Atmos. Chem. Phys. Discuss., 13, 16113–16150, 2013
www.atmos-chem-phys-discuss.net/13/16113/2013/
doi:10.5194/acpd-13-16113-2013

Atmospheric Chemistry and Physics Discussions
Open Access

The evolution of shipping emissions and the costs of recent and forthcoming emission regulations in the northern European emission control area

L. Johansson[1], J.-P. Jalkanen[1], J. Kalli[2], and J. Kukkonen[1]

[1]Finnish Meteorological Institute, P.O. Box 503, 00101 Helsinki, Finland
[2]University of Turku, Centre for Maritime Studies, P.O. Box 181, 28101 Pori, Finland

Received: 16 April 2013 – Accepted: 30 May 2013 – Published: 14 June 2013

Correspondence to: L. Johansson (lasse.johansson@fmi.fi)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

An extensive inventory of marine exhaust emissions is presented in the northern European emission control area (ECA) in 2009 and 2011. The emissions of SO_x, NO_x, CO_2, CO and $PM_{2.5}$ were evaluated using the Ship Traffic Emission Assessment Model (STEAM). We have combined the information on individual vessel characteristics and position reports generated by the Automatic Identification System (AIS). The emission limitations from 2009 to 2011 have had a significant impact on reducing the emissions of both SO_x and $PM_{2.5}$. The predicted emissions of SO_x originated from IMO-registered marine traffic have been reduced by 33 %, from 322 ktons to 217 ktons, in the ECA from 2009 to 2011. The corresponding predicted reduction of $PM_{2.5}$ emissions was 20 %, from 74 ktons to 59 ktons. The highest CO_2 and $PM_{2.5}$ emissions in 2011 were located in the vicinity of the coast of the Netherlands, in the English Channel, near the South-Eastern UK and along the busiest shipping lines in the Danish Straits and the Baltic Sea. The changes of emissions and the financial costs caused by various regulative actions since 2005 were also evaluated, based on the increased direct fuel costs. We also simulated the effects and direct costs associated with the forthcoming switch to low-sulfur distillate fuels in 2015. According to the projections for the future, there will be a reduction of 85 % in SO_x emissions and a reduction of 50 % in $PM_{2.5}$ emissions in 2015, compared with the corresponding shipping emissions in 2011 in the ECA. The corresponding relative increase in fuel costs for all shipping varied between 10 % and 63 %, depending on the development of the prices of fuels and the use of the sulfur scrubber equipment.

1 Introduction

It has been estimated in the recent literature that the upcoming Marpol Annex VI agreement will be costly for the shipping industry. The financial costs will increase from 25 % to 40 % within short-sea shipping lanes inside the northern European Sulfur Emission

Control Area, due to the shift to Marine Gas Oil (MGO) (0.1 %) fuel in 2015 (Notteboom et al., 2010). This cost increase will probably lead to changes in the modes of transportation. Possible consequences may be the reduction of capacity for short-sea services and an increased cargo transfer by trucks; these changes may undermine the planned benefits associated with reduced marine emissions. However, the estimates of these consequences have up to date taken into account neither (i) the increases of fuel costs for individual ships or ship categories nor (ii) spatially and temporally accurate activity data of ships.

Emission abatement strategies that specify reduced fuel sulfur content will result in lower emissions of both fine particulate matter and SO_2 from ships. This in turn tends to decrease adverse health effects in human populations, especially within the riparian states and in coastal cities. Also, greenhouse gas emissions from shipping are an increasing concern. Various cost effective mitigation plans have therefore been suggested for CO_2 originated from shipping, using various policies and technological improvements. Corbett et al. (2009) estimated that fuel savings up to 70 % per route could be achieved by halving the cruising speed of container ships, which would cause an equally dramatic decrease in CO_2 emissions from these vessels. However, the loading capacity and overall fleet size would probably need to be correspondingly increased (Corbett, 2009).

As the use of the auxiliary engines may be responsible for more than a half of the total fuel consumption, any reduction in cruising speed will inevitably cause an increase in auxiliary fuel consumption. Further, the engine load affects emission factors and engine efficiency. Ultimately, in order to evaluate the overall feasibility of slow-steaming scenarios, the increase in total operational time for ships needs to be accounted and reflected on fuel consumption savings and the need for additional ships.

This study addresses the shipping emissions of the northern European Emission Control Area (ECA), which includes the North Sea, the Baltic Sea and the English Channel, from 2011 to 2015. In the following, we refer to the northern European ECA simply as “the ECA”. (i) The first aim of this paper is to present an extensive inventory

ACPD
13, 16113–16150, 2013

of shipping emissions in the ECA in 2009 and 2011. We have presented the predicted emissions of CO, CO_2, SO_x, NO_x and $PM_{2.5}$ among different flag states and ship types. The high-resolution geographical distribution of CO_2 and $PM_{2.5}$ emissions has also been presented. (ii) The second aim of this paper is to present the results of model simulations for selected scenarios, assuming different regulations for the fuel sulfur limits, the reductions of the cruising speeds, and the installations of sulfur-scrubbers. For each of these scenarios, we have evaluated the respective impacts on shipping emissions and fuel costs. In particular, the direct fuel costs and emission reductions have been evaluated for the forthcoming Marpol Annex VI requirement, according to which there will be a shift to 0.1 % MGO fuel in 2015.

2 Methods

The emissions presented in this paper were evaluated using 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, 2013).

2.1 The STEAM model and its input values

This modelling approach uses as input values the position reports generated by the Automatic Identification System (AIS); this system is globally onboard every vessel that weighs more than 300 tons. The AIS system provides for automatic updates of the positions and instantaneous speeds of ships at intervals of a few seconds. For this paper, archived AIS messages provided by the North Sea and the Baltic Sea riparian states in 2009 were combined, covering the entire ECA. In order to avoid the processing of an excessive amount of data, the AIS message set used in this study has been down-sampled; the temporal separation between messages is commonly 6 min. The combined dataset for 2009 however, still contains more than 552 million archived AIS-messages. For the ECA in 2011, AIS-messages were extracted from a dataset given by The European Maritime Safety Agency (EMSA). This extracted dataset contains 607 million archived AIS messages.

The model requires as input also the detailed technical specifications of all fuel consuming systems onboard and other relevant technical details of the ships for all the ships considered. Such technical specifications were therefore collected and archived for over 50 000 ships from various sources of information; the data from IHS Fairplay was the most significant source.

The STEAM model is then used to combine the AIS-based information with the detailed technical knowledge of the ships. 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 sulphur content, multiengine setups, abatement methods and waves (Jalkanen et al., 2012).

2.2 Model performance and uncertainty considerations

The model has been able to predict aggregate annual fuel consumption of a collection of large marine ships with a mean prediction error of 9 % (Jalkanen et al., 2012). Large-scale comparisons to ship owner fuel reports have been constrained by the availability of vessel fuel reports, but have so far been done for a dataset of 20 vessels. The capability of the model for estimating instantaneous power consumption has been evaluated to be moderately less accurate, compared with the corresponding accuracy for predicting the fuel consumption, with a mean prediction error of 15 % in a thorough case-study (Jalkanen et al., 2012). The evaluated emissions agree fairly well with the results of several measurement campaigns presented in literature, for various engines, engine loads and pollutants. A more detailed description of the model evaluation studies have been presented in (Jalkanen et al., 2009, 2012). Model uncertainties have been previously assessed in (Jalkanen et al., 2013).

Accurate modelling of emission inventories with the presented method requires that (i) the vessel routes and shipping activities are evaluated correctly, (ii) the instantaneous power requirements of ships are successfully evaluated and (iii) the resulting fuel consumption and emissions are accurately predicted. Considering each of these three consecutive steps, the following sources of uncertainty can be identified. These uncertainties correspond to regional scale emission inventories, as compiled in this study.

2.2.1 Ship routes and harbor activities

High geographic accuracy (tens of meters) of shipping routes can be expected, due to the GPS based location signaling. The temporal and spatial coverage of archived AIS-messages was good in the ECA. There is therefore only a very small fraction of route segments that cross land masses, such as peninsulas or islands.

Accurate modelling of maneuvering activities in harbor areas would require a data set with more frequent (several times per minute) dynamic updates, as the speed of vessels can change frequently and rapidly. We applied in this study down-sampled AIS messages on six minute intervals. Furthermore, the use of auxiliary engines for ships at berth is difficult to predict as, in contrast to main engines, detailed engine specifications of auxiliary engines are rarely available. In some cases however, auxiliary engine information has been augmented with data from classification societies. We estimate that from moderate to high uncertainty can be associated with harbor emissions within regional emission inventories.

2.2.2 The characteristics of vessels and fuels

The ship characteristics database includes detailed information for more than 50 000 ships with a unique IMO identification number. However, the number of unidentified ships without IMO number has been increasing steadily. For instance, the unidentified ships was the second largest ship type category in terms of the number of ships in the ECA in 2011, accounting for 15 % of the total shipping fuel consumption. All unidentified ships are presumed to be small vessels, and we have treated those in the modeling by assuming only generic specifications (weighting 500 tons with a single 1000 kW four-stroke engine). The emissions originated from unidentified vessels are therefore known with a significantly lower accuracy.

The fuel type and especially the fuel sulfur content (FSC), affects significantly the SO_x and $PM_{2.5}$ emissions. We assume that all ships conform to ECA sulfur limits. Considering that ship owners have economic incentive to use fuel grades, which have the maximum allowed FSC, we can estimate that the uncertainty arising from fuel type evaluation is fairly small. However, some engines may use fuel with even lower FSC than the allowed maximum, for technical reasons. This causes additional uncertainties in the evaluation of the emissions, especially for the estimation of fuel type used in auxiliary engines. Moreover, after January 2010 in the ECA, some berthing ships may use a larger FSC for their auxiliary engines than the predicted FSC of 0.1 %.

