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The evolution of shipping emissions and the costs of regulation changes in the northern EU area

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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 (International Maritime Organization)-registered marine traffic have been reduced by 29 %, from 320 kt to 231 kt, in the ECA from 2009 to 2011. The corresponding predicted reduction of $PM_{2.5}$ emissions was 17 %, from 72 kt to 61 kt. 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 87 % in SO_x emissions and a reduction of 48 % 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 IMO-registered shipping varied between 13 % and 69 %, 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 of 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 et al., 2009).

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The auxiliary engines are responsible for a significant portion of the total fuel consumption, and any reduction in cruising speed will inevitably result in 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”. The first aim of this paper is to present an extensive inventory 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. 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 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, 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 on-board every vessel that weighs more than 300 t. The AIS system provides 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 data set for 2009 however, still contains more than 552 million archived AIS messages. For the ECA in 2011, AIS messages were extracted from a data set given by the European Maritime Safety Agency (EMSA). This extracted data set contains 607 million archived AIS messages.

The model requires as input also the detailed technical specifications of all fuel consuming systems on-board 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 (IHS, 2012) 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 sulfur content, multiengine set-ups, 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 data set 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 emissions 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 harbour activities

High geographic accuracy (tens of metres) 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. Therefore there is only a very small fraction of route segments that cross land masses, such as peninsulas or islands.

Accurate modelling of maneuvering activities in harbour 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 6 min 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 not commonly available. In some, cases however, auxiliary engine information has been augmented with data from classification societies. We estimate that moderate to high uncertainty can be associated with harbour 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 (International Maritime Organization) identification number. However, the number of unidentified ships without an IMO number has been increasing steadily. For instance, the unidentified ships were the second largest ship type category in terms of the number of ships in the ECA in 2011. All unidentified ships are presumed to be small vessels, and we have treated those in the modelling by assuming only generic specifications (weighting 500 t 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.

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 modelled 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 of NO_x for old ships that are not obliged to conform with Tier I requirements.

The conversion rate of fuel sulfur to 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 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 sulfur content in case of fuel conversion and switching, and exhaust gas cleaning systems

Clearly, the fuel sulfur content significantly affects the $PM_{2.5}$ and SO_x emissions per amount of fuel burned. The emissions of particulate sulfate (SO_4) included in the $PM_{2.5}$ emissions are assumed to have a linear dependency with FSC. The other modelled components (ash, elemental and organic carbon particles) are unaffected by FSC (Buhaug et al., 2009; Jalkanen et al., 2012). The remaining sulfur in the fuel, which has not been converted to sulfate, contributes to SO_x emissions. In the 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, a 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 2 h. For ships using EGCS instead of low sulfur fuel, the amount of 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 sulfur 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 sulfur content is therefore assumed to be

$$\mathrm{FSC} = \min\{\mathrm{FSC_C}, \mathrm{FSC_A}\}, \qquad (1)$$

where $\mathrm{FSC_C}$ is the maximum FSC that the engine can use and $\mathrm{FSC_A}$ is the maximum FSC allowed by the regulations in the considered area. However, if the ship has been equipped with EGCS, then $\mathrm{FSC_A}$ in Eq. (1) is evaluated to be equal to the (relatively higher) sulfur content that would, after gas cleaning, result in acceptable emissions of both $\mathrm{SO_x}$ and $\mathrm{PM_{2.5}}$. In such a case, $\mathrm{FSC_A}$ in Eq. (1) is therefore substituted with the fuel sulfur content before exhaust gas cleaning $\mathrm{SC_A}$, which is evaluated from

$$\begin{cases} \mathrm{FSC'_A} = \frac{\mathrm{FSC_A}}{1-\eta} & (2a)\\ \eta = \min\{\eta_{\mathrm{SO_x}}, \eta_{\mathrm{PM_{2.5}}}\}, & (2b) \end{cases}$$

where $\eta_{\mathrm{SO_x}}$ and $\eta_{\mathrm{PM_{2.5}}}$ are the EGCS's efficiencies in reducing the emissions of $\mathrm{SO_x}$ and $\mathrm{PM_{2.5}}$, respectively. These efficiencies are within the interval [0,1].

$\mathrm{FSC_C}$ 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 a 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 $\mathrm{FSC_C}$ 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 the main engines at cruising speed. Thus, if a vessel with a shaft generator has a speed greater than $2.5\,\mathrm{m\,s^{-1}}$ (5 knots), we assume that all auxiliary power will be produced with main engines; clearly, these use FSC that is associated with the main engines.

The maximum allowed FSC is determined based on region, date and speed. Vessels having a speed lower than 0.5 $\mathrm{m\,s^{-1}}$ (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.

