? (You may add references to some key atmospheric model works here.)"

Authors' response:

It is often the case that major cities also have large harbors. Good examples of these cases are the English Channel, St Petersburg, Istanbul, Hong Kong and Singapore. In these cities, ships are very close to significant human populations and it may result to significant health implications. It is also very difficult to match the air quality modeling work with corresponding measurements if the input data, i.e emissions are not accurately described. We have reported the results using CO_2 emissions as a baseline because of GHG emissions from ships are currently discussed at IMO and EU level and there exists a requirement in

EU for ships to report their fuel consumption on annual bases starting from 2018 (the MRV initiative, Monitoring, Reporting and Verification of GHG emissions). In order to help formulate a sensible policy for ship emission limits, one must have an idea of the potential costs and benefits of each change. For example, sulphur reductions in marine fuels can be justified with reduced human health effects, because benefits outweigh the costs. It is imperative that all relevant legislation concerning ship emissions are included in a proper way, which is the case in our work.

Further, we offer a possibility for any researcher working with ship emissions, a possibility to use their own fuel based emission factors which is possible through fuel consumption (CO2 emissions) modeling. Using CO2 as a baseline allows readers to assess the fuel consumed in each grid cell and facilitates the use of different emission inventories if the readers are not confident that the ones used by the authors are sufficiently accurate.

These issues are discussed in section 3.1 and we have added several references to relevant ship emissions/air quality vs health studies:

Jonson et al, ACP 2015

Bosch et al, 2009, cost benefit analysis to support the impact assessment accompanying the revision of directive 1999/32/EC on the sulphur content of certain liquid fuels, AEA Technology, European Commission report ENV.C.5/FRA/2006/0071

Corbett et al, 2007

Brandt et al, 2013

USEPA, 2008, Regulatory impact analysis control of emissions of air pollution from locomotive engines and marine compression ignition engines less than 30 liters per cylinder

Reviewer3:

"I assume that your updated ship emissions are to be used in atmospheric modelling. Can you make a a priori guess (non-quantative) what the expected benefits/impacts will be if an atmospheric model uses your updated ship emissions in contrast to the existing inventories?"

Authors' response:

Yes, this has been tested using the SILAM model, but the results have not been published yet. Our preliminary analysis indicates that modeled concentrations are in better agreement with air quality measurements of coastal stations than with the existing ship emission inventories. So far, this analysis has mostly concentrated in the Baltic Sea region, but a logical extension to other sea areas can be made.

Just as an example of these comparisons, Figures 1 and 2 present a case study for the Baltic Sea area. Two ship NOx emission inventories, one from current work and the other from TNO/MACC are compared to AirBase measurements. As can be seen with the STEAM case (Fig 1), the colors have shifted from bluish tones towards green and yellow, which indicate a better fit to experimental air concentrations of NOx. Largest changes are visible in the Polish coast and the Gulf of Finland.

We have also compared the STEAM ship emissions and SILAM chemical transport modeling results with satellite observations of NOx, but this analysis is not complete, yet. We would like to stress the preliminary nature of these conclusions, but it seems that in the Mediterranean Sea STEAM ship emission inventories are in better agreement with satellite NOx observations than TNO/MACC. For ship emitted sulphur, however, satellite observations are very difficult and the SOx signal is too weak to be seen. In the future, we will extend the AirBase/SILAM comparison to Mediterranean stations to get more insight on the SOx emitted by ships and its contributions to overall air quality in South Europe.

Of course, the overall contribution of Baltic Sea shipping to NOx concentrations is about 10 % from of airborne nitrogen (annual average) and improvements larger than this can hardly be expected.

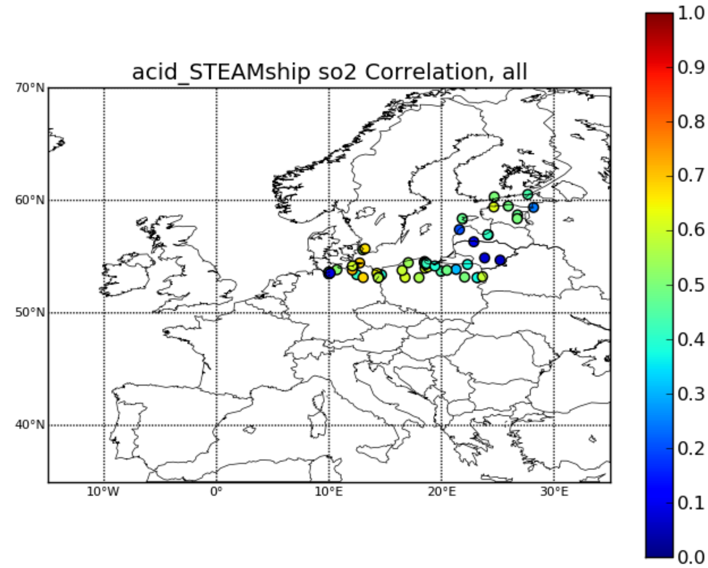

Figure 1. Comparison of SILAM modeling (with STEAM ship emission inventories; TNO/MACC for all other emission sectors) and air quality measurements. Correlation coefficients are indicated by the color scale.

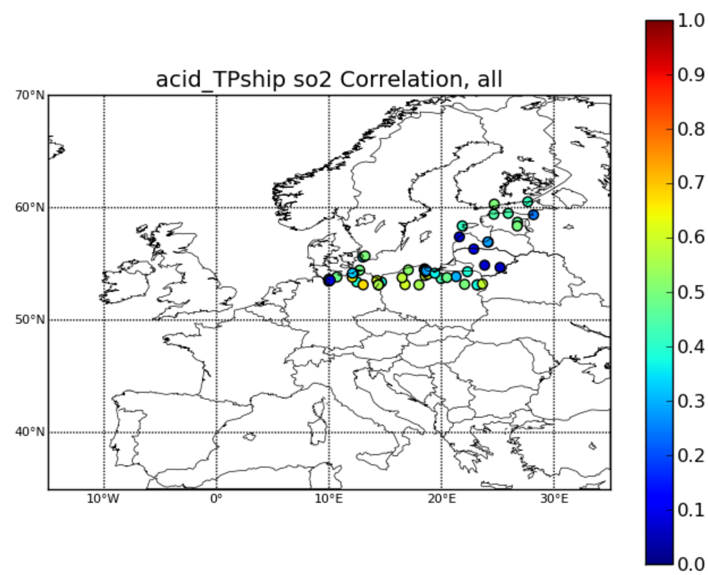

Figure 2. Comparison of SILAM modeling (with TNO/MACC emission inventories) and air quality measurements. Correlation coefficients are indicated by the color scale.

Referee3:

“I am somehow missing a statement on the consequences of the findings of this paper (STEAM simulations disagree with EMEP inventory.) Does this imply that atmospheric models should try to incorporate your inventory, or your ship emissions model? Who could be the user of the results/products/methods of your research? Can your inventories be made available to other atmospheric researchers (e.g., through a website or a data base)? This would greatly enhance the usefulness of your work.”

Authors’ response:

In our opinion, the ship emissions in the Mediterranean Sea warrant further study. There are already three independent reports (Vinken et al; Marmer et al; our study) which indicate that ship emissions in the Mediterranean Sea might be too high when compared with the EMEP inventories. Currently, annual EMEP reporting does not require ship emissions reporting from member states, because they are done separately by an outside contractor. We have shown that from technical point of view, it is possible to revise the ship emission inventories by incorporating real vessel traffic data and emissions modeling in such a manner that the work is based on sound technical principles instead of more general way. This can be done on annual basis, if AIS data and funding for the work are available.

The following was added to the Conclusions section:

“A logical step would be to include chemical transport modeling and comparisons with air quality measurements of coastal stations to determine whether modeled NOx and SOx concentrations are in line with measurements.”

Sharing the emission datasets generated in this work is warmly recommended. We have confirmed from the European Maritime Safety Agency that the gridded emission output of STEAM can be made available upon request. See the first page of this manuscript for contact details.

We have added the following to the end of the Discussion section:

“The emission outputs of STEAM can be made available for further research upon request to the authors.”

Referee3:

l. 8 "Emissions originated from ship traffic in European sea. . ." -> "Emissions originating from ship traffic in the European seas. . ."

Authors' response:

This was corrected

Referee3:

Update the references list.

Authors' response:

List of references has been updated

Response to Referee1

line14-15; p7471. In this discussion it should be noted that the most trafficked river in Europe is the Rhine which ends in Rotterdam; the biggest European port. AIS for non-recreational inland shipping has been subsidized in the Netherlands (and by now is compulsory). This explains a much higher share of small vessels in the Netherlands compared to other countries with much less important inland shipping routes.