2.2.3 The emissions of various species

We evaluate that the estimated CO_2 emissions have the lowest margin of error, compared with those of the other modeled species, as the amount of CO_2 per fuel burned can be estimated fairly accurately. Also the NO_x emission factor, which is almost unaffected by engine load and fuel type, can be estimated with a relatively good accuracy. We use Tier I and II NO_x limits for vessels, depending on the year they were built. There may therefore be some underestimation for old ships that are not obliged to conform with Tier I requirements.

The conversion rate of SO_4, the main component of $PM_{2.5}$ emissions, has been assumed to be independent of engine load. However, some recent studies suggest that this conversion rate may be affected by engine load (Petzold et al., 2010). Numerical computations with the model have indicated that conversion rates for SO_4 as presented

ACPD
13, 16113–16150, 2013

by (Petzold et al., 2010) would significantly reduce the estimated emissions of SO_4 (up to 50 % in mass). Furthermore, the emissions of organic and elemental carbon, as well as ash particles, have been assumed to be unaffected by the fuel type; this assumption may prove to be inaccurate. The highest margin of error is expected with estimated CO emissions, as the emission factor has been observed to be highly sensitive to engine load and its rapid changes.

2.3 Model extensions

The model refinements since the previous studies (Jalkanen et al., 2009, 2012, 2013) are presented in this section.

2.3.1 Evaluation of fuel sulphur content in case of fuel conversion and switching, and exhaust gas cleaning systems

Fuel sulfur content significantly affects the $PM_{2.5}$ and SO_x emissions per fuel burned. In ECA region, since the beginning of 2010, the maximum allowed FSC in inland waterway vessels and for ships at berth has been restricted to 0.1 %; however, the latter regulation applies only to vessels, which are berthing for more than 2 h. Otherwise, the maximum FSC has been limited to 1.0 % since July 2010.

Ship operators have several options for complying with FSC requirements, such as (i) fuel conversion, (ii) fuel switching and (iii) exhaust gas cleaning systems (EGCS). In fuel conversion, all fuel storage tanks, piping systems and combustion equipment are converted to be compatible with low sulfur fuel, which is to be used in all situations. In fuel switching, secondary low sulfur fuel storage and piping system is installed and low-sulfur fuel is switched on, when the ship operates inside the ECA area. The switching process, however, may take a considerable amount of time as the switched fuel needs to be warmed (Heavy Fuel Oil, HFO) or cooled (MGO) before use. Hence the requirement for 0.1 % FSC for ships at berth is applied only for the ships that berth longer than two hours. For ships using EGCS instead of low sulfur fuel, the amount of

ACPD
13, 16113–16150, 2013

exhausted SO_x and particle matter is not allowed to exceed the amount that would be exhausted by burning fuel with acceptable FSC.

In the STEAM model, FSC is determined separately for main and auxiliary engines, by taking into account engine specifications and region specific limitations, such as, e.g., the EU shipping sulphur directive. The process of fuel type modelling in STEAM, including FSC, grade and cost, is illustrated in Fig. 1. All vessels are assumed to use the cheapest accepted fuel available (commonly this is also the heaviest fuel). The fuel sulphur content is therefore assumed to be

$$FSC = \min(FSC_C, FSC_A) \quad (1)$$

where FSC_C is the maximum FSC that the engine can use and FSC_A is the maximum FSC allowed by the regulations in the considered area. FSC_C is estimated by using the engine's power output rating and engine angular velocity, measured as revolutions per minute (RPM), based on manufactured marine engines statistics presented in (Kuiken, 2008). Based on these statistics we assume that all main engines with larger power output than 4500 kW (and engine RPM < 1000) can use the heaviest fuel grades; engines smaller than 2000 kW use 0.5 % MDO fuel and otherwise FSC_C is estimated to be 1.0 %. However, according to ship specifications in our database, more than 17 000 ships can be assumed to be equipped with a shaft generator which allows auxiliary power to be produced with main engines in cruising speed. Thus, if a vessel with a shaft generator has a speed greater than 2.5 m s^{-1} (5 knots) we assume that all auxiliary power will be produced with main engines with a FSC that is not affected by auxiliary engine specifications.

The maximum allowed FSC, FSC_A is determined based on region, date and speed. Vessels having a speed lower than 0.5 m s^{-1} (1 knot) continuously for at least 2 h are assumed to be berthing, resulting in a FSC of 0.1 % in the ECA since the beginning of 2010. Further, if a ship owner has installed EGCS to comply with FSC requirements, then FSC_A is assumed to be the sulphur content of the cheapest fuel type available

ACPD
13, 16113–16150, 2013

that would still result in acceptable SO_x and $PM_{2.5}$ emissions, thus complying with regulations in the most economical way.

2.3.2 Evaluation of fuel prices and exhaust gas cleaning systems

Combining the fuel consumption and FSC modelling allows us to evaluate fuel costs for each ship using the STEAM model. According to marine fuel bunker statistics, at the port of Rotterdam the current Low Sulfur Marine Gas Oil (LSMGO with 0.1 % FSC) price in January 2013 was 960 USD per metric ton, whereas Heavy Fuel Oil (HFO380/180) costs approximately 611 USD per metric ton (Bunkerworld.com, 2012). The price of intermediate fuel oil with a maximum FSC of 1.0 % (LS180/380) fuel is priced at 668 USD ton^{-1}.

The price premium between HFO and LSMGO as well as their overall price development over time has proven to be highly volatile. For instance, the average price premium between HFO380 (max. 4.5 % FSC) and LSMGO between 1995 and 2009 has varied between 50 % and 140 % in Rotterdam (Notteboom et al., 2010). Three different price developments for MGO with respect HFO were used in the selected scenarios: 50 % price premium over HFO (FC50 %), 75 % price premium (FC75 %) and 100 % premium (FC100 %).

According to (Notteboom et al., 2010) the FSC in the heaviest and cheapest fuels available can be assumed to be no larger than 2.7 % as the world average of sulfur content in HFO fuels is 2.67 %. We assume that vessels use a mixture of fuels, which has an arbitrary average FSC between 2.7 % and 0.1 %, so that the evaluated FSC given by Eq. (1) has been achieved. The price estimate of this mixture of fuels is then computed as a function of sulfur content, according to regression curves presented in Fig. 2.

The three price functions in Fig. 2 correspond to the current state and two future price development possibilities: FC50 % curve corresponds to prices (HFO380, LS180 and LSMGO) as they were at the time of writing at Rotterdam, FC75 % and FC100 % gives the price estimates in case the price premium between LSMGO and HFO380

ACPD
13, 16113–16150, 2013

increases to 75 % and 100 % respectively. We apply these fuel prices for all past and future scenarios presented in this paper; the derived fuel costs (and thus the direct costs of regulations to ship owners) of each scenario are therefore comparable with each other.

The use of EGCS's offer potential fuel cost savings for ships that operate in ECA area, as IMO accepts EGCS's as alternatives to the use of low sulfur fuels. With a scrubber onboard, a ship can consume high FSC fuel and still comply with regulations. In Reynolds (2011) it was estimated that for any ship, which consumes annually more than 4000 metric tons of fuel in ECA, should be a potential candidate for an EGCS installation. Assuming 50 % price premium for LSMGO with respect to HFO and active use within ECA for at least six years after 2015, the net financial value for EGCS scrubber installment should be positive.

Scrubbers can use wet or dry physical scrubbing or chemical adsorption to remove combustion products. In Corbett (2010) it was concluded that the $PM_{2.5}$ removal is likely to be 75 ± 15 % with a scrubber on board. Other studies have indicated that the resulting reduction in PM mass can be in between 25 % and 98 %, depending on particle size distribution, although the removal rates by species are more uncertain (Lack and Corbett, 2012). Also, a significant reduction in SO_x output will occur. In Andreasen and Mayer (2007) it was estimated that a sea water scrubber-system can reduce 66 % of SO_x emissions.

2.3.3 Interpolation of shipping routes

In the STEAM model, the travel routes are evaluated in a stepwise manner, by a linear interpolation of the geographical coordinates, for each consecutive AIS message pair. Due to this method of determining routes, it is useful to analyze in addition the validity of each travel segment. The calibration and use of AIS-transmitters is also potentially susceptible to human errors. Especially smaller ships without an IMO number behave suspiciously in some cases, based on the geographic information included in their AIS-messages. Further, in order to ensure a good accuracy of the method, at open sea fairly extensive spatial and temporal gaps can be allowed, whereas at harbors the possible AIS down-time of ships (i.e., the interval between an end of a berthing activity and the start of cruising) needs to be substantially shorter. The methods for the evaluation of route segments were therefore refined for this study.

The validity of each linear route segment has been evaluated based on the average vessel speed v_a given by two consecutive AIS messages, the time duration Δt, which is computed from message timestamps and the distance Δs, which is calculated from the two message coordinate pairs. In addition, two other evaluation measures are used: the so-called implied speed, defined as $v_I = \Delta s / \Delta t$ and implied distance, defined as $\Delta s_I = v_a \Delta t$. The emission is computed for any route segment, if and only if the following three conditions are satisfied:

- The ship is physically able to travel the distance during the time interval in view of the specified design speed of the vessel. This criterion is confirmed if v_a or v_I is not significantly greater than the vessel's listed design speed.
- The temporal or spatial separation of a route or berthing segment does not exceed pre-selected maximum values. These maximum values have been specified separately for harbor activities and open sea activities. For each segment in the ECA, we have used the maximum values of 600 km and 24 h for open sea operations and 2 h for berthing activities.
- The vessel would not travel multiple times (or just a fraction of) the distance Δs within the given v_a and Δt. Thus, Δs_I must be close to Δs.