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 USD 960 per metric ton, whereas heavy fuel oil (HFO380/180) costs approximately USD 611 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 USD 668 per ton.

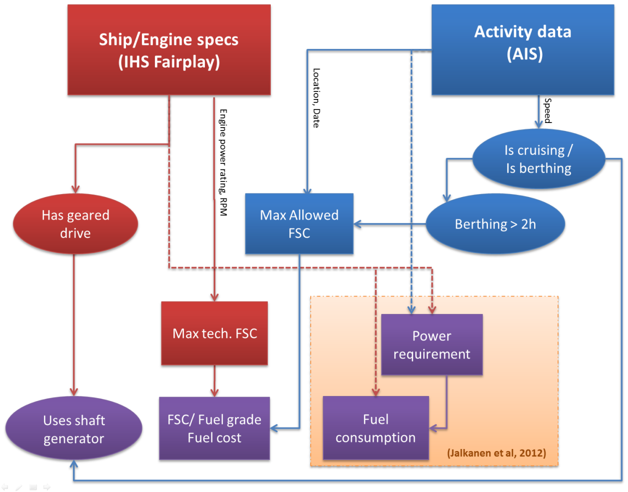

Fig. 1. Schematic diagram describing the variables used in modelling of FSC, fuel consumption and the use of shaft generators. Oval shape illustrates logical (yes/no) criteria. Red colour describes static, ship dependent attributes whereas blue colour describes dynamic, time dependent variables. Violet-coloured 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.

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 (FC is fuel cost) (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 have an arbitrary average FSC between 2.7 % and 0.1 %, so that the evaluated FSC given by Eq. 1 is 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: the

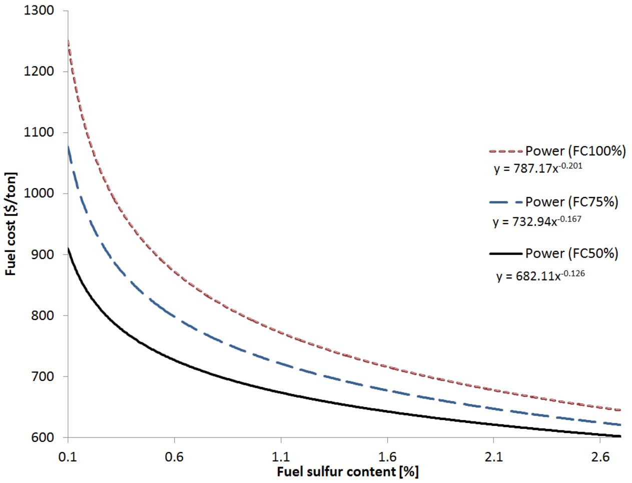

Fig. 2. Estimated fuel prices (USD/ton) as a function of the sulfur content of fuel, for three different fuel cost (FC) scenarios. The scenarios correspond to the current state (FC50 %) and two future price (FC75 % and FC100 %) scenarios; these have been defined in the text. The numerical equations of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

FC50 % curve corresponds to prices (HFO380, LS180 and LSMGO) as they were at the time of writing, in Rotterdam, FC75 % and FC100 % are the price estimates in case the price premium between LSMGO and HFO380 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 EGCSs offer potential fuel cost savings for ships that operate in the ECA area, as IMO accepts EGCSs as alternatives to the use of low sulfur fuels. With a scrubber on-board, a ship can consume high FSC fuel and still comply with regulations. In Reynolds (2011) it was estimated that any ship, which consumes annually more than 4000 metric tons of fuel in the ECA, should be a potential candidate for an EGCS installation. Assuming a 50 % price premium for LSMGO with respect to HFO and active use within the ECA for at least 6 yr 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 et al. (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 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 analyse in addition the validity of each travel segment. The calibration and use of AIS transmitters is also potentially susceptible to human errors. Especially as smaller ships without an IMO number behave erratically 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 harbours 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 time stamps, 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 harbour 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 formation of waves. Even a minor reduction of vessel speed can therefore significantly reduce the main engine's fuel consumption. The concept of slow-steaming refers to a situation, in which a marine vessel 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

$$\begin{cases} T_+ = \sum\limits_i (\Delta t_{\mathrm{iR}} - \Delta t_i) & \text{(3a)} \\ v_{\mathrm{iR}} = (1-a) v_i & \text{(3b)} \\ \Delta t_{\mathrm{iR}} = \Delta t_i \, (1+a), & \text{(3c)} \end{cases}$$

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) and v_i is the average speed in i-th segment of a route before applying speed reduction. 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 for 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).