Authors' response:

Thank you for pointing this out. This explains the large share of small vessels in the Dutch fleet. This is now explained in Section 3.2.

"The large number of small vessels in the AIS data in the case of the Dutch fleet can be explained by the fact that the use of the AIS equipment is compulsory in the non-recreational inland vessels in the Netherlands. In Finland, there are over 190 000 motor boats (Trafi, 2014) and 525 Finnish vessels were picked up by AIS in Europe. Clearly, the representation of small vessel traffic substantially varies between countries; their activities are incompletely represented in the AIS signals."

Referee1:

The contents of Table 3 should be discussed in a bit more detail, especially the very high % of auxiliary engines (AE) (= 100%- ME%) should be explained and /or commented on: There seem to be many ships where AE% is > 40% and sometimes higher than 50% - which makes one wonder what the main engine really is if it is only used for 30-50% of the time. It seems that in several cases the ME could be used for tasks that the AE performs when in port? So how do you know they use only the AE?

Authors' response:

We have given this a bit more thought.

First, we have rerun the model with the most recent model version, because some changes have occurred since the results of this paper we generated. This has changed the numbers somewhat and we have updated all the corresponding figures and tables. The changes involved concerned especially the aux engine timer which regulates the use of aux engines in cases where ship remains stationary but it still sends out frequent AIS position reports. These periods were previously modeled with hoteling AE usage assumptions regardless of the duration of hoteling period. In the most recent model version hoteling has been divided into two parts, "hoteling" and "berthing" modes, which means that "berthing" mode will have a reduced AE usage compared to "hoteling". The rationale of this is that when cargo operations are finished, the need for AE power is gradually reduced. This approach is similar to the work done for Port of Long Beach (Starcrest LLC, http://www.polb.com/civica/filebank/blobdload.asp?BlobID=10194, Table 2.12) emission inventories, but it still needs to be confirmed with future experimental work. This has a direct impact on the auxiliary power need of vessels. The details of this feature can be found in the Interactive Discussion of Johansson et al, 2013 ACP paper.

Second, we did a comparison of the 2nd GHG study results for the assumptions regarding the use AE power and the fuel consumed in Main and Aux engines (see Buhaug et al, 2009, Tables A1.25 and A1.8) and comparison to values of Table 3 of our work. In the 2nd IMO GHG study there exist vessel classes which consume more than half of their fuel in Aux engines, too. Further, we have introduced two more columns to Table 3 which indicate the average vessel cruising speed and the share from total CO2 produced. The addition of average cruising speed gives the reader an opportunity to assess the extent of slow steaming in EU area and the %CO2 produced indicates the significance of the ship class in relation to total CO2 produced. It can be seen that those vessels which use more than 50% of their fuel in Aux engines are Service vessels and tugboats. This is well in line with the 2nd IMO GHG study. Further, the contribution of these vessels to total CO2 output is relatively small, less than 2.5%.

Third, the auxiliary engine usage logic is done with the following method (see Figure 3 below). The model evaluates the need for power other than propulsion by looking at cargo and passenger capacity of the vessel as well as the operating mode. Based on these numbers, the power needed by ship systems is evaluated. Once the required kilowatts are predicted, then the model looks at the engine setup of the vessel. How is power transmitted to the propeller, is it a 2-stroke engine with direct connection to the propeller? Is there a reduction gear or power take-off in between? Is the propeller fixed pitch or controllable pitch type? These are used to determine whether it is possible for a ship to use its main engine in power generation with a shaft generator or are aux engines needed for power generation. In the model it is assumed that shaft generators are only used during the cruise mode, not during hoteling or maneuvering modes. If the power transmission is electric (diesel-electric vessel) then the additional power need required by ship systems has to come from main engines.

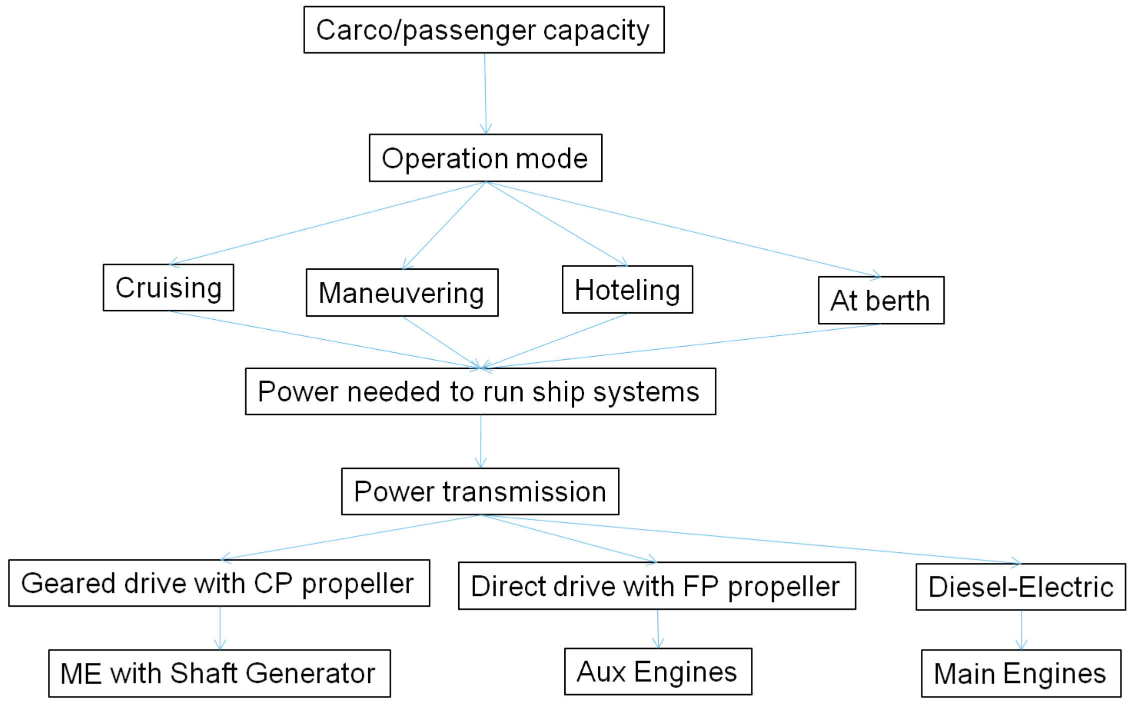

Figure 3. Aux Engine usage determination in STEAM. It should be noted that in the model the use of shaft generator is only assumed during the cruise mode.

We have modified the Section 3.3 to:

"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, auxiliary engine power profiles, main and auxiliary engine setup and power transmission method. 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). The share of auxiliary engine fuel consumption from total consumption is very high for Service vessels and Tugboats. This is consistent with the 2nd IMO GHG report of Buhaug et al (2009), but the contribution of these vessels to total fuel consumption or CO_2 emission from shipping in the study area is quite small, less than 2.5%."

Referee1:

l5-10 p7473 - discussion on uncertainty here seems related to the above comment on Table 2.

Authors' response:

Could this comment relate to table 3 instead? Table lists CO2 hotspots and their contribution to overall CO2 emissions. If so, the points listed in the previous bullet point of the author response are valid in this context, too.

Referee1:

p 7474 - bottom of page: There appears a bit of inconsistency in the reasoning here - while the argument now is that the current 2011 estimate is in line with Vinken et al. for 2006 - a bit earlier in the paper it was argued that it made sense that NOx emissions were lower due to the economic crisis of 2008-2009. Vinken et al. is before, this paper is after. Please give some interpretation / comment on this.

Authors' response:

Despite the difference in study periods, Vinken et al: 2006, this work: 2011, some general conclusions can be made. Vinken et al report NOx emission for the EU area as 1.0 TgN whereas our study suggests 0.9 TgN. Vinken et al state that for the Mediterranean Sea, EMEP values are too high, which was also found in our study. We have removed the Baltic Sea discussion concerning the comparison of Vinken et al and our work from this manuscript. First of all, the analysis of Vinken et al concern snapshots of a densely trafficked shipping lane in the Baltic Sea, not the Baltic Sea in its entirety. For this ship lane snapshot area, Vinken et al report that EMEP emissions are underestimated. Further, Vinken et al give 40-60% uncertainty in their satellite based top-down emission inventory. It may be worthwhile to do a more thorough comparison using STEAM and the approach of Vinken et al in the future, but it was not done in this study. It should also be noted that EMEP has recently updated their emissions for all sea areas for 2011. The new inventories are closer to our work than before.