2.3.4 Slow-steaming

Required propelling power for any marine vessel increases strongly as a function of its speed, due to the friction against water and the forming of waves. Even a minor reduction of vessel speed can therefore significantly reduce the main engine fuel consumption. The concept of slow-steaming refers to a situation, in which a marine vessel

ACPD
13, 16113–16150, 2013

reduces its speed to achieve significant fuel savings. However, the fuel savings and emission reductions are obviously obtained at the expense of a longer cruising time.

In order to evaluate the net benefits in the selected slow-steaming scenario, the total travel time differential is calculated for each route segment. We assume a fractional speed reduction with a factor of $a \in [0,1]$. The increase in travel time T_+, the reduced slow-steaming speed v_{iR} and the increased duration Δt_{iR} are given by

$$\begin{cases} T_+ = \sum_i (\Delta t_{\mathrm{iR}} - \Delta t_i) & \text{(2a)} \\ v_{\mathrm{iR}} = (1-a)v_i & \text{(2b)} \\ \Delta t_{\mathrm{iR}} = \Delta t_i (1+a) & \text{(2c)} \end{cases}$$

where Δt_i is the duration of the travel of the ship during the ith segment of a route (defined by two consecutive AIS-messages), without assuming slow speed and v_i is the average speed in ith segment of a route, without assuming slow speed. Δt_{iR} is the increased duration of travel with the slow-steaming speed. The reduced speed v_{iR} is used for instantaneous main engine power estimation, which in turn is used for engine load, fuel consumption and subsequently, for emission estimation. To account the fact that engines are being used longer with each segment using the reduced speed, the duration Δt_{iR} is used instead of Δt_i in emission calculation. Besides the instantaneous speed, the main engine power requirement is affected by various ship attributes, such as hull dimensions and propeller properties. This fairly complicated process was discussed in more detail in (Jalkanen et al., 2012).

2.4 Selected scenarios of the emissions and fuel costs

2.4.1 Scenarios in the past, since 2005, 2009 and January of 2010

We have evaluated the emissions and fuel costs for three separate scenarios in the past, all of which assume that no abatement of shipping emission had been done. (i) First, we have evaluated the emissions and fuel cost differentials for a scenario, in which we assumed that no FSC regulations had been imposed in the ECA after 2005. We have therefore assigned $FSC_A = 2.7\,\%$ in Eq. (1), and compared the resulting SO_x and $PM_{2.5}$ emissions and fuel costs with the status quo emission estimates in 2011.

Further, similar simulations are presented for scenarios assuming that (ii) no further regulations had been introduced after 2009, i.e., $FSC_A = 1.5\,\%$, and (iii) no further regulations had been introduced after January of 2010, i.e., $FSC_A = 1.5\,\%$ and 0.1 % for berthing ships.

2.4.2 Scenarios for the future, in 2015

We have simulated the effects of the upcoming FSC requirements in 2015, by using the archived AIS-data for 2011 and assigning $FSC_A = 0.1\,\%$ for all ships and activities.

Another simulation for 2015 was performed, in which EGCS installation candidate vessels were identified (cf. Sect. 2.2.2) and were assumed to be equipped with scrubber abatement equipment. Vessels which are equipped with abatement equipment may use cheaper and heavier fuel than LSMGO, provided that the emissions do not exceed those that would be achieved with LSMGO without abatement equipment.

2.4.3 Slow steaming scenario

In the slow steaming scenario, we have evaluated the shipping emissions and statistics, as if each ship would have fared 10 % and 30 % slower while cruising ($a = 0.1$ and $a = 0.3$ in Eq. 2c). However, we assume that the speed reduction at slow speeds would not be economically desirable for ship owners. The speed reduction is therefore applied only, if the instantaneous speed exceeds $5.1\,\mathrm{m\,s^{-1}}$ (10 knots). As the engine power needs to be continuous in time, any reduced speed will not be reduced below this selected threshold value.

The increase in cruising time has been calculated according to Eq. (2a–c), and the resulting emissions and fuel consumption with the reduced speed has been compared with the baseline emission estimates and fuel consumption and costs for 2011. Thus, we account for the increase in auxiliary fuel consumption as well as the decrease in main engine loads. We have not taken into account however the potential need for increasing the fleet size, due to the increase in cruising time.

3 Numerical results

The results were evaluated using the shipping emission model STEAM, with the archived AIS and ship properties data for the ECA region in 2009 and 2011. In the following, we first present an inventory of the emissions in 2009 and 2011 in the ECA, second, we address the spatial concentration distributions of the emissions in 2011, and third, present model predictions for the various assumed scenarios in the past and for the future.

3.1 Emission budgets in 2009 and 2011

The predicted emission inventories and shipping statistics are presented in Table 1 for the ECA in 2009. The maximum allowed FSC at the time was 1.5 %.

The corresponding shipping emission inventories according to EMEP have also been included in Table 1. However, there are some methodological differences between the current study and the methods used by EMEP. First, the STEAM model evaluated the $PM_{2.5}$ emissions, including the moisture ($SO_4 + 6.5H_2O$) for sulphate particles (Jalkanen et al., 2012), whereas EMEP has used the dry weight of SO_4. Secondly, the EMEP estimates include neither harbor activities nor non-IMO registered ships, whereas those have been included in the STEAM computations. At least the influences of the latter two methodical differences between the two computations are substantial. For instance, according to the STEAM predictions, approximately 25 % of the total fuel was consumed at harbors in the ECA in 2009, and the non-IMO registered ships were responsible for 8 % of total CO_2 emissions.

ACPD
13, 16113–16150, 2013

The total shipping emissions predicted using STEAM were fairly close (< 7 %) to the corresponding EMEP emissions in case of NO_X, while the STEAM estimated SO_x emissions were 17 % lower. There were more notable differences in case of $PM_{2.5}$ and CO.

In 2009, approximately 16.5 and 32.6 million tons of CO_2 were emitted at the Baltic Sea and at the North Sea (for simplicity, the latter is here interpreted to include also the English Channel), respectively. The most significant flag states were the Scandinavian countries Norway, Sweden and Denmark, the Netherlands and the UK. The cargo ships were the single most significant ship type in terms of the CO_2 emissions.

The corresponding emission estimates in the ECA in 2011 are presented in Table 2. In contrast to 2009, the maximum allowed FSC for ships at berthing was limited to 0.1 %, and otherwise to a maximum of 1.0 %. The contribution from non-IMO registered ships in terms of CO_2 has increased to 15 %; this has probably been caused by an increase of small ships that have installed AIS-transmitters. The annual marine traffic has essentially remained unchanged from 2009 to 2011, in terms of cargo payload and traveling amounts. However, the CO_2 emissions have increased approximately 9 %, mainly due to the increase in non-IMO registered shipping.

However, there have been significant changes in the distribution of emissions for the various flag states. For instance, the number of ships sailing under the flag of Norway has substantially decreased, while the fleet of the Netherlands has significantly increased. A geographical difference map between the CO_2 emissions in 2011 and 2009 reveals a strong increase in the sea regions in the vicinity of the Netherlands, and a distinct decrease near the coasts of Norway (the results not shown here). These changes could be caused either by changes in shipping activities or changes in the use of AIS-equipment.

The imposed emission limitations up to date have had a significant impact on the emissions of SO_x and $PM_{2.5}$. According to results in Tables 1–2, the SO_x emissions originated from IMO-registered marine traffic have been reduced from 2009 to 2011 from 322 ktons to 217 ktons. The corresponding predicted reduction for $PM_{2.5}$ from

ACPD
13, 16113–16150, 2013

74.0 ktons to 59.4 ktons. During the same period, the corresponding CO_2 emissions have increased by 3 % for IMO-registered traffic. Also the estimated NO_x emissions from IMO-registered traffic are slightly lower in 2011 than in 2009. The reason for this reduction is that starting from January 2011, the NO_x emission factor must not exceed the IMO specified Tier II factor, which is slightly lower than the previous Tier I requirement for all engines. We have assumed that ships built after 2008 conform to the new Tier II limitations, as the engine manufactures have been well prepared for those requirements. However, the effect of the implementation of Tier II for the emissions of NO_x from 2009 to 2011 seems miniscule, but will certainly increase when the fleet will be renewed in time.

The temporal evolution of the emissions of CO_2 has been presented in Fig. 3 for different ship categories in both 2009 and 2011. The shipping activities in terms of CO_2 have not substantially changed from 2009 to 2011. However, the number of non-IMO registered ships has increased from 8161 (in 2009) to 14 137 (in 2011). However, this increase has not necessarily been caused by an increase in fleet size. A larger fraction of smaller ships have installed AIS-transmitters, as these have become more affordable.

Based on the fuel consumption statistics for IMO registered vessels, 38 % of the total fuel was consumed by auxiliary engines in 2009 and 2011. Approximately 17 000 ships in the ship properties database has been associated with a shaft generator, which allows the main engine to provide power to ship systems, while the ship is cruising. Without shaft generators the predicted fuel consumption of main and auxiliary engines would be almost equal. It has been predicted that the use of HFO significantly outweights the use of distillate fuels. Commonly a ratio, such as 85 %/15 %, has been used to distinguish the use of distillate fuels and the heavier grades. However, according to results this assumption seems to be biased. Assuming that fuels with a lower FSC than 1 % were distillate fuels (MDO or MGO), the ratio of HFO and distillate fuel consumption was approximately 76 %/24 % in 2009. In 2011, this ratio has changed significantly, to 60 %/40 %. The high fraction of the distillate fuels is caused by two

ACPD
13, 16113–16150, 2013

main factors. First, a major fraction of the fuel consumption originates from auxiliary engines during harbor activities; most of the auxiliary engines cannot use HFO due to engine restrictions (e.g., engine size, RPM and stroke type). Second, distillate fuel consumption for ships at berthing has increased significantly after the introduction of Marpol ANNEX VI regulation.

