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A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area

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Abstract

A method is presented for the evaluation of the exhaust emissions of marine traffic, based on the messages provided by the Automatic Identification System (AIS), which enable the identification and location determination of ships. The use of the AIS data enables the positioning of ship emissions with a high spatial resolution, which is limited only by the inaccuracies of the Global Positioning System (typically a few metres) that is used in vessel navigation. The emissions are computed based on the relationship of the instantaneous speed to the design speed, and these computations also take into account the detailed technical information of the ships' engines. The modelling of emissions is also based on a few basic equations of ship design, including the modelling of the propelling power of each vessel in terms of its speed. We have also investigated the effect of waves on the consumption of fuel, and on the emissions to the atmosphere. The predictions of fuel consumption were compared with the actual values obtained from the shipowners. For a RoPax vessel, the predicted and reported values of fuel consumption agreed within an accuracy of 6%. According to the data analysis and model computations, the emissions of NO_x, SO_x and CO_2 originating from ships in the Baltic Sea in 2007 were in total 400 kt, 138 kt and 19 Mt, respectively. A breakdown of emissions by flag state, ship's type and year of construction is also presented. The modelling system can be used as a decision support tool in the case of issues concerning, e.g., health effects caused by shipping emissions, the construction of emission-based fairway dues systems or emissions trading. The computation of emissions can also be automated, which will save resources in constructing emission inventories. Both the methodologies and the emission computation program can be applied in any sea region in the world, provided that the AIS data from that specific region are available.

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1 Introduction

Problems in air quality related to emissions from shipping have been reported globally (Corbett et al., 2007; Dalsøren et al., 2007; Endresen et al., 2003; Corbett et al., 1999; Capaldo et al., 1999), regionally (Wang et al., 2007; Gergakaki et al., 2005; Davis et al., 2001; Delft, 2006; Lloyds, 1999; ENTEC, 2005; Kesgin et al., 2001, ENTEC, 2002) and for large port areas (Yang et al., 2007; Starcrest, 2008; Dong et al., 2002; Isaksson et al., 2001). In addition to the influence of collisions and groundings, the adverse health and environmental effects of marine traffic caused by its atmospheric emissions can also be substantial. Ship traffic has been recently estimated to contribute to approximately 60 000 premature deaths globally (Corbett et al., 2007). The highest mortality rates were reported around the English Channel, on the eastern coast of the USA and in Southeast Asia; these were proposed to be caused by an increased number of cardiopulmonary cases due to increased concentrations of ultrafine particulate matter. One of the key components of the particulate matter, sulphates, can be effectively reduced by using low-sulphur fuel in marine diesel engines. Within the International Maritime Organization (IMO) there is already an agreed process for the long-term reduction of the sulphur content of marine fuel (IMO, 1973).

The Baltic Sea is a busy area for short-sea marine traffic. It was also the first control area for SO_x emissions (SECA), with control legislation taking effect from 19 May 2006. At any given moment, there are more than 2000 vessels anchored or en route to different harbours and about 3500–5000 different vessels are in operation in the area every month. Most of the existing methods to estimate emissions of ship traffic up to the present have relied on simplified information (Endresen et al., 2005; Endresen et al., 2007; Dalsøren et al., 2007; Endresen et al., 2003; Dentener et al., 2006) and are based on averages in terms of the number and size of vessels, the distances travelled between ports, engine power levels and/or the amounts of fuel. Global inventories of ship emissions have been presented, e.g., by Endresen et al. (2003) and Wang et al. (2008), but their application to the Baltic Sea has lead to an underestimation in the air emissions due to shipping, mainly due to an insufficient description of the short-sea traffic (Wang et al., 2008).

In order to reduce the risk of collision between ships, the IMO has stipulated that a navigational aid called the Automatic Identification System (AIS) is to be used in ships globally (IMO, 1974) as a tool for the short-range identification and tracking of ships. AIS is based on VHF radio transmissions; the typical maximum range of an AIS base station is therefore from 50 to 90 km, depending on the height of the antenna and atmospheric conditions. A complete coverage of the system can therefore only be expected in areas where the AIS base station network is sufficiently closely-spaced, such as, e.g., in the Baltic Sea area. The use of AIS is mandatory for all larger ships, exceeding the 300 gross tonnage limit, and there is no bias towards data from specific ship types. The latter may be the case for ICOADS (International Comprehensive Ocean-Atmosphere Data Set) and AMVER (Automated Mutual-Assistance VEssel Rescue system) (Endresen et al., 2003); these may lead to a biased evaluation of emissions that can emphasize, for example, the influence of cargo ships. Both ICOADS and AMVER may serve well as data sources for global ship emission assessments, but AIS information can be used to provide more accurate assessments in specific regions.