In addition to the removal of Baltic Sea ship emission comparison, we have added the following in Section 3.4:

"The difference between the NOx emissions of the STEAM and EMEP inventories in the Baltic Sea shipping is 18% (the emission values of STEAM is higher). However, the comparison with Vinken et al. (2006) is challenging for the Baltic Sea, as Vinken et al. (2006) report only emissions along the major ship tracks, which are not representative of the emissions in the whole of the Baltic Sea area."

Referee1:

In section 3.4 the EDGAR inventory is missing - would be good to include this next to EMEP as it is one of the most widely used inventories.

Authors' response:

This is a good suggestion, but unfortunately in EDGAR inventories we could not find area definitions which would summarize emissions by sea area (http://edgar.jrc.ec.europa.eu/overview.php?v=CO2ts1990-2013). Instead, a total number is given for CO2 emissions from global international shipping during 2011, which is 606 million tons. This number is lower than the value reported in the 3rd IMO GHG study, which lists the global international shipping contribution as 850 million tons. The methodology used in the 3rd IMO GHG study is very close to the one used in our work and it is likely that values provided by EDGAR database for EU area may be lower than the ones we report. The EDGAR inventories are based on top-down fuel sales statistics of IEA, which have been compared to the bottom-up modeling in the 3rd IMO GHG study.

It should be noted that we have not conducted any detailed area by area analysis between EDGAR and STEAM, but it should definitely be part of the future work.

Referee1:

l8 and further p7475: The SO2 emissions are directly related to the S content of the fuel - so the conclusion can only be that the EMEP inventory has about 2 x the S content.- which seems unlikely - At the same time it seems unlikely that this factor 2 can be entirely covered by the in-port emissions which may use lower S fuels (or if so please calculate and explain) - so a bit more discussion is needed here - for example what is the role of the high % of AE in this study (see Table 3) - can that help to partly explain the gap?

Authors' response:

We have no knowledge how EMEP sulphur content assignment for marine fuels is done, but in STEAM fuel type assignment is done based on engine characteristics. The model evaluates whether engine stroke type, crankshaft revolutions per minute and engine power output are suitable for the use of residual fuels. This assignment is done based on the book "Diesel Engines for ship propulsion and power plants" by K. Kuiken (Target Global Energy Training, Onnen, the Nethrlands, 2008). When suitability for residual/distillate fuel is determined, STEAM assigns fuel sulphur content for each engine taking relevant legislation into account. For example, for passenger vessel in SECAs this would lead to 1.0%S during year 2011. Similar analysis is conducted for aux engines. Also in these cases, the suitability for residual fuel use will depend on aux engine characteristics and whether the ship is in EU harbor areas or not. Of course, we cannot fully predict correct fuel sulphur content for vessels which would be capable of using residual fuels, but the ship owner has voluntarily decided to use distillate fuels with lower sulphur content than what is required by the law. We have the opportunity to assign sulphur content vessel by vessel for ME and AE separately if bunker delivery notes from vessels have been made available for us. Unfortunately real sulphur content is known only for handful for vessels (less than 50 cases), but real values could be used in STEAM.

It should be noted that EMEP has revised their emission inventories in 2015 and the SOx emissions in the Mediterranean Sea have been reduced significantly, from over 1300 to 957 thousand tons. Regardless, the values reported in our work (595 thousand tons) is still about two thirds of the EMEP values, but the EMEP 2015 update for 2011 results brought their values closer to our work.

Plotting the EMEP timeseries of SOx and NOx from Mediterranean shipping indicate that NOx and SOx emissions decreased in a similar way during 2007-2010, probably reflecting the overall decrease in shipping and economic activity (Fig 4).

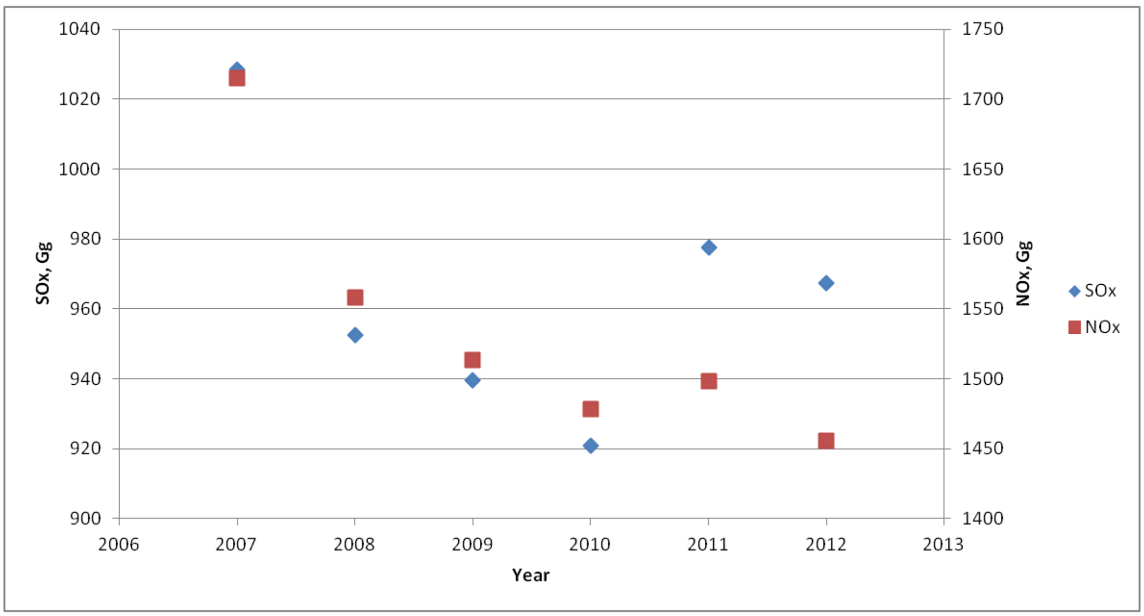

Figure 4. EMEP timeseries of NOx and SOx emissions from Mediterranean Sea shipping. All values are in Gg, taken from http://www.ceip.at/ms/ceip_home1/ceip_home/webdab_emepdatabase/emissions_emepmodels/

As can be seen from Fig 4, from 2010 onwards SOx emissions in EMEP Mediterranean ship emission inventories increased by over 6% whereas NOx emissions from ships increased only by 1.4%. Assuming that NOx values reflect the change in shipping activity (not taking the IMO Tier II rules for NOx into account), it is curious that SOx emissions have increased more than NOx, because at the same time EU sulphur directive came into force in January 2010. This required reduction of marine fuel sulphur content in harbor areas and has additional requirements for passenger vessels outside the ECAs. These changes would have been expected to decrease the SOx emissions from Mediterranean shipping from 2010 and onwards, not to increase them. This warrants further study and should be confirmed with air quality measurements.

The SOx emission values reported in our work for the Mediterranean Sea are 594 800 tons (in SO2). At the same time, the CO2 emitted is 48 344 100 tons. These values correspond to 297.7 Gg of S and 15.5 Tg of fuel (assuming weighted CO2 to fuel conversion factor 3.113 g/g of CO2). This leads to average fuel sulphur content of 1.9% for the Mediterranean shipping. It should be noted that the fuel used in harbor areas must comply with the 0.1%S requirement (and passenger vessels with 1.5%S), which lowers the average sulphur content of ship fuels in the Mediterranean Sea. In our work, residual fuels have been assigned fuel sulphur content of 2.7%S. Calculating backwards from values in Table 3, the average fuel sulphur content of some major ship types are 1.91%S for containerships, 1.64%S for tankers, 1.2%S for RoPax vessels and 1.4%S for cruise ships. It should be noted that these values have contributions from both fuel used in Main and Aux engines and a large part of these fleets sail the SECAs.

We have added the following to Section 3.4:

"Plotting the EMEP timeseries of SO_x and NO_x for the shipping in the Mediterranean indicate that the NO_x and SO_x emissions decreased in a similar way during 2007-2010, probably reflecting the overall decreases in both shipping and economic activity. However, between 2009 and 2010, the SO_x emissions in EMEP inventories increased by more than 6%, whereas the corresponding NO_x emissions from ships increased only by 1.4%. At the same time, the EU sulphur directive came into force in January 2010, with requirements for the reduction of marine fuel sulphur content. This would have been expected to decrease the SO_x emissions from the shipping in the Mediterranean, instead of increasing them. However, in 2010 the new NO_x limits (IMO Tier II) were implemented for vessels constructed since 2010 , but in 2011 only 3% of the fleet were new ships. Calculating backwards from SO_2 values of Table 1, the average fuel sulphur content (denoted here by S) of some major ship types yields 1.9% S for container ships, 1.6% S for tankers, 1.2% S for RoPax and 1.4% S for cruise vessels. It should be noted that these values represent a combination of SO_x from both main and auxiliary engines, which may use fuels with different fuel sulphur content. Also, these averages include contributions from vessels sailing both the SECA and the non-SECA's. The differences in the STEAM and EMEP inventories warrant further study; these differences should also be examined using dispersion modelling and air quality measurements. "

Referee1:

l 10-11 7476 - please recalculate both to CO2 or both to tons of fuel - not 1 as fuel and 1 as CO2 - this is for the reader very inconvenient.