3.2 The geographical distribution of shipping emissions in 2011

In 2011, the geographical distribution of CO_2 and $PM_{2.5}$ emissions in the ECA has been presented in Figs. 4 and 5, respectively. 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 highest CO_2 and $PM_{2.5}$ emissions originated from shipping are located near the coast of the Netherlands, in the English Channel and along the busiest shipping lines in the Danish Straits and the Baltic Sea.

In particular, in the vicinity of the coast of the Netherlands, the predicted $PM_{2.5}$ emissions per unit sea area that are from three to five times higher, compared with the corresponding values in the major shipping lanes at the Baltic Sea. Near several major ports (e.g., Antwerp, Rotterdam, Amsterdam, Hamburg, Riga, Tallinn, Helsinki and St. Petersburg), there are localized high amounts of $PM_{2.5}$ emissions that exceed the corresponding emissions even within the busiest shipping lanes in the ECA.

The geographic distribution of CO_2 emissions varies substantially between ship types, as illustrated in Fig. 6. Passenger ships operate relatively more at short distances, compared with the other presented ship categories. There is especially intensive passenger ship traffic between the ports of France and the U.K, and there is a busy traffic also between Rostock and Trelleborg, and between Helsinki and Tallinn. The geographical distributions of CO_2 emissions originated from container ships and cargo ships are similar with each other. However, the container ships were responsible for approximately 18 % more CO_2 emissions in 2011 than cargo ships. A substantial fraction of both container and cargo ships are located along the main shipping lanes from south-west (the English Channel) to north-east (St. Petersburg). Miscellaneous ships operate intensively near the ports and the oil rigs at the North Sea. Almost 4 % of the fuel consumed at the North Sea is used by service ships that operate between oil rigs and ports.

3.3 Results for the selected scenarios of the emissions and fuel costs

Since May of 2006, the maximum allowed FSC in the ECA has been gradually lowered. In 2015, it will be reduced to 0.1 % for all large marine vessels operating within the area.

3.3.1 Results for the scenarios in the past, since 2005, 2009 and January 2010

The relative SO_x and $PM_{2.5}$ emissions and fuel costs for the selected scenarios have been summarized in Fig. 7, in relation to modelled emissions and fuel costs in 2011. The simulations for the past assumed that there would have been no regulative actions since 2005, 2009 or January of 2010, and then proceeded to evaluate the emissions and fuel costs for the reference year of 2011. In the following, we call these scenarios for simplicity the 2005, 2009 and 2010 scenarios.

For the 2005 scenario, the SO_x emissions in 2011 would have been more than double (+131 %), compared with the actual situation in 2011. The emissions of SO_x and $PM_{2.5}$ for this scenario would have been 537 ktons and to 110 ktons, respectively. As expected, the direct fuel costs would have been lower that for the actual situation in 2011, about 11.6 billion dollars, based on the current Rotterdam bunker fuel prices; this is 1.6 billion dollars less than the actual estimated fuel costs in 2011.

In the 2009 scenario, there would be 367 ktons and 85 ktons of SO_x and $PM_{2.5}$ emissions, respectively. These estimates are slightly larger than the presented values that were estimated with the actual data set for 2009. The total fuel costs for all ships would be 11.86 billion dollars, which is only 260 million dollars more than the costs in the 2005 scenario. The reason is that the price of marine fuel with a FSC close to 1.5 % is only slightly higher than the fuel price for 2.7 % HFO, which was accepted before May 2006 in the ECA.

ACPD
13, 16113–16150, 2013

In the 2010 scenario, in which FSC maximum was set to 1.5 % and 0.1 % for ships at berth, ships would exhaust 305 ktons of SO_x and 76 ktons of $PM_{2.5}$, having fuel cost of 12.8 billion dollars, which is roughly 400 million dollars less than the estimated fuel costs for 2011 and 940 million more than in the 2009 scenario. Thus, we estimate that the requirement to switch to low sulfur distillates while berthing decreased the SO_x emissions in harbours by 64.4 ktons and the $PM_{2.5}$ emissions by 9.4 ktons. The reduction of FSC to a maximum of 1.0 % starting from 1 July of 2010, reduced SO_x emissions further by 70 ktons and $PM_{2.5}$ emissions by 10 ktons; the combined direct fuel costs of these reductions is approximately 1.3 billion dollars.

3.3.2 Results for the scenarios for the future, in 2015

The 2015 scenario was simulated with the ECA 2011 data sets, i.e., by assuming that the shipping activities and the properties of the ships will be the same in the future, and by setting a maximum allowed FSC to 0.1 % for all activities. Three different fuel price scenarios were included, as the evolution of the relative prices of these fuels is uncertain; these are denoted briefly by FC50 %, FC75 % and FC100 % (FC = fuel cost). These fuel price scenarios correspond to the cases, in which the fuel prices remain the same as in 2011, and MGO is 50 %, 75 % or 100 % more expensive than HFO.

The SO_x emissions in this scenario will be reduced to a mere 33.5 ktons and fine particle emissions will be reduced to 37.1 ktons. In comparison with the situation in 2011, the SO_x emissions will be reduced by 85 % and the $PM_{2.5}$ emissions will be reduced by 43 %. The relative reduction of $PM_{2.5}$ emissions is smaller in comparison to those of SO_x, as marine engines produce significant amounts of carbon and ash particles, regardless of FSC. The direct fuel costs will increase to 15.7, 18.5 or 21.5 billion dollars, depending on the fuel price development, which corresponds to a cost increase of 19–63 %.

Reynolds (2011) estimated that ships with an annual fuel consumption of more than 4000 tons would gain economic benefit from scrubber installation, instead of using 0.1 % MGO fuel in 2015, provided that MGO will be at least 50 % more expensive than

HFO and each ship with an installed scrubber will be active for at least 5 yr after installation. Using the modelled fuel consumption statistics for the year 2011, the possible candidates for EGCS installment suggested by Reynolds were identified; a total of 635 candidate ships were found. While there was more than 30 000 different ships operating at the time, these 635 ships account for 21 % of the total fuel consumption in the ECA. These ships have been listed in Table 3 according to their ship category. Most of these candidate ships are either container ships or RoPax vessels.

Another simulation was performed with the 2015 regulations, in which a typical scrubber abatement method was assumed to be installed to each candidate ship. The fuel costs of this scenario were significantly lower compared with the corresponding scenario without the scrubbers: 14.5, 16.8 or 19.2 billion dollars (a cost increase from 10 % to 46 %). Further, most of the economic benefits from the use of scrubbers (and from using cheaper fuel simultaneously) were in the Baltic Sea shipping. A major portion of the identified EGCS candidate ship operates mainly in the Baltic Sea.

The economic benefits from the use of scrubbers in 2015 are clear, based on these computations. However, the cost of an EGCS installment per vessel can be from 5 to 9 million dollars (Reynolds, 2011), and there are also maintenance costs. These installment and maintenance costs have not been taken into account in the presented scenarios. Further, for technical reasons not all ships can be equipped with such an installment and it might also not be economically viable, if the vessel is reaching the end of its lifespan.

3.4 Slow steaming

We have investigated the savings in fuel consumption and the reduction of emissions, due to reducing vessel speeds. In evaluating the financial costs, we have not addressed the additional costs associated with longer cruising times, such as, e.g., increased personnel costs, costs related to the slower delivery of the cargo, and the potential need for increasing the fleet size.

For simplicity, the amount of speed reduction was selected to be proportional to actual speed, viz. 10 % or 30 %. However, such speed reduction was imposed only, if vessel speed was higher than 5.1 $m s^{-1}$ (10 knots), as it would be unlikely to achieve significant economic savings by reducing speeds that are lower this selected threshold value. The estimated savings in the consumption and costs of fuel, and the reductions in emissions have been presented in Table 4a–b.The results of these slow-steaming scenarios are shown separately for those vessel categories, for which the fuel consumption > 1.0 % of total fuel consumption in the ECA in 2011. The presented ship types, except for the container ship category, are sub-classes of the vessel categories presented in Tables 1 and 2.

Even a reduction of 10 % in cruising speed will effectively reduce the main fuel consumption of several ship categories. In total, CO_2, NO_x, SO_x, and $PM_{2.5}$ emissions are reduced by 6.6 %, 8.8 %, 10.7 % and 8.5 % respectively. Depending on the ship type, the achieved reduction in main fuel consumption ranges from 6.7 % to 17.8 %. The relative change of the operational time (berthing, maneuvering and cruising) is significantly smaller. For instance, the fuel costs of RoPaX ships would be reduced by 10.9 %, while the operational time increases by 2.9 %. RoRo and vehicle carriers would achieve the reductions in fuel costs of 13.3 % and 9.8 %, while their operational time would increase by 4.6 % and 3.9 %. Together, the categories of RoPaX, RoRo and vehicle carriers contribute 16.8 % of the total fuel consumption in the ECA. Container ship category, which is the largest vessel category in the ECA, would gain a modest 5.9 % reduction in fuel costs, and an increase of operational time of +3.8 %.