2.3.5 Auxiliary fuel consumption of non-IMO registered vessels

The number of unidentified vessels in AIS data has steadily increased during recent years. According to AIS data, a substantial fraction of these vessels seem to be inactive; these are mostly berthing. Such vessel behaviour in the model would result in an excessive amount of auxiliary fuel consumption, especially as the number of berthing small vessels increases in time.

We have therefore added to the model a limiting rule for the auxiliary fuel consumption of non-IMO-registered vessels. After 2 h (i.e. a reasonable time required for unloading the vessel) of continuous berthing, the rate of auxiliary fuel consumption is assumed to start to decrease linearly as a function of time. We have assumed that after 8 h of berthing, the rate of auxiliary fuel consumption has been decreased to one fifth (1/5) of the initial auxiliary fuel consumption rate.

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 $\mathrm{FSC_A} = 2.7\,\%$ in Eq. (1), and compared the resulting $\mathrm{SO_x}$ and $\mathrm{PM_{2.5}}$ 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. $\mathrm{FSC_A} = 1.5\,\%$, and (iii) no further regulations had been introduced after January of 2010, i.e. $\mathrm{FSC_A} = 1.5\,\%$ 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 $\mathrm{FSC_A} = 0.1\,\%$ for all ships and activities.

Another simulation for 2015 was performed, in which EGCS installation candidate vessels were identified (cf. Sect. 2.3.2) 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. 3c). 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. (3a)–(3c), 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

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*t]	Ships	Travel [10^6 km]
All ships	EMEP		1 098 720	409 540	55 500	122 151			
All ships	STEAM	43 121 100	944 100	327 000	73 500	94 900	2699	23 973	325
	IMO-registered	41 848 800	923 400	319 900	71 600	89 300	2699	15 049	296
	non-IMO-registered	1 272 300	20 600	7100	1900	5600	0	8924	29
	Baltic Sea	15 545 400	321 100	117 600	26 400	32 300	765	–	–
	North Sea	27 530 200	622 200	209 000	47 100	62 400	1933	–	–
Top flags	United Kingdom	3 826 900	82 100	28 200	6300	9000	184	2495	29
	Norway	3 600 500	72 800	23 900	5600	8000	136	2277	32
	Sweden	3 190 500	56 900	25 000	5500	6500	86	1693	23
	Netherlands	2 855 700	57 300	20 000	4600	6400	110	2164	32
	Liberia	2 472 000	63 600	20 400	4500	5400	267	1014	11
	Denmark	2 353 500	46 500	16 400	3800	6400	91	1241	21
	Bahamas	2 299 000	53 400	17 600	3900	4600	167	734	14
	Germany	2 091 400	46 200	16 600	3600	4800	122	1803	15
	Finland	1 990 700	38 200	16 800	3600	4100	66	496	13
	Malta	1 782 400	40 900	13 000	2900	3500	157	836	15
	Antigua and Barbuda	1 726 900	35 700	11 500	2600	3300	86	840	21
	Cyprus	1 571 500	35 400	11 600	2600	3300	113	467	12
	Marshall Islands	960 600	24 500	7700	1700	1900	118	522	5
	Greece	923 600	26 000	8500	1800	1700	165	316	3
	Gibraltar	836 500	18 500	5700	1300	1500	46	245	8
	Panama	698 200	18 400	6100	1300	1500	77	344	3
	Italy	623 400	14 800	5400	1100	1200	42	198	3
	Hong Kong	607 500	16 000	5300	1100	1300	80	334	2
	Russia	483 600	9400	2600	600	1000	17	711	6
	France	475 300	10 000	4000	800	1300	7	394	3
Ship types	Passenger ships	7 785 700	147 200	64 200	13 900	18 200	54	863	39
	Cargo ships	11 283 500	246 900	83 500	18 800	21 900	844	5908	122
	Container ships	9 113 800	222 900	76 800	16 800	22 000	679	1868	39
	Tankers	9 267 700	228 200	73 700	16 400	17 400	1123	3284	61
	Other	4 397 800	78 000	21 400	5600	9600	0	3126	35

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 sulfate particles (Jalkanen et al., 2012), whereas EMEP has used the dry weight of SO_4. Secondly, the EMEP estimates include neither harbour activities nor non-IMO-registered ships, whereas those have been included in the STEAM computations. The accounting of harbour activities is a major methodological difference. According to the predictions using the STEAM model, approximately 22 % of the total fuel was consumed at harbours in the ECA in 2009. Despite this, the total shipping emissions predicted using the STEAM model were 14 % smaller than the corresponding EMEP emissions in case of NO_x, while the SO_x emissions predicted using the STEAM model were 20 % lower. There were also notable differences between the predictions of these two modelling systems in case of $PM_{2.5}$ and CO.