Authors' response:

This has been corrected

Referee1:

l 18 p 7477 - The authors mention correctly the importance of the high resolution for AQ and health studies. However, to support this point the reviewer would also like to know about accessibility of the data for other scientists. Are they available upon request? or in other ways?. it is fine to say that this data will improve air quality and health studies but that is only true if the data are available for use.

Authors' response:

Yes, the emission grids can be made available for further study. We have added the following at the end of the manuscript:

"The gridded emission datasets of this work can be made available for further research upon request to the authors."

Referee1:

l12 and further p7478. This paragraph is not conclusion but belongs in the introduction or possibly somewhere in the discussion section. Last but not least in the Conclusions something more should be said about the large discrepancy in SOx emissions for the MEd Sea between this work and EMEP / IIASA . Now it is only mentioned. But as said earlier SOx emissions are simply and directly controlled by the S content of the fuel. So the fuels assumed to be burned in these studies are very different - how likely is that and how can it be explained or - if it can't be explained what kind of data or research is needed to solve this?

Authors' response:

We have moved the paragraph to the Introduction section.

We have also modified the beginning of the Conclusions –section to:

"The comparison of emitted pollutants with existing ship emission inventories revealed that there are some 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 18%, 39% and 49% lower than the corresponding values in the EMEP and IIASA inventories. The $PM_{2.5}$ emissions from the STEAM inventory were 24% lower than indicated by the EMEP emission inventory. Satellite observations using the Ozone Monitoring Instrument (OMI) also indicated smaller annual emissions of NOx in the Mediterranean,

compared with the predictions of the EMEP inventory. These differences should be investigated further with a longer ship emission time series, which takes into account the relevant changes of the environmental legislation . From a technical point of view, it is feasible to have annual updates of bottom-up ship emission inventories.

Further research is required including emission modelling in combination with consecutive chemical transport modelling, comparisons with measured atmospheric concentrations of pollutants and source apportionment. The reasons for these deviations between different emission inventories should be investigated further and confirmed with independent experimental datasets, as these can have significant policy implications concerning health and environmental impact assessments within the transport sector. A logical step would be to include chemical transport modeling and comparisons with air quality measurements especially at coastal stations to determine, whether the predicted NO_x and SO_x concentrations are in an agreement with the measurements.”

Referee1:

further minor comments. line 16 p 7461 "Furthermore, important emission sources, like harbours have been often neglected from regional emission studies." This statement needs to be either better specified or removed. Harbours contain many different sources; International shipping, inland shipping, refineries, handling of goods, mobile machinery for unloading etc etc. . There will be no national or regional inventory with zero emissions in ports. (they might be incomplete though)

Authors’ response:

This has been modified to:

“Furthermore, important emission sources, like ships in harbours have been often neglected from regional emission studies.”

Referee1:

line 6, p7466 - The sulphur content of the fuel has been modelled explicitly for each vessel... This needs some clarification. There are regulations by Sea (e.g. SECA) and the avg fuel S content in shipping is known but I don’t see how you can model the fuel S content by ship. There will be ships with lower than avg fuel S and some with higher S content than avg but how to know which is true for an individual ship w/o actual sampling and measurement?

Authors’ response:

This is described in the earlier responses to reviewer1. Please see the comment regarding the Aux engine usage modeling and the discussion regarding large differences between EMEP SOx and STEAM SOx inventories. In short, the fuel type assignment (residuals or distillates) is done based on engine stroke type, power and crankshaft revolutions. If the engine is capable of using HFO, HFO is assumed. Sulphur content is assigned per vessel and for ME and AE separately. This depends on relevant legislation (IMO Marpol Annex VI, EU directives), geographical area and the time period under study. We assume all vessels to comply with these requirements. Of course, voluntary use of low sulphur fuel in cases where dirtier fuel would be possible cannot be described accurately without knowledge of actual fuel sulphur content. Same applies to use of illegal high sulphur fuel. These features cannot be modeled correctly without sampling the fuel carried onboard the vessels.

Referee1:

l2 7473 habe = have - In general it would be good to ask someone to check for missing cases of the word "the" or "a" - this happens occasionally in the text but it takes me too much time to identify page and line numbers to list them.

Authors' response:

The typo pointed out has been corrected. We have done our best to check the language for missing articles.

Referee1:

The legend of Table 1 refers to Annex II for details but no Annex is present or given.

Authors' response:

Reference to Annex was removed from Table 1 legend.

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

Jukka-Pekka Jalkanen, Lasse Johansson and Jaakko Kukkonen

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Abstract

Emissions originating 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~~121, ~~2.9~~3.0, 1.2, 0.2 and 0.~~3~~ 2 million tons, respectively. The emissions of CO_2 from Baltic Sea were evaluated to be more than a half (~~58~~ 55 %) of the emissions of the North Sea shipping; the combined contribution of these two sea regions was almost as high (~~96~~ 88 %) 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~~ 40 % 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 cornerstone of air quality modelling research is an up-to-date description of emissions from all sectors of anthropogenic (i.e. industry, agriculture, transport) and non-anthropogenic (i.e biogenic,

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desert dust, wildland fires) activities. However, information on emissions may have limited dynamical features, such as the geographical or temporal variations of emissions. This is especially important for transport emissions, which vary substantially both spatially and temporally.

Determination of shipping activity has previously been one of the largest unknowns in assessing the emissions from the maritime transport sector. 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 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, 2002; 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 ships in harbours have been often neglected from regional emission studies.

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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.

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In this work, 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 trafficked, 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.

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.

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 2009, 2012; Johansson, 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 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 Figure 1~~Figure 1Figure 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.

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 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. 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 x 2.5 km in the EU-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 Figure 2~~Figure 2Figure 2~~ and Figure 3~~Figure 3Figure 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 Figure 4~~Figure 4Figure 4~~. The region

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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 Figure 1Figure 1Figure 1).

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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 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 U.K, 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 Figure 3Figure 3Figure 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 activities. 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 40% 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 eight of the total emissions of CO_2 from shipping, respectively. The emissions of NO_x from the ships in the Mediterranean Sea (1 229 000 tons, calculated as NO_2) are almost as high as those in the Baltic Sea (329 000 tons) and the North Sea (649 000 tons) combined. The emissions of NO_x from other areas considered in this study are slightly higher than the contribution from the North Sea shipping. The share of the Mediterranean Sea traffic is even larger in case of the SOx 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 Figure 4~~Figure 4Figure 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. It is also likely that inland shipping is only partially covered in our analysis.

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; USEPA, 2008; Bosch et al, 2009; Brandt et al, 2013; Jonson et al, 2015). However, policy changes for 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.

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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 16 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 Figure 5~~Figure 5Figure 5~~. The emissions have been presented as fractions (%) of the total emissions in the European sea areas in Figure 5~~Figure 5Figure 5~~.

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The emissions were largest for the Liberian and second largest for the Italian fleet. The U.K., Malta, Bahamas, Norway and the Netherlands also have had major fleets. In addition to major European states, such as Italy, U.K., 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 16 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.

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 1.7% of the total CO_2 emissions, although the number of such small vessels is over 41% of all vessels. 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. The large number of small vessels in the AIS data in the case of the Dutch fleet can be explained by the fact that the

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use of the AIS equipment is compulsory in the non-recreational inland vessels in the Netherlands. In Finland, there are over 190 000 motor boats (Trafi, 2014) and 525 Finnish vessels were picked up by AIS in Europe. Clearly, the representation of small vessel traffic substantially varies between countries; their activities are incompletely represented in the AIS signals.

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 for various ship types have been presented in Figure 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 container (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 Figure 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 NOx 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 possible to determine these explicitly, which will significantly decrease the large uncertainties that have 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, auxiliary engine power profiles, main and auxiliary engine setup and power transmission method. 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). The share of auxiliary engine fuel consumption from total consumption is very high for service vessels and tugboats. This is consistent with the 2nd IMO GHG report by Buhaug et al. (2009); however, the contribution of these vessels to the total fuel consumption or CO_2 emission from shipping in the study area is small, less than 2.5%.