The reductions of the NO_x, SO_x and $PM_{2.5}$ emissions are larger than those for CO_2. The reason is that the main engines generally use fuel with a higher FSC and large two-stroke main engines are responsible for higher NO_x emissions per provided energy unit, compared with smaller auxiliary engines. On the other hand, the CO emissions per provided energy unit tend to increase for lower engine loads.

For the scenario with a speed reduction of 30 % – the emissions of CO_2, NO_x, SO_x and $PM_{2.5}$ are reduced by 14.6 %, 20.2 %, 24 % and 18.1 %, respectively. Due to the selection of the above mentioned threshold speed ($5.1\,m\,s^{-1}$), only the ships, which are cruising faster than $7.4\,m\,s^{-1}$ (approximately 14.3 knots) are subject to a full 30 % reduction in speed. Substantial reductions due to a reduced speed would be expected for RoPaX ships, vehicle carriers, crude oil tankers and passenger cruisers.

Inter-comparing the results for these two speed reduction scenarios reveals that the savings of fuel costs with respect to the increases of operational times are higher in the scenario with a 10 % speed reduction. This is to be expected, as the slower cruising speed results in a higher fuel consumption of auxiliary engines. A major increase in operational time also results in a need for using additional ships.

4 Conclusions

The marine exhaust emissions were evaluated using the STEAM model in the ECA in 2009 and 2011. The combined emissions of CO_2 from shipping sources in the ECA were evaluated to substantially increase from 49 to 54 million tons from 2009 to 2011 (+10 %, using 2009 as the base year). However, the number of the IMO-registered ships and the cargo transport in terms of payload increased only slightly during this period. The notable increase of predicted CO_2 emissions from 2009 to 2011 was therefore probably caused by the increased use of AIS transmitters in small ships. The estimated contribution of non-IMO registered vessels to total CO_2 emissions was 15 % in 2011.

The predicted SO_x emissions originated from IMO-registered marine traffic have been reduced from 322 ktons to 217 ktons from 2009 to 2011 (–33 %, using 2009 as the base year). The corresponding predicted reduction for $PM_{2.5}$ was from 74.0 ktons to 59.4 ktons (–20 %, using 2009 as the base year). The emission limitations from 2009 to 2011 have obviously had a significant impact on reducing the emissions of both SO_x and $PM_{2.5}$.

The highest CO_2 and $PM_{2.5}$ emissions originated from shipping in 2011 were located in the vicinity of the coast of the Netherlands, in the English Channel, near the South-Eastern UK and along the busiest shipping lines in the Danish Straits and the Baltic

ACPD
13, 16113–16150, 2013

Sea. Near several major ports (e.g., Antwerpen, Rotterdam, Amsterdam, Hamburg, Riga, Tallinn, Helsinki and St. Petersburg), there were especially high $PM_{2.5}$ emissions per square kilometer, which exceeded the corresponding emission values even within the busiest shipping lanes in the ECA. The geographic distribution of emissions was substantially different for various ship types. Clearly, the emission inventories of this study could be used as input values for evaluating the atmospheric dispersion, population exposure and health impacts caused by shipping.

A number of scenario computations for the past were performed, to evaluate more extensively the effects of the gradually decreasing maximum allowed FSC. As a result of the restrictions, the SO_x and fine particle matter emissions originated from IMO-registered shipping have steadily decreased. A model simulation was performed, in which we assumed that the FSC regulations as they were issued in 2005 would have been in effect until 2011, without any subsequent fuel sulphur content restrictions. The simulation showed that the SO_x emissions in the ECA would have been 131 % higher (i.e., more than twice as high), compared with the predicted values in 2011, including all the implemented regulations. The corresponding $PM_{2.5}$ emissions would have been 67 % higher. However, the direct fuel costs would have been 12 % lower, according to the predictions.

The potential impacts of the forthcoming reductions regarding the maximum allowed FSC in 2015 were also studied, with simulations using the archived data in 2011. It was estimated that the emissions of SO_x will be reduced by 86 % and those of $PM_{2.5}$ by 44 %, with respect to the estimated emissions in the ECA in 2011. The direct fuel costs were estimated to increase by 19 % from 2011 to 2015, assuming the contemporary bunker prizes. However, if the price premium of MGO with respect to HFO by that time will increase to 100 %, due to the increase in demand, then the direct fuel costs would annually be 64 % higher.

Based on the estimated fuel consumption and current fuel prices, it was evaluated that more than 630 IMO-registered ships might benefit from a retro-fit scrubber installation. These candidate ships were responsible for approximately 21 % of the total fuel

ACPD
13, 16113–16150, 2013

consumption in the ECA in 2011. Assuming that each of these ships would use sulfur scrubbers instead of using 0.1 % sulphur content MGO in 2015, the estimated fuel cost would increase in 2015 either only by 10 % (using the contemporary bunker prizes) or by 46 % (assuming 100 % price premium between HFO and MGO). However, we did not address in these computations the installment costs and running maintenance costs. It is also not technically feasible to retro-fit all of the candidate ships with such an EGCS device.

The possibility to achieve emission reductions by decreasing vessel cruising speeds was also investigated. We applied numerically speed reductions of 10 % and 30 % to speeds exceeding $5.1\,\mathrm{m\,s^{-1}}$ (10 knots). Furthermore, we accounted for the increases in auxiliary engine fuel consumption, decreases in engine loads and computed the resulting fuel savings and emission reductions for each pollutant and ship category individually. The resulting fuel savings were significant even with a 10 % reduction of cruising speed. The relative reduction of NO_x, SO_x and $PM_{2.5}$ emissions was estimated to be higher than the reduction in total fuel consumption. The effectiveness of speed reduction as a way to curb emissions varies substantially between ship types. Especially RoPax, RoRo and vehicle carrier ships could substantially save in fuel costs, while the increase in operational time would not be significantly increased. The ratio of fuel savings and the increase in operational time was better using the smaller 10 % speed reduction for all ship types. However, the reduced cruising speeds may result in a need for larger fleet sizes.

Acknowledgements. We gratefully acknowledge the support of the Finnish Transport Safety Agency (TraFi), the member states of the Marine Environment Protection Committee of the Baltic Sea (Helcom) and the funding for Finnish Academy CLAIH project in this work. We are thankful for the European Maritime Safety Agency for providing the ship movement data for this research. The research leading to these results has received funding from the European Regional Development Fund, Central Baltic INTERREG IV A Programme within the project SNOOP. The publication has been partly-produced in co-operation with the BSR InnoShip project (project no #051 in the Grant Contract). The project is part-financed by the EU Baltic Sea Region Programme 2007–2013, which supports transnational cooperation in the

ACPD
13, 16113–16150, 2013

Baltic Sea region. The research leading to these results has also received funding from the European Union's Seventh Framework Programme FP/2010–2013 within the TRANSPHORM project, grant agreement no 243406. This publication reflects the author's views and the Managing Authority of Central Baltic INTERREG IV A programme 2007–2013 cannot be held liable for the information published by project partners. This publication cannot be taken to reflect the views of the European Union.

References

Andreasen, A. and Mayer, S.: Use of Seawater Scrubbing for SO_2 Removal from Marine Engine Exhaust Gas, Energ. Fuel., 21, 3274–3279, 2007.

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.

BunkerWorld: available at: http://www.bunkerworld.com, (last access: 10 January 2013), 2013.

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., Pålsson, C., Winebrake, J. J. Wu, W.-Q., and Yoshida, K.: Second IMO GHG study 2009, International Maritime Organization, London, UK, 2009.

Corbett, J. J., Wang, H., and Winebrake, J. J.: The effectiveness and costs of speed reductions on emissions from international shipping, Transport. Res., 14, 593–598, 2009.

Corbett, J. J., Winebrake, J. J., and Green, E. H.: An assessment of technologies for reducing regional short-lived climate forcers emitted by ships with implications for arctic shipping, Carb. Manage., 1, 207–225, doi:10.4155/cmt.10.27, 2010.

Hulskotte, J. H. J. and Denier van der Gon, H.: Fuel consumption and associated emissions from seagoing ships at berth derived from an on-board survey, Atmos. Environ., 44, 1229–1236, 2010.

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, K.: A comprehensive inventory of the ship traffic exhaust emissions in the Baltic Sea from 2006 to 2009, AMBIO, Springer, doi:10.1007/s13280-013-0389-3, Sweden, 2013.
Kuiken, K.: Diesel engines II – for ship propulsion and power plants, Target Global Energy Training, Onnen, the Netherlands, ISBN:978-90-79104-02-4, 2008.
Lack, D. A. and Corbett, J. J.: Black carbon from ships: a review of the effects of ship speed, fuel quality and exhaust gas scrubbing, Atmos. Chem. Phys., 12, 3985–4000, doi:10.5194/acp-12-3985-2012, 2012.
Notteboom, T., Delhay, E., and Vanherle, K.: Analysis of the Consequences of Low Sulphur Fuel Requirements, ITMMA – Universiteit Antwerpen, available at: http://bsa-bg.com (last access: 14 June 2013), 2010.
Petzold, A., Weingartner, E., Hasselbach, J., Lauer, P., Kurok, C., and Fleischer, F.: Physical properties, chemical composition, and cloud forming potential of particulate emissions from a marine diesel engine at various load conditions, Environ. Sci. Technol., 44, 3800–3805, doi:10.1021/es903681z, 2010.
Reynolds, K. J.: Exhaust gas cleaning systems selection guide, Ship operations cooperative program, The Glosten Associates, USA, 2011.