In 2009, approximately 15.5 and 27.5 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

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*t]	Ships	Travel [10^6 km]
All ships	STEAM	48 029 900	1 010 400	239 300	63 800	110 900	2985	30 165	375
	IMO-registered	45 570 700	970 900	231 100	60 900	101 000	2985	15 411	320
	non-IMO-registered	2 459 200	39 500	8200	2900	9900	0	14 754	55
	Baltic Sea	17 614 600	356 100	87 400	23 200	37 400	890	–	–
	North Sea	30 033 600	648 900	151 300	40 200	72 600	2091	–	–
Top flags	Netherlands	4 004 100	75 000	17 700	5000	9900	126	7295	52
	United Kingdom	3 931 500	82 200	19 400	5100	9400	209	1916	29
	Norway	3 332 500	65 200	15 100	4100	7600	98	1513	28
	Liberia	2 984 000	73 200	15 800	4100	7300	352	1117	13
	Sweden	2 898 600	50 600	15 900	4000	5500	70	936	19
	Germany	2 659 400	53 800	12 400	3400	7100	124	2730	23
	Denmark	2 652 700	52 400	12 600	3400	7100	118	1126	22
	Bahamas	2 281 100	52 000	12 000	3100	4700	171	698	14
	Antigua and Barbuda	2 233 900	44 900	10 800	2800	4500	115	825	26
	Malta	2 100 200	45 300	10 300	2700	4300	162	937	18
	Finland	2 051 500	38 100	11 300	2800	4300	66	507	13
	Cyprus	1 934 000	41 100	9400	2500	4300	135	484	15
	Marshall Islands	1 217 400	29 400	6400	1600	2700	155	681	6
	Hong Kong	985 600	24 100	5400	1400	2500	131	440	4
	Gibraltar	972 200	20 900	4700	1200	2000	55	248	11
	Italy	791 300	18 000	4500	1100	1600	56	237	4
	Greece	764 400	20 900	4500	1100	1700	150	250	3
	France	734 500	15 500	4100	1000	1900	25	944	6
	Russia	650 400	12 500	2200	700	1400	22	670	7
	Panama	643 900	15 800	3400	900	1500	69	336	3
Ship types	Passenger ships	7 804 500	145 500	44 000	10 900	17 300	54	825	39
	Cargo ships	12 608 500	268 200	65 500	17 000	25 200	978	6183	133
	Container ships	10 377 300	242 400	55 300	14 500	27 800	857	1711	44
	Tankers	8 934 900	212 100	47 800	12 400	18 200	1096	3337	61
	Other	5 845 400	102 500	18 300	5900	12 300	0	3355	43

Denmark, the Netherlands and the United Kingdom. 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 doubled since 2009, but it is still only 5 % of the total estimated CO_2; this increase has probably been caused by an increase of the number of small ships that have installed AIS transmitters. The number of non-IMO-registered ships has increased from 8924 (in 2009) to 14754 (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, partly as these have become more affordable. The temporal evolution of the emissions of CO_2 has been presented in Fig. 3 for different ship categories and non-IMO-registered vessels both in 2009 and 2011.

The annual IMO-registered marine traffic has significantly increased from 2009 to 2011, in terms of both the CO_2 emissions (+8.9 %) and the cargo payload amounts (+10.6 %), possibly caused by the recovery of the European economy during the study period. There have been significant changes in the distribution of emissions for the various flag states as well. 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.

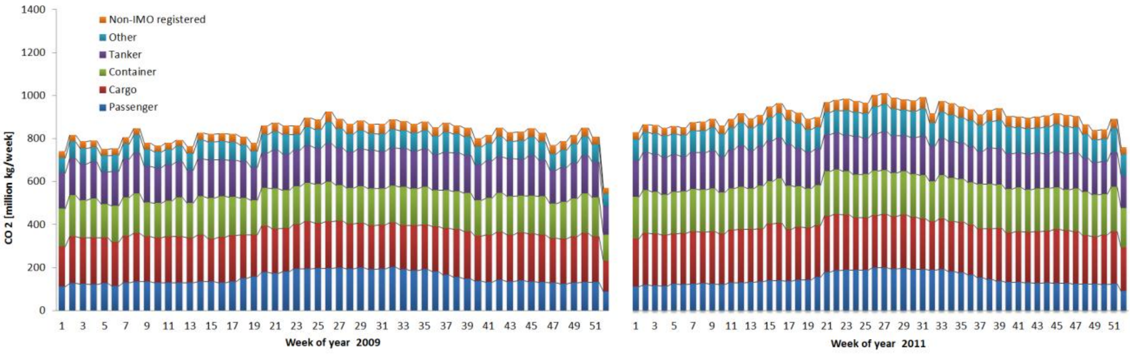

Fig. 3. Seasonal variation of the predicted CO_2 emissions in the ECA in 2009 and 2011, presented separately for different ship types. Cargo ships include bulk carriers, general cargo vessels and vehicle carriers. Passenger ships include RoPax ships, ferries and passenger cruisers.