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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 Hammingh 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 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 January 1st, 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 NOx for the Mediterranean Sea reported in this work are lower than in the EMEP inventory; qualitatively the same conclusion was reported by Marmer et al (2009). Marmer et al. (2009) 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 80% of the corresponding value in the EMEP inventory, allowing for the update in 2015 of the EMEP emissions in 2011 (EMEP, 2015). Vinken et al. (2014) used satellite observations of NOx from the OMI instrument to constrain top-down emissions from ships. The study area of this study (defined by AIS coverage illustrated in Figure 1~~Figure 1Figure 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.

The reported total NO_x emission for all European sea areas in our study is 2.96 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. The difference between the NOx emissions of the STEAM and EMEP inventories in the Baltic Sea shipping is 18% (the emission values of STEAM is higher). However, the comparison with Vinken et al. (2006) is challenging for the Baltic Sea, as Vinken et al. (2006) report only emissions along the major ship tracks, which are not representative of the emissions in the whole of the Baltic Sea area.

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The annual SO_x emissions reported in this study for various sea regions are 84, 148 and 595 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 69, 163 and 978 thousand tons, taking into account the update of the EMEP inventory in 2015. For the Baltic Sea and the North Sea, the inventories are approximately in agreement (their differences are 22% and 10%), but there is a larger difference in the predicted emissions of SOx in the Mediterranean Sea. The SO_x emissions predicted in this study for the Mediterranean are about two thirds of the corresponding values in the EMEP inventory.

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, 2014b; Pirjola et al, 2014).

Plotting the EMEP timeseries of SO_x and NO_x for the shipping in the Mediterranean indicate that the NO_x and SO_x emissions decreased in a similar way during 2007-2010, probably reflecting the overall decreases in both shipping and economic activity. However, between 2009 and 2010, the SO_x emissions in EMEP inventories increased by more than 6%, whereas the corresponding NO_x emissions from ships increased only by 1.4%. At the same time, the EU sulphur directive came into force in January 2010, with requirements for the reduction of marine fuel sulphur content. This would have been expected to decrease the SO_x emissions from the shipping in the Mediterranean, instead of increasing them. However, in 2010 the new NO_x limits (IMO Tier II) were implemented for vessels constructed since 2010 , but in 2011 only 3% of the fleet were new ships. Calculating backwards from SO_2 values of Table 1, the average fuel sulphur content (denoted here by S) of some major ship types yields 1.9% S for container ships, 1.6% S for tankers, 1.2% S for RoPax and 1.4% S for cruise vessels. It should be noted that these values represent a combination of SO_x from both main and auxiliary engines, which may use fuels with different fuel sulphur content. Also, these averages include contributions from vessels sailing both the SECA and the non-SECA's. The

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differences in the STEAM and EMEP inventories warrant further study; these differences should also be examined using dispersion modelling and air quality measurements.

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), whereas in this work, the Mediterranean shipping was responsible for 48 million tons of CO_2 emitted.

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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 Hammingh et al. (2013) is 71 – 153 million tons (for various years between 2000-2009), based on the work of Hammingh 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 Hammingh 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.

4. Conclusions

The comparison of emitted pollutants with existing ship emission inventories revealed that there are some 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 18%, 39% and 49% lower than the corresponding values in the EMEP and IIASA inventories. The $PM_{2.5}$ emissions from the STEAM inventory were 24% lower than indicated by the EMEP emission inventory. Satellite observations using the Ozone Monitoring Instrument (OMI) also indicated smaller annual emissions of NOx in the Mediterranean, compared with the predictions of the EMEP inventory. These differences should be investigated further with a longer ship emission time series, which takes into account the relevant changes of the environmental legislation . From a technical point of view, it is feasible to have annual updates of bottom-up ship emission inventories.

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Further research is required including emission modelling in combination with consecutive chemical transport modelling, comparisons with measured atmospheric concentrations of pollutants and source apportionment. The reasons for these deviations between different emission inventories should be investigated further and confirmed with independent experimental datasets, as these can have significant policy implications concerning health and environmental impact assessments within the transport sector. A logical step would be to include chemical transport modeling and comparisons with air quality measurements especially at coastal stations to determine, whether the predicted NO_x and SO_x concentrations are in an agreement with the measurements.

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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 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 gridded emission datasets of this work can be made available for further research upon request to the authors.

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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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Tables and Figures

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 'GT', eight vessel size categories and their contributions to emitted CO_2 are presented. The NO_x emissions have been calculated as NO_2 and SO_x as SO2.

EU - 2011		CO_2	NO_x	SO_x	PM2.5	CO	Payload	Ships	Travel
		[ton]	[ton]	[ton]	[ton]	[ton]	[10^9 ton*km]		[10^6 km]
All		120 722 000	2 964 300	1 208 000	181 600	197 000	10 540	47 233	889
	IMO	118 709 900	2 930 900	1 201 500	179 900	194 100	10 540	27 728	827
	Unidentified	2 012 100	33 300	6 500	1 600	2 800	0	19 505	61
Region	Mediterranean Sea	48 344 100	1 228 600	594 800	82 900	77 400	4 400	-	288
	Atlantic Ocean	19 276 900	511 200	272 600	36 600	32 900	2 349	-	124
	North Sea	20 736 000	477 400	108 200	22 100	35 800	1 463	-	190
	Baltic Sea	15 004 000	328 800	83 900	16 200	21 500	864	-	128
	English Channel	6 699 900	171 700	40 200	7 700	10 800	677	-	47
	Irish & British Seas	4 975 500	121 900	59 000	8 200	8 000	421	-	41
	Norwegian Sea	2 399 200	49 500	17 900	2 900	4 000	104	-	35
	Black Sea	1 305 700	32 600	14 100	2 000	2 400	145	-	15
	Bay of Biscay	865 800	19 300	8 600	1 200	1 400	56	-	9
	Inland	790 400	15 600	5 300	900	1 600	40	-	10
	Red Sea	224 400	5 200	2 300	300	400	21	-	1
Ship types	Container Ship	34 089 400	924 300	414 000	59 200	67 600	3 440	1 213	131
	Tanker	26 145 600	668 000	273 500	41 000	38 400	3 616	2 879	160
	Cargo Ship	20 078 800	508 600	208 800	30 400	34 500	2 887	5 220	285
	RoPaX	16 956 700	359 900	127 700	21 000	20 000	122	9 884	74
	Vehicle Carrier	9 427 900	229 700	99 300	14 400	13 200	475	961	56
	Cruise Ship	5 004 800	107 200	43 500	6 700	6 500	0	253	14
	Other	3 012 500	57 200	15 000	3 000	6 000	0	4 002	43
	Service Vessel	2 036 100	39 200	8 700	1 900	3 600	0	866	15
	Fishing Vessel	1 381 800	26 000	7 200	1 300	2 900	0	1 829	33
	Passenger Ferry	576 000	10 400	3 500	600	900	0	621	15
GT	(GT<4000 t)	14 496 600	272 700	72 000	14 000	25 700	395	31 770	359
	(4000 t<GT<10 000 t)	15 092 900	330 000	114 800	18 700	24 500	758	4 042	161
	(10 000 t<GT<20 000 t)	15 018 800	376 000	146 000	21 800	24 000	968	2 814	100
	(20 000 t<GT<30 000 t)	18 822 100	478 400	195 800	29 000	27 400	1 573	2 668	95
	(30 000 t<GT<45 000t)	16 536 800	436 200	181 000	26 500	25 200	1 664	2 548	68
	(45 000 t<GT<60 000 t)	10 878 200	289 100	123 400	18 000	17 100	1 137	1 060	37
	(60 000 t<GT<80 000 t	10 127 000	278 400	120 500	17 400	18 500	1 301	855	28
	(GT>80 000 t)	19 749 300	503 100	254 200	35 700	34 200	2 745	1 476	40

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 [degrees, N]	Longitude [degrees, E]	CO_2 (r = 10km) [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 %

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. Cruising speed indicates average cruising speed observed in AIS data. The last column on the right-hand side indicates the significance of contribution to overall CO_2 emissions. These ship types are responsible for over 98% of total CO_2 emitted.