ACPD
13, 16113–16150, 2013

Table 1. Predicted emissions and shipping statistics for the ECA in 2009. Shipping emission inventories by EMEP have also been presented for comparison purposes. Payload is the amount of transferred freight inside the ECA, which has been estimated based on ship's deadweight and its type-specific fraction of payload reported in (Buhaug et al., 2009).

ECA 2009		CO_2 [ton]	NO_x [ton]	SO_x [ton]	$PM_{2.5}$ [ton]	CO [ton]	Payload [10^9 km ton]	Ships	Travel [10^6 km]
All ships	EMEP	–	1 098 720	409 540	55 500	122 151	–	–	–
All ships	STEAM	49 362 000	1 032 900	350 370	80 710	96 300	3205	23 599	372.0
	IMO-registered	44 344 000	948 700	322 180	73 970	84 400	3205	15 438	335.8
	non-IMO registered	5 017 000	84 200	28 180	6740	11 800	0	8161	36.2
	Baltic Sea	16 506 000	330 200	115 030	26 510	31 100	871	–	–
	North Sea	32 576 000	697 800	233 930	53 900	64 500	2332	–	–
Top flags	Norway	4 937 000	95 000	30 790	7340	10 040	181	1945	44.8
	UK	4 272 000	89 100	30 510	7000	8730	216	2494	30.1
	Sweden	4 140 000	73 000	28 850	6610	7890	99	1692	25.8
	Denmark	3 859 000	70 900	23 890	5730	9120	131	1244	26.5
	Netherlands	3 148 000	60 800	20 460	4820	6200	115	2169	34.8
	Liberia	2 636 000	65 500	21 050	4710	5010	303	1014	11.6
	Bahamas	2 542 000	57 500	19 330	4410	4560	220	735	16.0
	Germany	2 435 000	50 500	17 910	4080	5470	140	1809	16.2
	Malta	1 853 000	41 500	13 240	3040	3320	186	834	17.0
	Finland	1 788 000	33 100	13 120	2940	3330	51	497	13.6
	Antigua and Barbuda	1 752 000	35 300	11 320	2680	2980	97	838	23.0
	Cyprus	1 649 000	36 800	12 050	2760	3060	144	476	13.0
	Marshall Islands	1 034 000	25 500	8110	1820	1780	142	522	5.5
	Greece	985 000	26 500	8890	1920	1630	186	304	3.9
	Gibraltar	803 000	16 900	5160	1230	1390	48	248	9.4
	Panama	756 000	18 600	6140	1390	1530	94	344	3.3
	Russia	751 000	14 500	4020	1010	1380	30	677	10.0
	Hong Kong	609 000	15 400	5180	1160	1220	95	328	2.5
	Italy	577 000	13 600	4880	1070	1070	49	200	3.6
	France	551 000	11 500	4570	1000	1190	7	397	2.9
Ship types	Passenger	7 093 000	128 900	54 600	12 200	14 590	44	961	37.8
	Cargo	11 769 000	254 600	83 190	19 160	19 810	999	5791	133.6
	Container	9 788 000	220 900	75 080	17 240	23 400	792	2066	41.2
	Tanker	10 141 000	244 900	79 820	17 890	17 330	1367	3484	67.2
	Misc	5 552 000	99 300	29 470	7460	9320	0	3136	56.1

ACPD
13, 16113–16150, 2013

Shipping emissions and fuel costs in EU ECA

L. Johansson et al.

Table 2. Predicted emissions and shipping statistics for the ECA in 2011.

ECA 2011		CO_2 [ton]	NO_x [ton]	SO_x [ton]	$PM_{2.5}$ [ton]	CO [ton]	Payload [10^9 km ton]	Ships	Travel [10^6 km]
All		53 951 000	1 085 100	238 300	66 900	108 500	3265	30 167	377.3
	IMO-registered	45 635 000	944 100	217 000	59 400	89 100	3265	16 030	322.5
	Non-IMO registered	8 407 000	139 900	21 200	7490	18 900	0	14 137	54.7
Region	Baltic Sea	19 471 000	377 200	85 400	23 800	36 900	1014	–	–
	North Sea	34 378 000	699 700	152 100	42 600	70 400	2251	–	–
Top flags	Netherlands	5 750 000	102 400	20 000	6100	11 600	125	7298	52.4
	UK	4 482 000	90 700	20 700	5690	9400	231	1914	29.0
	Germany	4 046 000	75 900	14 600	4450	9170	142	2742	23.3
	Denmark	3 579 000	67 100	14 400	4260	8580	160	1134	22.3
	Norway	3 346 000	63 900	13 500	3930	6980	115	1518	27.6
	Sweden	3 346 000	56 900	15 700	4250	5660	75	937	18.7
	Liberia	2 940 000	69 200	15 000	4040	6140	361	1118	12.9
	Bahamas	2 302 000	50 700	11 500	3120	4370	196	700	14.1
	Finland	2 089 000	38 200	10 060	2680	3680	60	505	13.4
	Antigua and Barbuda	2 068 000	40 500	9510	2590	3550	115	822	26.0
	Malta	2 028 000	43 400	9520	2610	3850	183	935	17.6
	Cyprus	1 926 000	40 700	9070	2480	3650	155	484	14.5
	Marshall Islands	1 166 000	27 200	5870	1580	2250	153	682	6.0
	Belgium	1 166 000	20 500	3440	1130	2420	15	1273	6.9
	France	1 012 000	20 800	5470	1410	2120	31	951	6.4
	Hong Kong	1 002 000	23 300	5240	1430	2320	141	436	3.8
	Gibraltar	858 000	17 500	3950	1080	1540	51	252	10.5
	Greece	734 000	19 100	4250	1090	1430	148	248	2.9
	Italy	698 000	15 800	3830	990	1320	61	236	4.0
	Panama	695 000	16 100	3380	940	1440	83	335	2.9
Ship types	Passenger	6 896 000	124 700	37 100	9520	13 280	45	856	34.1
	Cargo	12 777 000	269 700	63 000	16 830	21 800	1125	6348	134.9
	Container	11 358 000	247 400	53 700	15 210	28 590	972	2132	42.6
	Tanker	8 893 000	204 800	45 200	12 060	16 320	1115	3385	60.9
	Misc	5 577 000	97 900	18 200	5810	9140	0	3309	49.7

ACPD
13, 16113–16150, 2013

Shipping emissions and fuel costs in EU ECA

L. Johansson et al.

Table 3. The numbers of candidate ships for the installment of the exhaust gas cleaning systems (EGCS), and their fraction of the total fuel consumption, presented separately for each ship type. The values are based on the estimated fuel consumption in the ECA in 2011. Ships with an annual fuel consumption of at least 4000 tons have been qualified as such candidates, according to (Reynolds, 2011).

Ship category	The number of candidate ships for installed EGCS	Fraction of the total fuel consumption
All	635	21 %
Container	258	7.0 %
ROPAX	132	7.1 %
RORO	82	2.8 %
Crude oil tanker	42	1.2 %
Passenger cruiser	23	0.6 %
Chemical tanker	21	0.5 %
Bulk carrier	13	0.3 %
Vehicle carrier	9	0.2 %
Product tanker	8	0.2 %
General cargo	6	0.2 %

ACPD
13, 16113–16150, 2013

L. Johansson et al.

Table 4. The predictions for the slow-steaming scenarios, assuming speed reductions of 30 % (a) and 10 % (b). Speed reductions have been applied only for instantaneous speeds exceeding 10 knots. "Share of total FC 2011" refers to the estimated share of total fuel consumption in the ECA in 2011. Operational time is the combined duration of berthing, maneuvering and cruising.

Slow-steaming (30 %) Ship category	Share of total FC 2011 [%]	ΔMain fuel cons. [%]	ΔOperational time [%]	ΔFuel cost [%]	ΔCO_2 [%]	ΔNO_x [%]	ΔSO_x [%]	$\Delta PM_{2.5}$ [%]	ΔCO [%]
RoRo	4.5	−42.0	15.8	−31.2	−32.9	−36.7	−40.0	−34.4	6.9
Vehicle carrier	2.1	−41.5	12.9	−22.5	−24.3	−33.9	−34.6	−24.2	14.2
Refrigerated cargo ship	1.7	−39.7	9.6	−14.9	−16.9	−26.6	−31.0	−20.0	13.2
Container ship	19.4	−34.5	12.2	−13.0	−14.4	−22.6	−23.8	−13.9	5.5
LPG tanker	1.1	−34.4	9.2	−15.0	−16.8	−25.2	−28.8	−22.7	19.1
RoPaX	10.1	−34.0	9.7	−25.0	−26.3	−29.9	−32.0	−29.2	13.6
Crude tanker	4.6	−31.7	8.1	−20.6	−21.8	−28.8	−28.2	−25.8	26.4
Chemical tanker	8.3	−31.4	8.9	−15.5	−17.1	−24.4	−27.2	−22.9	19.6
Bulk cargo	6.7	−31.1	9.0	−16.2	−17.7	−24.8	−26.7	−23.1	26.8
Passenger cruiser	1.4	−30.8	9.2	−18.2	−19.7	−22.6	−26.5	−21.8	7.3
Product tanker	2.1	−29.1	5.5	−15.2	−16.8	−24.1	−26.1	−22.3	22.1
Tug boat	2.4	−23.9	1.2	−6.5	−7.7	−8.6	−18.7	−12.6	4.8
Service ship	3.1	−23.6	2.5	−8.0	−9.3	−9.7	−17.9	−13.6	0.5
Fishing boat	1.2	−21.6	2.1	−4.9	−5.9	−7.3	−14.6	−8.5	4.3
General cargo	10.9	−19.5	4.7	−9.1	−10.1	−13.8	−16.8	−13.3	14.5
Other	1.9	−18.7	2.0	−8.1	−9.4	−10.0	−18.7	−13.8	2.8
Dredge	1.0	−14.7	1.9	−6.9	−7.6	−8.7	−12.2	−10.1	5.3