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 and 2, the SO_x emissions originated from IMO-registered marine traffic have been reduced from 2009 to 2011 from 320 kt to 231 kt. The corresponding predicted reduction for $PM_{2.5}$ from 71.6 kt to 60.9 kt. The estimated NO_x emissions from IMO-registered traffic are slightly larger in 2011 than in 2009 (+5.1 %). The increase of the emissions of NO_x was smaller than the corresponding increase of emissions of CO_2. The reason for this is that after January 2011, the NO_x emission factor was not allowed to 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 minuscule, but will certainly increase when the fleet is renewed in time.

Based on the modelled fuel consumption statistics for IMO-registered vessels, 33 % of the total fuel was consumed by auxiliary engines in 2011. However, the ratio of the auxiliary fuel consumption and the total fuel consumption varies significantly between ship types (18 % for passenger ships, 30 % for cargo ships, 35 % for container ships, 31 % for tankers and 64 % for other ships). Approximately 17 000 ships in the ship properties database have been associated with a shaft generator, which allows the main engine to provide power to ship operating systems while cruising. Theoretically, it can be shown by numerical computations that if there would have been no shaft generators available, the predicted fuel consumption of the main and auxiliary engines would have been almost equal in the ECA in 2011.

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 of IMO-registered vessels was approximately 76 % / 24 % in 2009. In 2011, this ratio changed to 70 % / 30 %. The high fraction of the distillate fuels is caused by two main factors. First, a major fraction of the fuel consumption originates from auxiliary engines during harbour 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 the Marpol Annex VI regulation.

3.2 The geographical distribution of shipping emissions in 2011

For 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 are from three to five times higher, compared with the corresponding values in the major shipping lanes of 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 UK, and there is busy traffic also between Rostock and Trelleborg, and between Helsinki and Tallinn. The

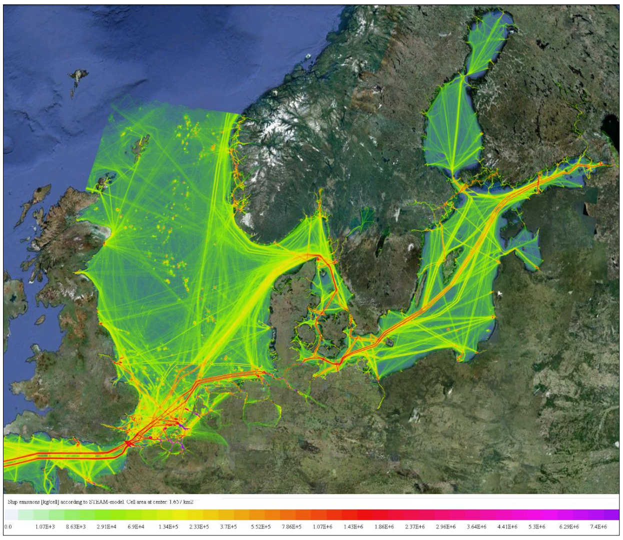

Fig. 4. Predicted geographic distribution of shipping emissions of CO_2 in the ECA in 2011. The colour code indicates emissions in relative mass units per unit area.

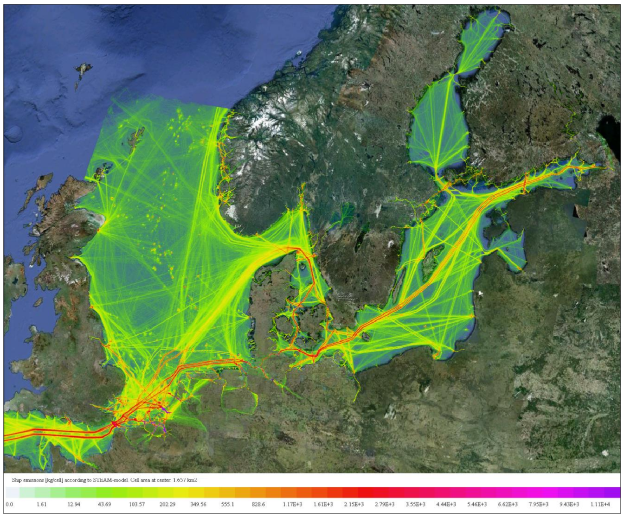

Fig. 5. Predicted geographic distribution of shipping emissions of $PM_{2.5}$ in the ECA in 2011. $PM_{2.5}$ has been assumed to consist of organic and elemental carbon, ash and moist sulfate particles.