Ship type	Disaggregated ship type	cruise [%]	man. [%]	hotel [%]	Build year	ME Fuel [%]	design speed	Ships	Cruising speed	of all CO2 [%]
Container Ship	Container Ship	59 %	3 %	38 %	2002	75 %	21.7	2373	15.9	27.6 %
Container Ship	Reefer	48 %	4 %	48 %	1991	72 %	18.2	500	14.6	1.6 %
RoPaX	RoPaX	40 %	5 %	56 %	1990	75 %	19.0	1207	13.6	14.5 %
Cargo Ship	Bulk Carrier	59 %	2 %	39 %	1999	85 %	14.2	4008	12.1	9.0 %
Cargo Ship	General Cargo	51 %	4 %	45 %	1991	78 %	12.5	5855	9.9	8.2 %
Tanker	Chemical Tanker	53 %	3 %	44 %	2003	71 %	14.0	2385	12.0	8.8 %
Tanker	Crude-Oil Tanker	51 %	5 %	44 %	2003	76 %	14.6	1216	12.0	6.9 %
Tanker	LNG tanker	71 %	4 %	25 %	2002	82 %	19.2	219	14.7	2.7 %
Tanker	Product Tanker	40 %	6 %	54 %	1996	59 %	12.9	949	10.4	2.3 %
Vehicle Carrier	RoRo Cargo	52 %	2 %	45 %	1991	78 %	17.1	448	13.5	4.7 %
Vehicle Carrier	Vehicle Carrier	68 %	3 %	29 %	2002	84 %	19.5	510	15.6	3.4 %
Cruise Ship	Cruise Ship	53 %	3 %	44 %	1989	73 %	18.8	251	13.5	4.3 %
Service Vessel	Service Vessel	20 %	14 %	67 %	1997	44 %	13.7	866	9.4	1.7 %
Fishing Vessel	Fishing Vessel	24 %	20 %	56 %	1988	52 %	12.5	1826	8.9	1.2 %
Other	Tugboat	15 %	8 %	77 %	1994	47 %	12.9	1588	8.3	0.7 %
Other	Dredger	19 %	12 %	69 %	1983	55 %	10.5	377	8.1	0.5 %

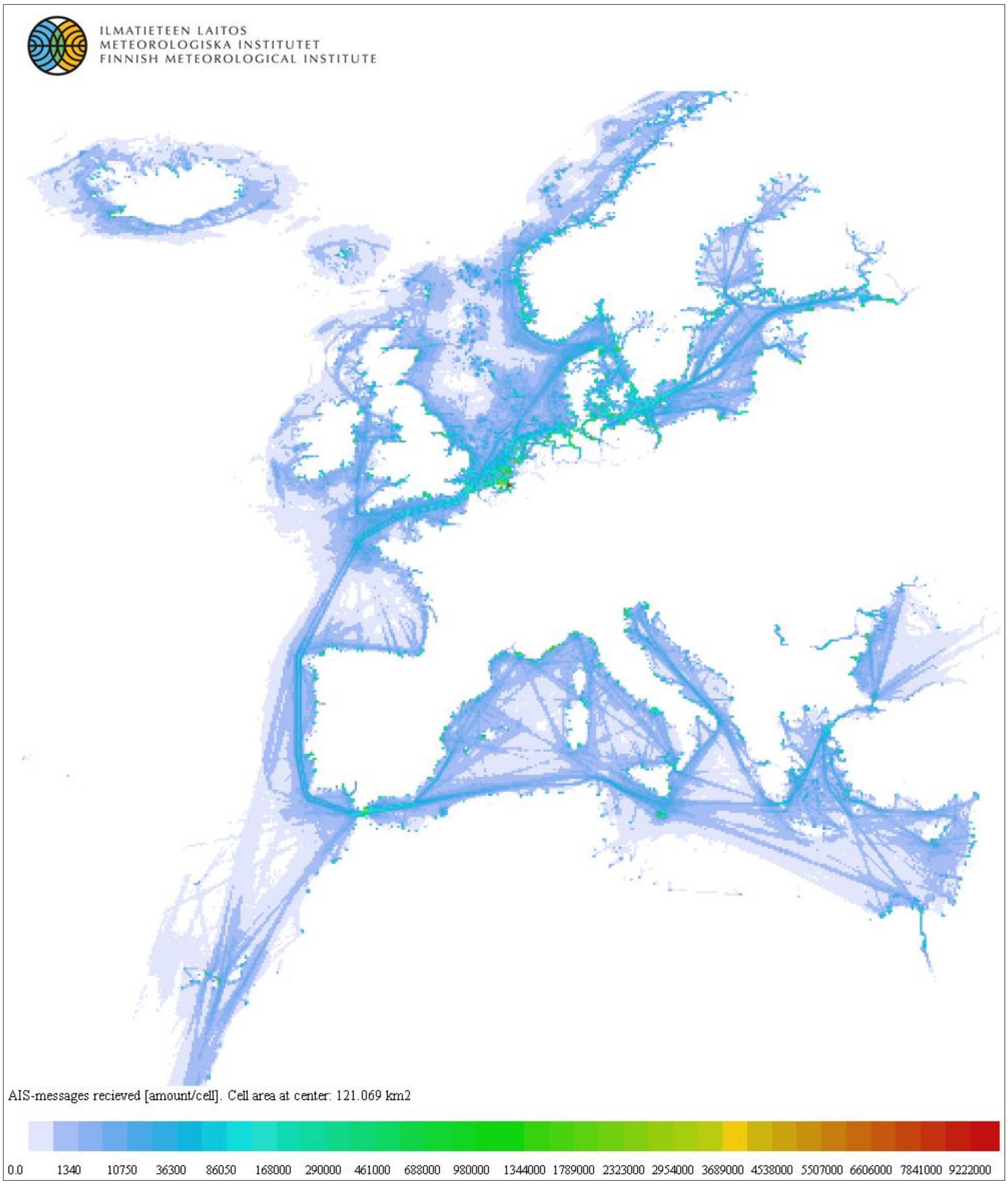

Figure 1. The geographical coverage of the terrestrial AIS network in Europe. The color scale illustrates the number of position reports per unit area, received in the EU sea areas in 2011.

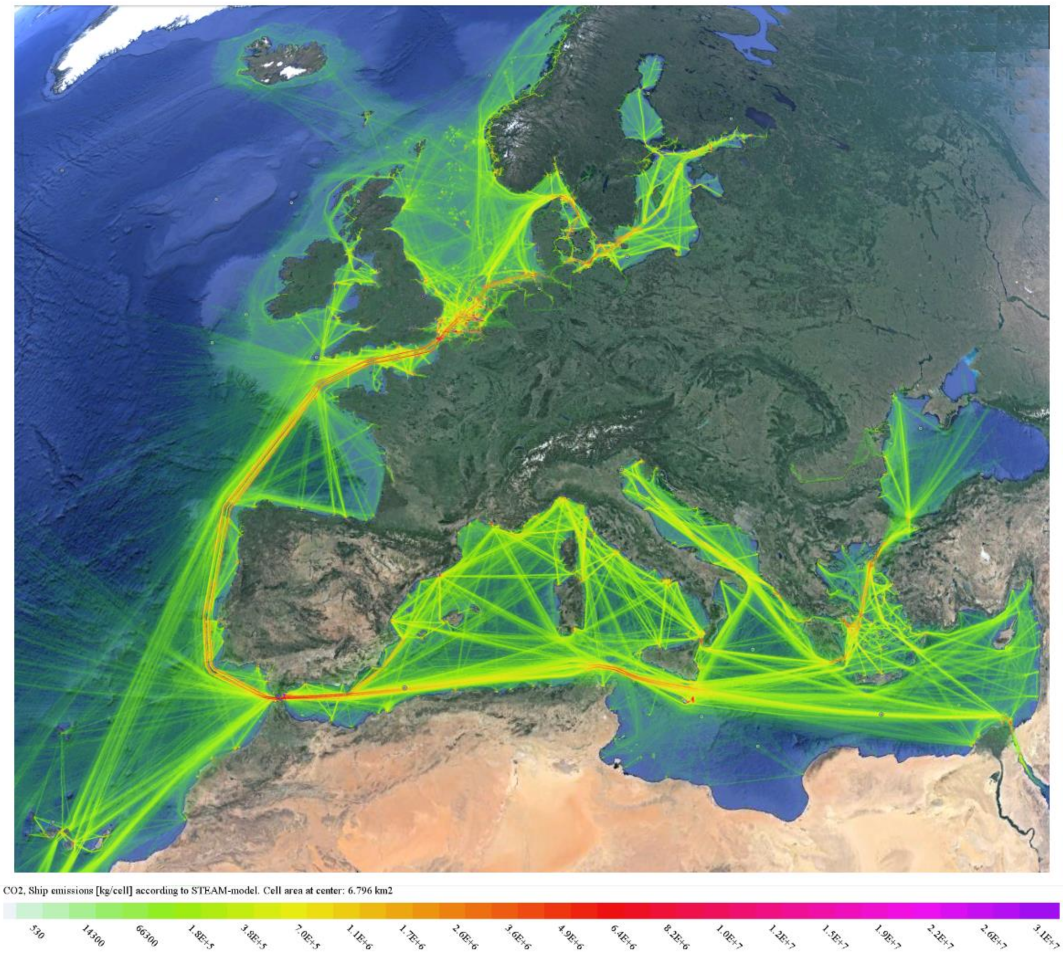

Figure 2: Predicted geographic distribution of shipping emissions of CO_2 in Europe in 2011. The colour code indicates emissions in relative mass units per unit area.