Slow-steaming (10 %) Ship category	Share of total FC 2011 [%]	ΔMain fuel cons. [%]	ΔOperational time [%]	ΔFuel cost [%]	ΔCO_2 [%]	ΔNO_x [%]	ΔSO_x [%]	$\Delta PM_{2.5}$ [%]	ΔCO [%]
RoRo	4.5	−17.8	4.6	−13.3	−14.1	−15.4	−17.0	−15.5	4.2
Vehicle carrier	2.4	−17.5	3.9	−9.8	−10.6	−14.2	−14.8	−11.8	8.0
Refrigerated cargo ship	1.7	−16.0	3.1	−6.3	−7.1	−10.7	−12.7	−9.4	7.0
LPG tanker	1.2	−15.2	3.3	−6.9	−7.7	−11.0	−12.9	−10.6	9.3
RoPaX	10.9	−14.6	2.9	−10.8	−11.4	−12.5	−13.8	−12.8	3.4
Chemical tanker	8.3	−14.6	3.4	−7.4	−8.2	−11.2	−12.7	−10.9	9.9
Container ship	19.4	−14.5	3.8	−5.9	−6.5	−9.9	−10.4	−7.0	3.8
Crude tanker	4.6	−14.0	3.0	−9.2	−9.8	−12.4	−12.5	−11.5	12.7
Passenger cruiser	1.4	−13.7	2.9	−8.4	−9.1	−10.1	−12.2	−10.4	1.2
Bulk cargo	6.7	−13.6	3.4	−7.3	−7.9	−10.6	−11.8	−10.3	12.2
Product tanker	2.1	−12.2	2.1	−6.5	−7.2	−9.9	−11.0	−9.5	10.2
Service ship	3.1	−11.6	1.1	−4.0	−4.6	−4.8	−8.8	−6.7	0.0
Tug boat	2.1	−11.2	0.5	−3.0	−3.6	−4.0	−8.8	−5.9	1.8
Fishing boat	1.1	−11.1	1.0	−2.6	−3.1	−3.7	−7.6	−4.6	2.0
General cargo	10.1	−9.5	2.1	−4.5	−5.1	−6.7	−8.3	−6.8	7.3
Other	1.9	−7.5	0.8	−3.2	−3.8	−3.9	−7.6	−5.6	1.5
Dredge	1.0	−6.7	0.9	−3.2	−3.5	−3.9	−5.5	−4.6	2.6

ACPD
13, 16113–16150, 2013

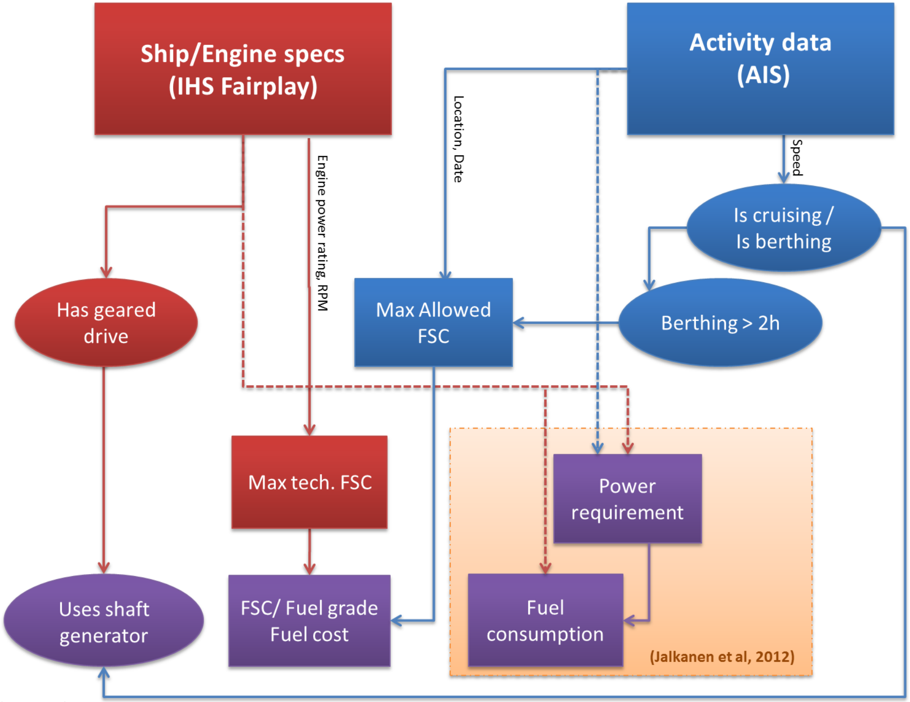

Fig. 1. Schematic diagram describing the variables used in modelling of FSC, fuel consumption and the use of shaft generators. Oval shape illustrates logical (yes/no) criteria. Red color describes static, ship dependent attributes whereas blue color describes dynamic, time dependent variables. Violet-colored variables are evaluated using dynamic and static variables. Some variables have been presented in reduced text-form for viewing pleasure. The modelling of power requirement and fuel consumption is further explained in (Jalkanen et al., 2012). The use of shaft generators affects engine loads by shifting auxiliary engine use to main engines and thus, affects the fuel consumption indirectly.

ACPD
13, 16113–16150, 2013

ACPD
13, 16113–16150, 2013

Shipping emissions and fuel costs in EU ECA

L. Johansson et al.

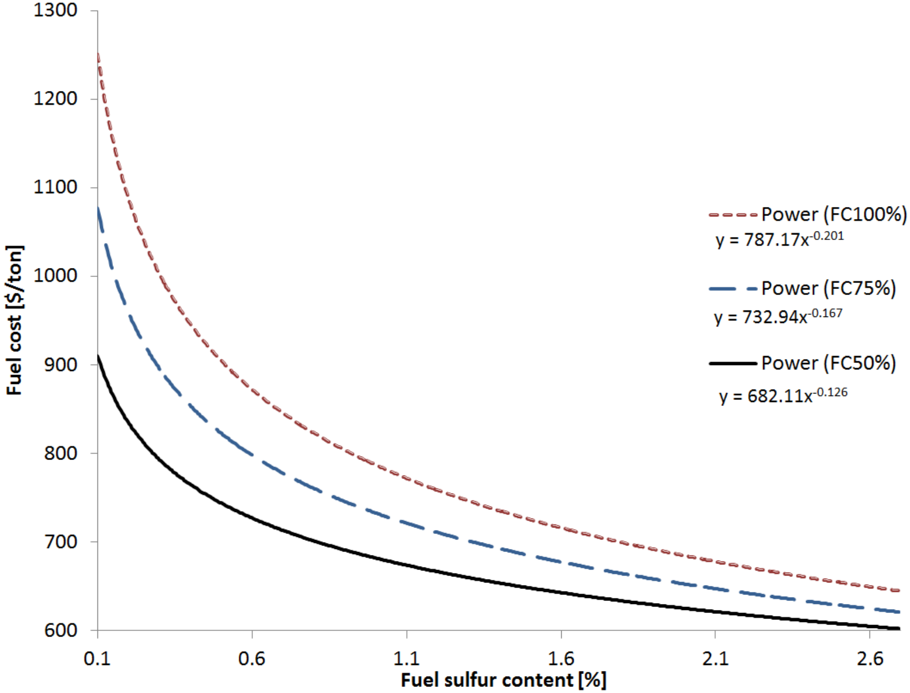

Fig. 2. Estimated fuel prices (USD ton^{-1}) as a function of the sulfur content of fuel, for three different fuel cost (FC) scenarios. The scenarios correspond to the current state (FC50 %) and two future price (FC75 % and FC100 %) scenarios; these have been defined in the text. The numerical equations of the fits have also been reported.

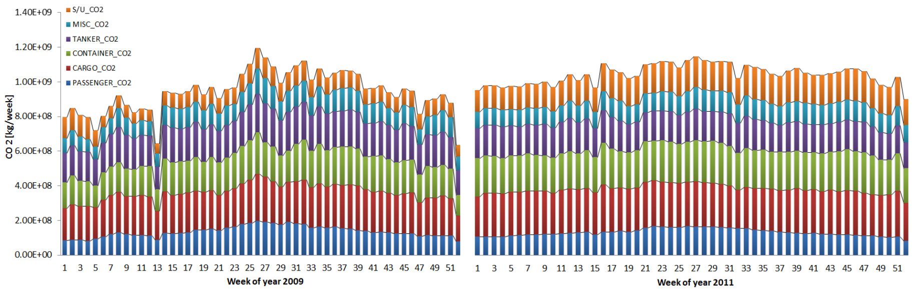

Fig. 3. Seasonal variation of the predicted CO_2 emissions in the ECA in 2009 and 2011, presented separately for different ship types. Cargo ships include bulk carriers, general cargo vessels and vehicle carriers. Passenger ships include RoPaX ships, ferries and passenger cruisers.