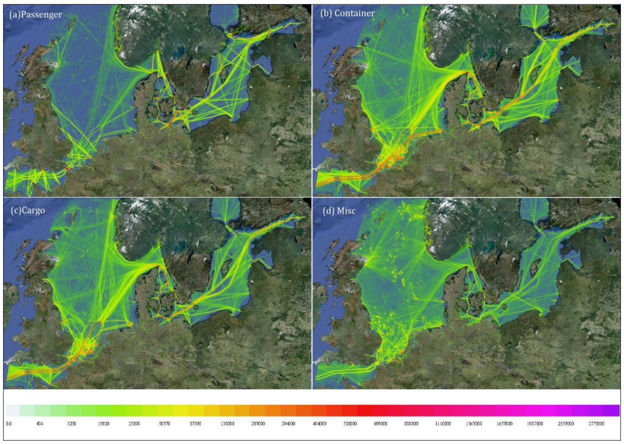

Fig. 6. Predicted geographic distribution of the shipping emissions of CO_2 for passenger **(a)**, container **(b)**, cargo **(c)** and miscellaneous **(d)** ships in the ECA in 2011. Passenger ships include RoPax vessels, cruisers, ferries and other passenger ships. Cargo ships include general cargo,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

geographical distributions of CO_2 emissions originated from container ships and cargo ships are similar with each other. However, the cargo ships were responsible for approximately 21 % more CO_2 emissions in 2011 than container 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 on the North Sea. Almost 4 % of the fuel consumed on 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 of 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 (+127 %), compared with the actual situation in 2011. The emissions of SO_x and $PM_{2.5}$ for this scenario would have been 525 kt and to 104 kt, respectively. As expected, the direct fuel costs would have been lower that for the actual situation in 2011, about USD 9.8 billion, based on the current Rotterdam bunker fuel prices; this is USD 1.0 billion less than the actual estimated fuel costs in 2011.

In the 2009 scenario, there would be 337 kt and 76 kt 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

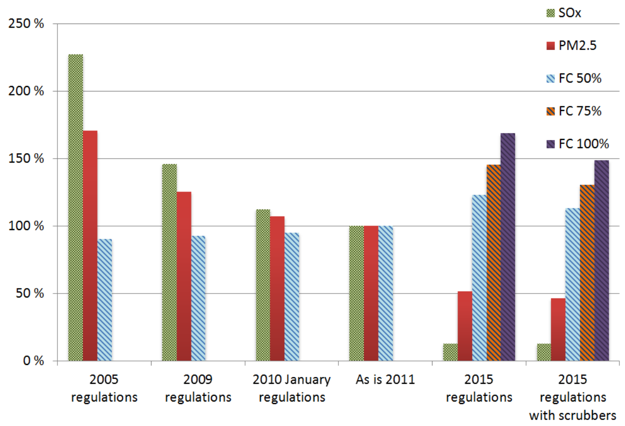

Fig. 7. Relative emissions of SO_x and $PM_{2.5}$, and direct fuel costs of IMO-registered marine traffic in the ECA in 2011, for the various selected scenarios. The situation in 2011 has been evaluated also using three different assumed options regarding the regulations of marine emissions in the past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

all ships would be USD 10.4 billion, which is only USD 250 million 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.

In the 2010 scenario, in which FSC maximum was set to 1.5 % and 0.1 % for ships at berth, ships would exhaust 309 kt of SO_x and 72 kt of $PM_{2.5}$, having fuel cost of USD 10.6 billion, which is roughly USD 220 million less than the estimated fuel costs for 2011 and 580 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 only by 28.4 kt and the $PM_{2.5}$ emissions by 4.2 kt. The reduction of FSC to a maximum of 1.0 % starting from 1 July 2010, reduced SO_x emissions further by 77.9 kt and $PM_{2.5}$ emissions by 11.3 kt; the combined direct fuel costs of these reductions is approximately USD 0.8 billion.

3.3.2 Results for the scenarios of 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 %. 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 29.2 kt and fine particle emissions will be reduced to 31.4 kt. In comparison with the situation in 2011, the SO_x emissions will be reduced by 87 % and the $PM_{2.5}$ emissions will be reduced by 46 %. 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 USD 13.3, 15.7 or 18.3 billion, depending on the fuel price development, which corresponds to a cost increase of 23–69 %.