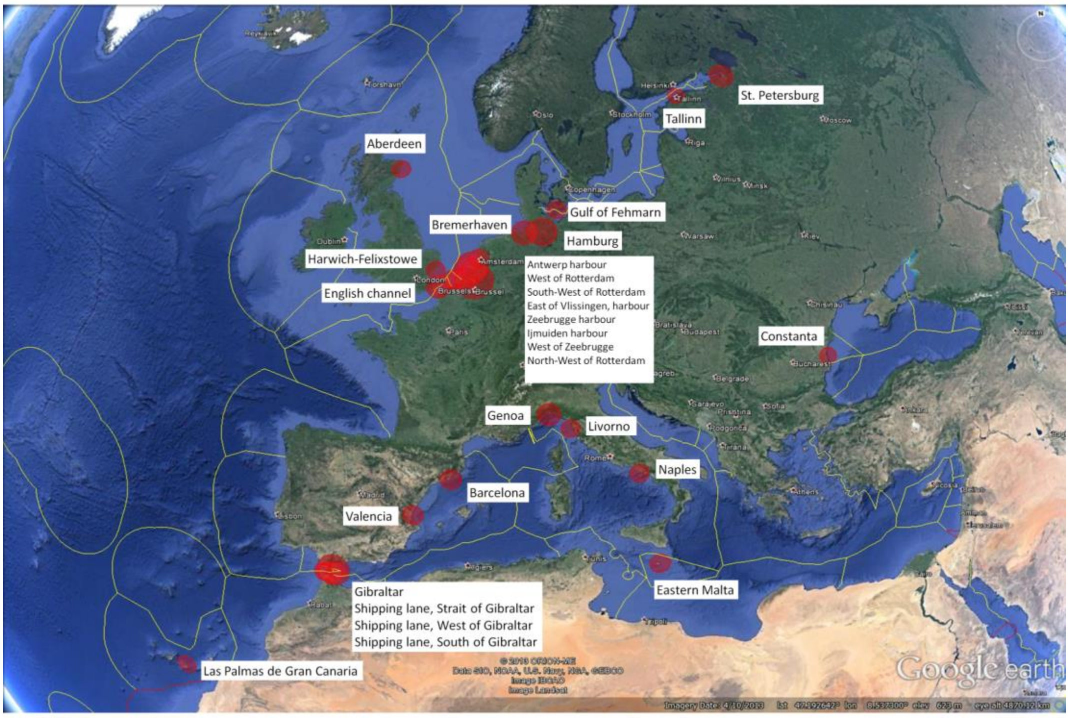

Figure 3: The 30 locations, in which there were highest ship emissions of CO_2 in Europe in 2011. The area of each circle is proportional to the annual CO_2 emission.

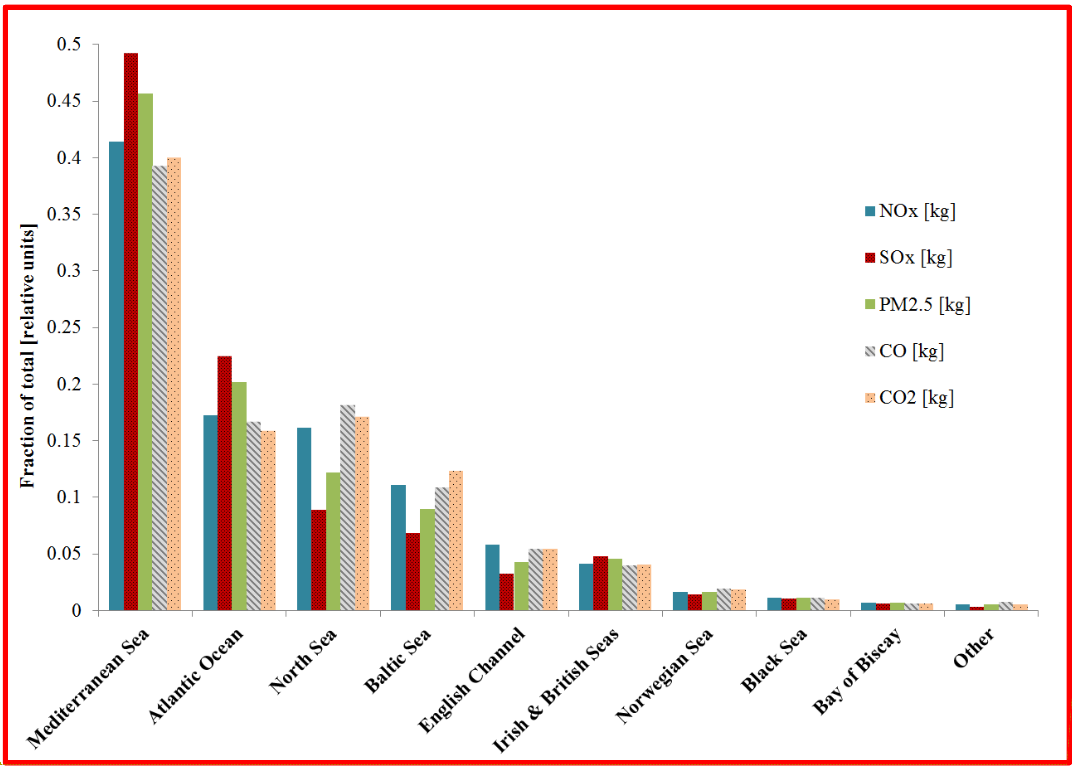

Figure 4 The fractions of shipping emissions for European sea regions in 2011

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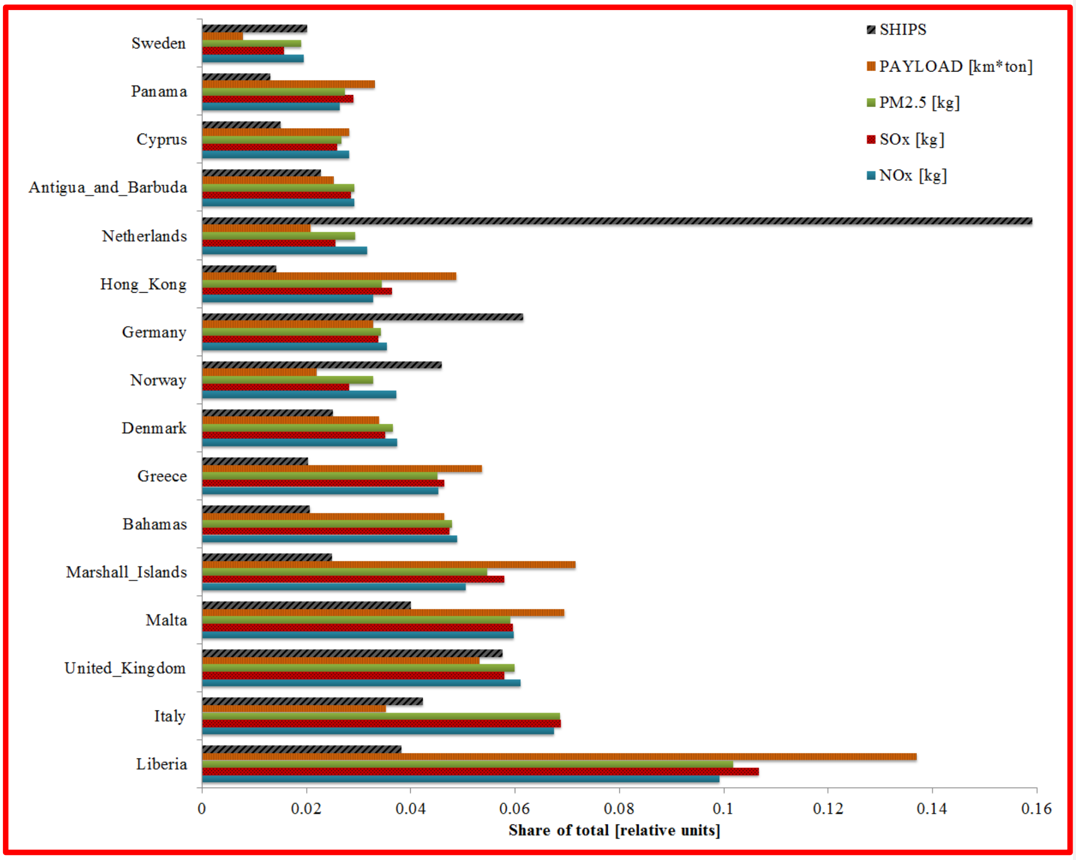