ACPD
13, 16113–16150, 2013

Shipping emissions and fuel costs in EU ECA

L. Johansson et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

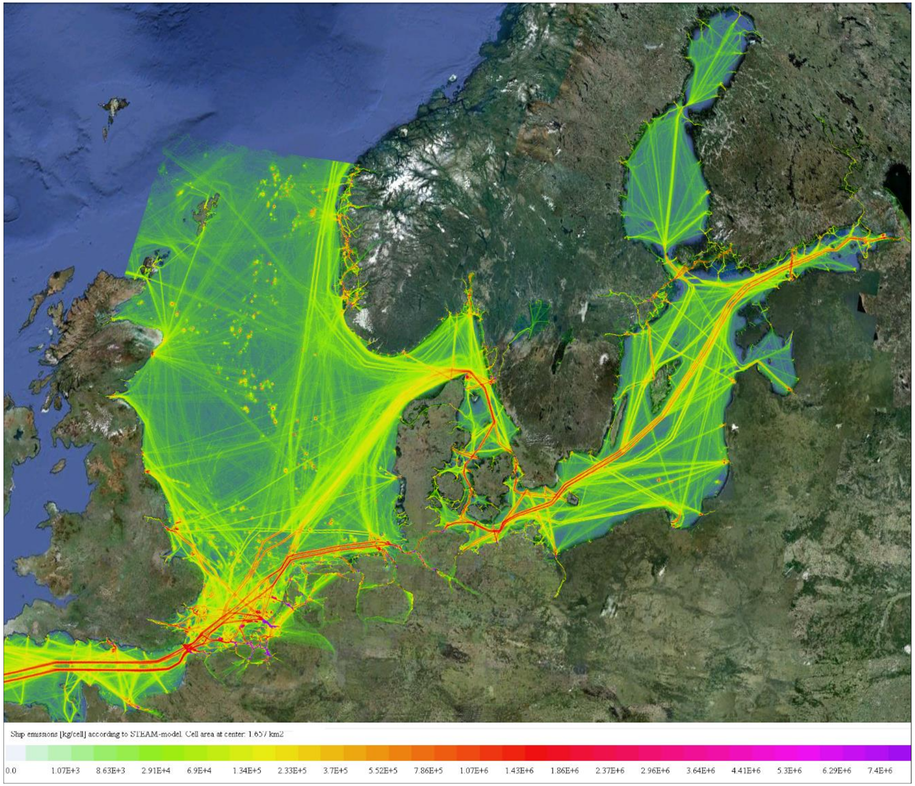

Fig. 4. Predicted geographic distribution of shipping emissions of CO_2 in the ECA in 2011. The colour code indicates emissions in relative mass units per unit area.

ACPD
13, 16113–16150, 2013

Shipping emissions and fuel costs in EU ECA

L. Johansson et al.

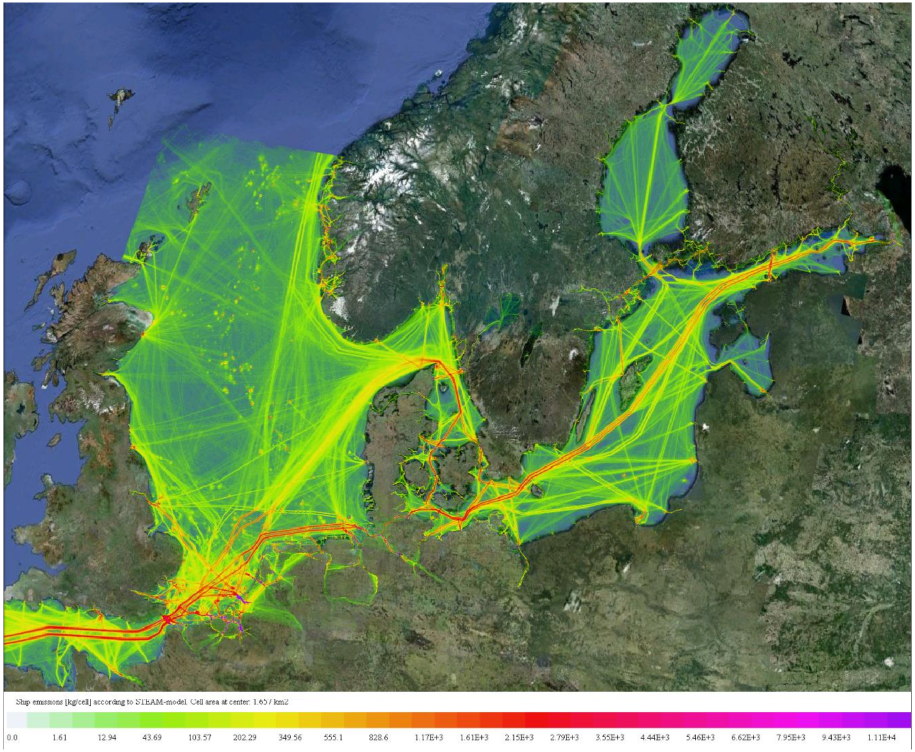

Fig. 5. Predicted geographic distribution of shipping emissions of $PM_{2.5}$ in the ECA in 2011. $PM_{2.5}$ has been assumed to consist of organic and elemental carbon, ash and moist sulfate particles.

ACPD
13, 16113–16150, 2013

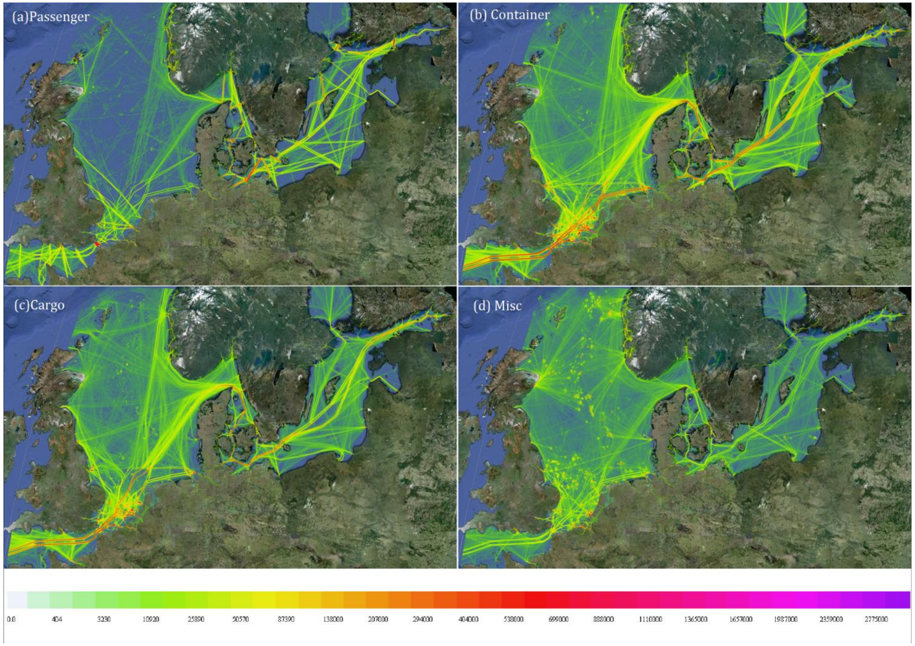

Fig. 6. Predicted geographic distribution of the shipping emissions of CO_2 for passenger **(a)**, container **(b)**, cargo **(c)** and miscellaneous **(d)** ships in the ECA in 2011. Passenger ships include RoPaX vessels, cruisers, ferries and other passenger ships. Cargo ships include general cargo, RoRo, vehicle carriers and bulk carriers. Miscellaneous ships include yachts, fishing boats, tugs, ice breakers, barges dredge ships, etc.

ACPD
13, 16113–16150, 2013

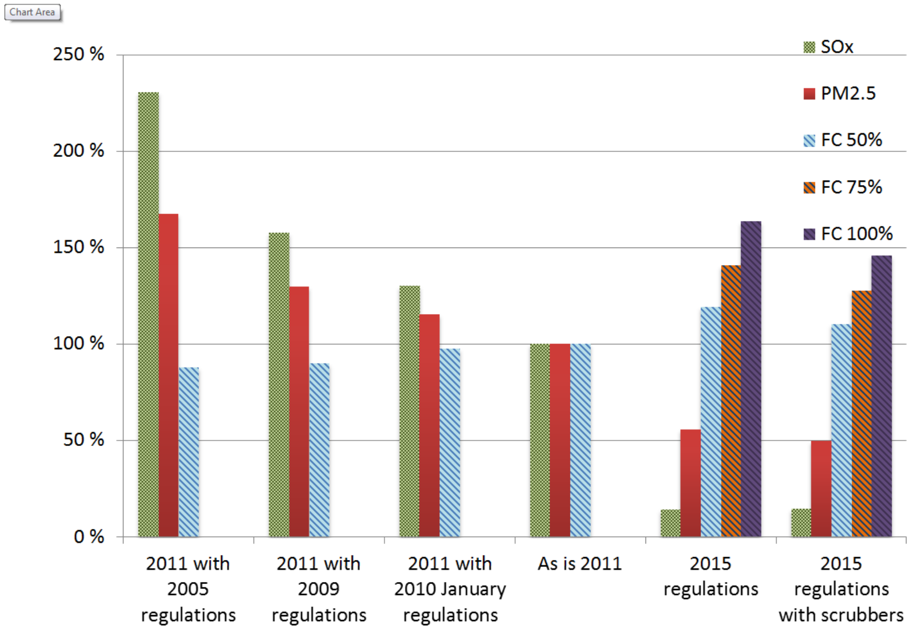

Fig. 7. Relative emissions of SO_x and $PM_{2.5}$, and direct fuel costs of IMO-registered marine traffic in the ECA in 2011, for the various selected scenarios. The situation in 2011 has been evaluated also using three different assumed options regarding the regulations of marine emissions in the past (the three sets of columns on the left-hand side). The scenarios for the future have been presented using three fuel cost (FC) options (the two sets of columns on the right-hand side).

ACPD
13, 16113–16150, 2013

Shipping emissions and fuel costs in EU ECA

L. Johansson et al.