Reynolds (2011) estimated that ships with an annual fuel consumption of more than 4000 t 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: USD 12.3, 14.2 or 16.1 billion (a cost increase from 13 % to 49 %). 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 ships operates mainly in the Baltic Sea. The estimated $PM_{2.5}$ emissions in this scenario were slightly smaller than in the 2015 scenario without scrubbers. The reason for this is that the virtual scrubbers reduced 66 % from SO_x emissions and 75 % from $PM_{2.5}$ emissions and, thus, FSC_A in Eq. (2a) and (2b) results in a slightly lower FSC than would be required in terms of a $PM_{2.5}$ emission factor in 2015.

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 USD 5 to 9 million (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 systems and it might also not be economically viable, if the vessel is reaching the end of its lifespan.

Table 3. The numbers of candidate ships for the installment of the 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 t 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 %

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 $\mathrm{m\,s^{-1}}$ (10 knots), as it would be unlikely to achieve significant economic savings by reducing speeds that are lower than 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 and b.The results of these slow-steaming scenarios are shown separately for those vessel categories, for which the fuel consumption is > 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 9.4 %, 11.7 %, 13.2 % and 11.5 % respectively. 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. However, the CO emissions per provided energy unit tend to increase for lower engine loads.

Depending on the ship type, the achieved reduction in main fuel consumption ranges from 6.5 % to 18.3 %. 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 13.6 %, while the operational time increases by 3.2 %. RoRo and vehicle carriers would achieve the reductions in fuel costs of 14.3 % and 12.5 %, while their operational time would increase by 5.0 %. Together, the categories of RoPax, RoRo and vehicle carriers contribute 22.4 % of the total fuel consumption in the ECA. The container ship category, which is the largest vessel category in the ECA, would gain a more modest 8.6 % reduction in fuel costs, and an increase of operational time of +4.7 %.

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 20.7 %, 26.7 %, 29.6 % and 24.5 %, respectively. Due to the selection of the above mentioned threshold speed (5.1 $\mathrm{m\,s^{-1}}$), only the ships which are cruising faster than 7.4 $\mathrm{m\,s^{-1}}$ (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 have increased from 43 to 48 million tons from 2009 to 2011 (+11 %, using 2009 as the base year), mostly caused by the increase in cargo transport in the ECA region during the study period. Although the number of non-IMO-registered vessels strongly increased, the estimated contribution of these presumably small vessels was only 5 % in terms of CO_2 emissions in 2011.

The predicted SO_x emissions originating from IMO-registered marine traffic have been reduced from 320 kt to 231 kt from 2009 to 2011 (−29 %, using 2009 as the base year). The corresponding predicted reduction for $PM_{2.5}$ was from 71.6 kt to 60.9 kt (−17 %, 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 $PM_{2.5}$.

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.

(a) 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 [%]
Vehicle carrier	2.8 %	−45.4 %	15.6 %	−29.8 %	−31.4 %	−40.3 %	−39.9 %	−34.3 %	28.8 %
Refrigerated cargo	1.7 %	−43.7 %	11.5 %	−20.6 %	−22.9 %	−33.2 %	−36.8 %	−28.4 %	26.5 %
RoRo	6.1 %	−42.5 %	15.4 %	−34.1 %	−35.5 %	−38.8 %	−41.1 %	−37.3 %	6.3 %
RoPax	13.5 %	−40.8 %	10.1 %	−31.7 %	−33.0 %	−35.3 %	−38.5 %	−36.6 %	−7.9 %
Passenger cruiser	2.3 %	−39.0 %	12.1 %	−27.7 %	−29.0 %	−31.1 %	−34.0 %	−32.2 %	−10.3 %
Container ship	19.9 %	−38.2 %	14.6 %	−19.4 %	−20.9 %	−29.7 %	−30.0 %	−20.4 %	12.8 %
Tanker, LPG	1.4 %	−36.9 %	9.1 %	−18.1 %	−20.0 %	−28.5 %	−31.9 %	−26.9 %	29.3 %
Bulk cargo	6.5 %	−33.6 %	8.8 %	−18.2 %	−19.8 %	−27.5 %	−29.3 %	−25.7 %	29.4 %
Tanker, crude	5.3 %	−33.1 %	7.8 %	−22.3 %	−23.5 %	−30.5 %	−29.6 %	−27.6 %	31.1 %
Tanker, chem.	9.3 %	−32.1 %	9.1 %	−18.0 %	−19.6 %	−26.9 %	−28.8 %	−25.3 %	27.1 %
Tanker, product	2.3 %	−31.3 %	5.1 %	−17.7 %	−19.3 %	−27.0 %	−28.6 %	−25.1 %	27.9 %
General cargo	10.9 %	−18.0 %	3.9 %	−9.5 %	−10.5 %	−14.2 %	−16.2 %	−13.6 %	16.6 %
Dredge	1.2 %	−16.4 %	1.5 %	−7.6 %	−8.4 %	−9.6 %	−13.4 %	−11.2 %	3.5 %
Service ship	4.0 %	−14.3 %	1.6 %	−5.1 %	−5.8 %	−6.2 %	−10.8 %	−8.5 %	1.1 %
Fishing boat	1.4 %	−12.6 %	1.2 %	−3.0 %	−3.6 %	−4.7 %	−8.8 %	−5.5 %	4.3 %
Tug boat	2.3 %	−11.8 %	0.5 %	−2.6 %	−3.1 %	−3.7 %	−8.7 %	−5.5 %	3.3 %