Figure 5: Relative contributions of various flag states to selected emissions, the numbers of ships and cargo payload in Europe in 2011. We have selected 20 states that had the highest emissions of CO_2. These states have been presented in terms of the emissions of CO_2; the lowest entry (Liberia) in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

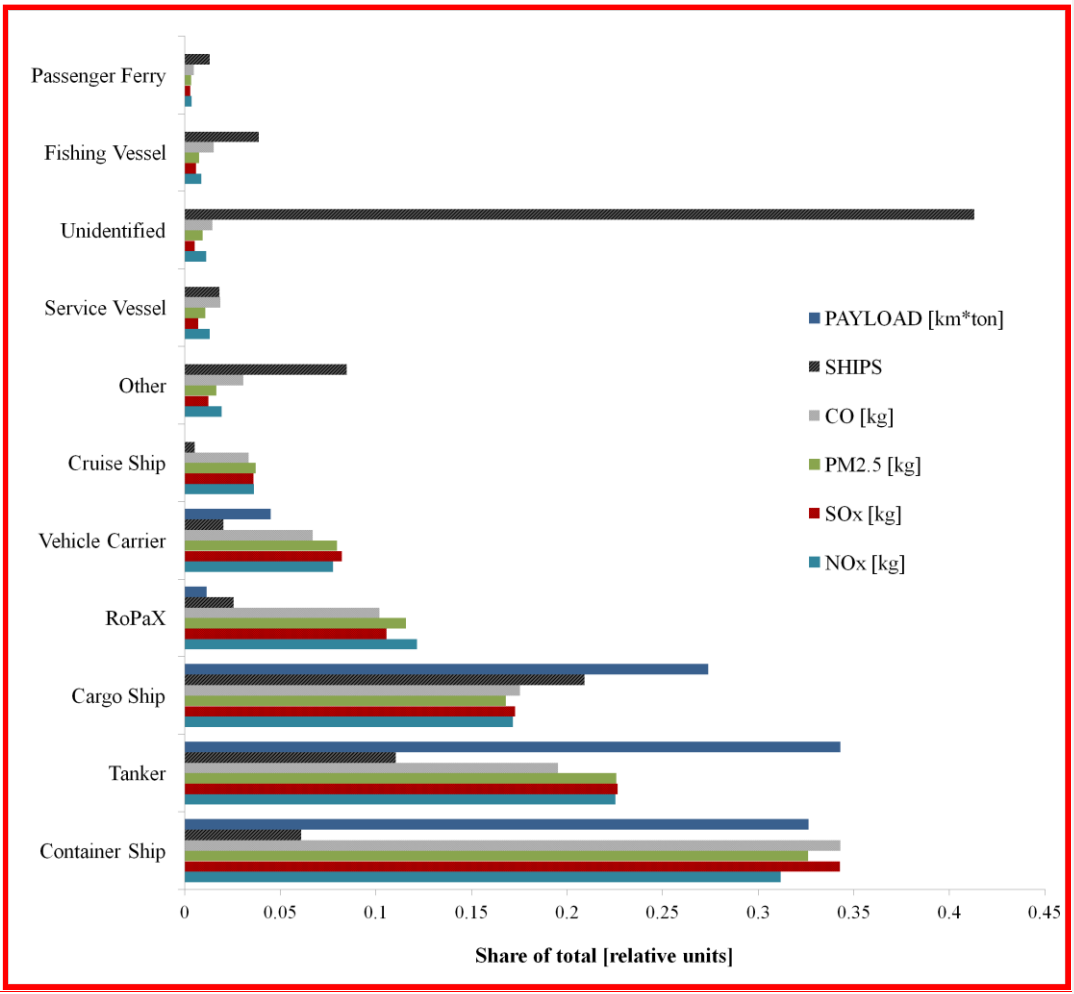

Figure 6: The fractions of European shipping emissions and payload, classified in terms of the ship types, in 2011

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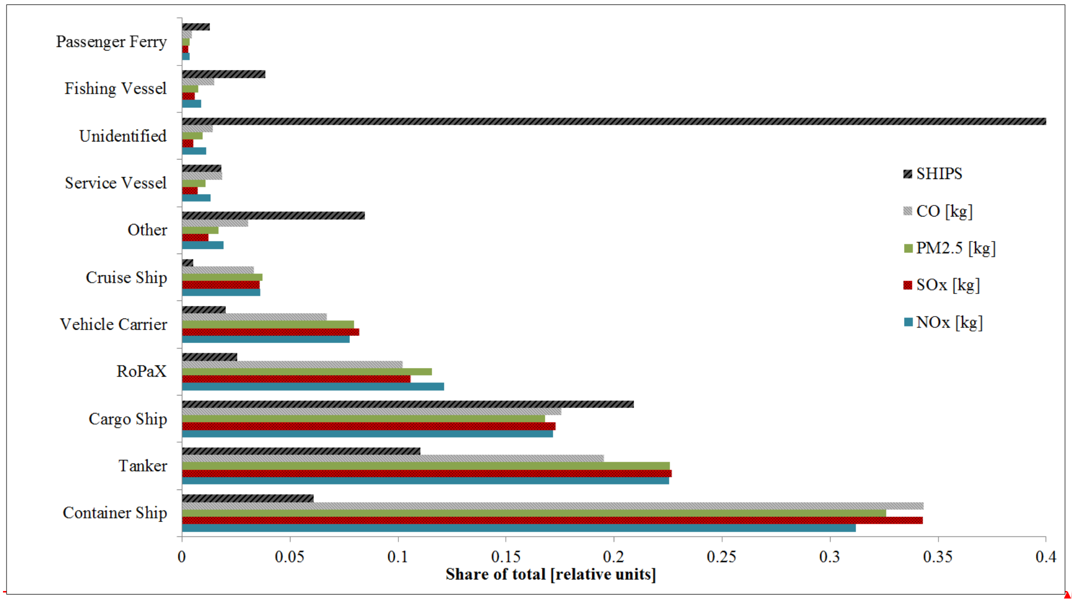

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Figure 6: The fractions of European shipping emissions and payload, classified in terms of the ship types, in 2011.

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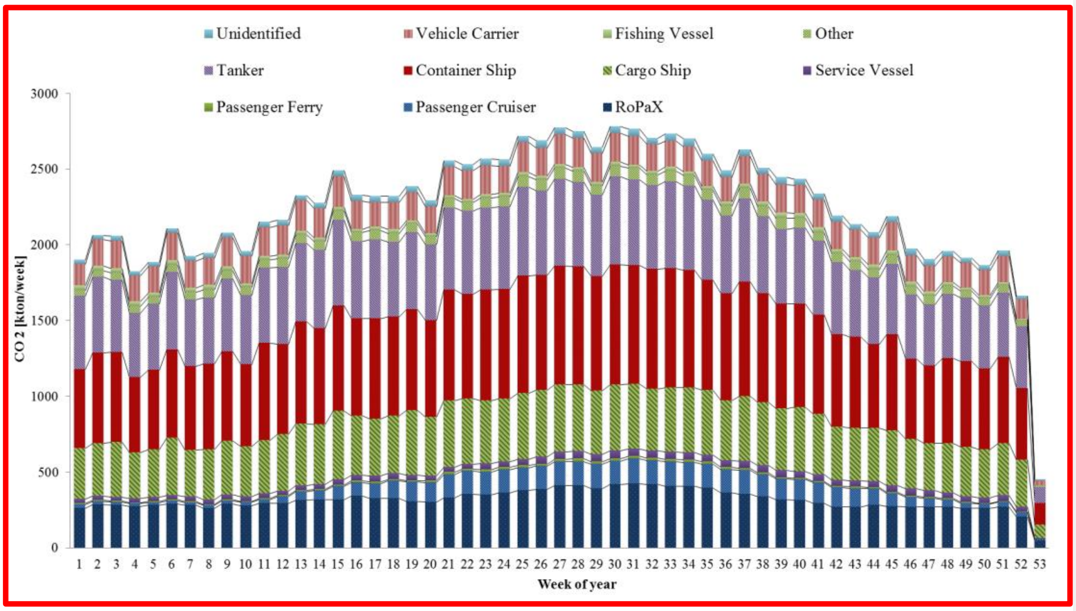

Figure 777: Seasonal variation of the shipping emissions of CO2 in the European sea regions in 2011, classified in terms of various vessel categories.