(b) 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 [%]
Vehicle carrier	2.8 %	−18.3 %	5.0 %	−12.5 %	−13.1 %	−16.0 %	−16.4 %	−15.0 %	15.5 %
RoRo	6.1 %	−17.7 %	5.0 %	−14.3 %	−14.9 %	−16.0 %	−17.1 %	−16.3 %	5.8 %
Refrigerated cargo	1.7 %	−17.5 %	3.8 %	−8.7 %	−9.6 %	−13.2 %	−14.9 %	−12.6 %	14.4 %
RoPax	13.5 %	−17.4 %	3.2 %	−13.6 %	−14.2 %	−15.0 %	−16.5 %	−15.7 %	−2.7 %
Passenger cruiser	2.3 %	−16.6 %	3.9 %	−12.1 %	−12.7 %	−13.4 %	−14.8 %	−14.1 %	−5.3 %
Tanker, LPG	1.4 %	−16.4 %	3.5 %	−8.4 %	−9.2 %	−12.3 %	−14.3 %	−12.4 %	14.5 %
Bulk cargo	6.5 %	−15.9 %	3.6 %	−8.8 %	−9.6 %	−12.7 %	−14.0 %	−12.4 %	15.1 %
Container ship	19.9 %	−15.8 %	4.7 %	−8.6 %	−9.2 %	−12.8 %	−12.9 %	−10.4 %	8.3 %
Tanker, chem.	9.3 %	−15.2 %	3.8 %	−8.8 %	−9.5 %	−12.5 %	−13.7 %	−12.2 %	14.3 %
Tanker, crude	5.3 %	−15.0 %	3.1 %	−10.3 %	−10.9 %	−13.5 %	−13.6 %	−12.7 %	15.8 %
Tanker, product	2.3 %	−14.0 %	2.1 %	−8.1 %	−8.8 %	−11.8 %	−12.9 %	−11.4 %	14.3 %
General cargo	10.9 %	−9.7 %	2.0 %	−5.3 %	−5.8 %	−7.4 %	−8.8 %	−7.6 %	9.6 %
Service ship	4.0 %	−8.2 %	0.9 %	−2.9 %	−3.3 %	−3.5 %	−6.2 %	−4.9 %	0.6 %
Dredge	1.2 %	−7.7 %	0.7 %	−3.6 %	−3.9 %	−4.5 %	−6.3 %	−5.2 %	2.7 %
Fishing boat	1.4 %	−7.1 %	0.7 %	−1.7 %	−2.1 %	−2.6 %	−4.9 %	−3.3 %	2.6 %
Tug boat	2.3 %	−6.5 %	0.3 %	−1.4 %	−1.7 %	−2.0 %	−4.8 %	−3.0 %	1.6 %

The highest CO_2 and $PM_{2.5}$ emissions originating 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 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 kilometre, 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 sulfur content restrictions. The simulation showed that the SO_x emissions in the ECA would have been 127 % 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 71 % higher. However, the direct fuel costs would have been 10 % 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 87 % and those of $PM_{2.5}$ by 48 %, with respect to the estimated emissions in the ECA in 2011. The direct fuel costs were estimated to increase by 23 % from 2011 to 2015, assuming the contemporary bunker prizes. However, if the price premium of MGO with respect to HFO by that time increases 100 %, due to the increase in demand, then the direct fuel costs would annually be 69 % 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 retrofit scrubber installation. These candidate ships were responsible for approximately 21 % of the total fuel consumption in the ECA in 2011. Assuming that each of these ships would use sulfur scrubbers instead of using 0.1 % sulfur content MGO in 2015, the estimated fuel cost would increase in 2015 either only by 13 % (using the contemporary bunker prizes) or by 49 % (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 retrofit 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 numerically applied 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, tankers 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.

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