AIS data results in an extensive data flow yielding hundreds of thousands of position reports per ship every year. Up to the present time, harbour arrivals and departure data, and the locations of main shipping lanes have mostly been used in deciding where ships sail (Bewersdorff et al., 2008; Georgakaki et al., 2005). The ENTEC ship emission study (ENTEC, 2002) was based on a period of four months of vessel movements in the EU area, and extrapolated annual emissions were presented. In the ENTEC study, the treatment of short-sea traffic was inaccurate, as it listed only one port of call per day/vessel, even if a vessel engaged in regular traffic between two harbours several times a day. This assumption could lead to substantial inaccuracies, especially for relatively short-distance sea routes, such as the traffic across the Gulf of Finland between Helsinki and Tallinn, for which the passenger traffic is intensive.

Accounting fully for short-sea traffic, the emission model described in this paper, STEAM (**S**hip **T**raffic **E**mission **A**ssessment **M**odel), allows for the computation of emissions with a temporal resolution of one second. For most applications, longer summation periods are used. As the estimated engine power levels are based on a few basic equations of ship design, the use of average ship properties is restricted only to cases where the ship data is insufficient. Previous studies have listed methodological uncertainties related to the location of emissions (Corbett et al., 2003; Wang et al., 2008; Georgakaki et al., 2005) Furthermore, previous studies have mostly, if not completely, neglected the effects of emission abatement techniques, changes in ship speed and the consequent effects on emissions, as well as the true position of the ships The need for a system describing the realistic behaviour of ships and both the temporal and spatial distribution of emissions is evident (Lauer et al., 2007; Richter et al., 2004).

Our work is, to our knowledge, the first attempt to model ship emissions in international sea areas using the AIS data as a starting point. The objective of this study is to highlight the improvement in the accuracy and reliability of ship emission inventories that is obtained by using the real ship movements given in AIS position reports. In addition, significant improvements can be achieved in information regarding, for example, daily traffic numbers, flag state and ship types. Some selected results regarding the marine traffic in the Baltic Sea are presented. The scientific aim was to develop a methodology that can make optimum use of the more accurate information of ship movements given in AIS position reports. We have designed the computational system to be sufficiently flexible and versatile, in order to be potentially applicable globally in the future.

2 Material and methods

The main algorithms of the STEAM model are described schematically in Fig. 1. The program first decodes the received AIS transmissions and checks whether any new ships are encountered. If the IMO registry number of the ship cannot be found in the internal ship database, the Lloyds ship register (Lloyds, 2009) is queried for the technical details. The ship type is determined based on the database entry of the IMO registry number, or if this number is missing, on AIS data. If a vessel cannot be identified at all, it is assumed to be a small craft. The program uses crankshaft rpm (rpm, revolutions per minute) data to assign NO_x emission factors which are based on the following (IMO, 1973):

$$\text{Emission\_factor (g/kWh)} = \begin{cases} 17, \text{ for engines} \leq 130\text{rpm} \\ 45.0 * n^{-0.2}, \text{ for engines} 130<n<2000, n= \text{engine rpm} \\ 9.8, \text{for engines over 2000 rpm} \end{cases} \quad (1)$$

It is assumed that the NO_x emission factors of all engines, regardless of their year of construction, obey the IMO curve and are independent of the fuel consumption; the predictions of the emissions of SO_x and CO_2 are, on the other hand, based on engine-specific fuel consumption.

If engine data is unavailable, the ship is assumed to use a 500 rpm medium speed diesel engine by default. Propelling power is then evaluated, and the user has the option of including the effects of waves in the emission estimates, resulting on the increased power demand, which depends on wave height and contact angle with the ship. The auxiliary engine profile is determined based on the ship type and operating mode. After main and auxiliary engine power levels have been estimated, emission factors are applied based either on the IMO NO_x curve directly or using information on measured emissions levels and installed abatement techniques. The process presented in Fig. 1 is repeated for all the ships and emissions. To ensure the continuity of the data, the route and fuel consumption values are linearly interpolated based on the received AIS signals. Interpolation is not done if the time difference between two position reports is longer than 72 h. If the time between consecutive position reports is longer than this limit value, no emission is predicted to occur during the data gap. Clearly, if the technical data for a ship is outdated or inaccurate, or significant gaps in the AIS data are encountered, the accuracy of the predictions deteriorates.

2.0.1 Engine power estimates for individual ships

Once the ship has been identified and its location has been determined, detailed and up-to-date technical information about each vessel is used, especially regarding the main and auxiliary engines, boilers, generators and design speed. When the speed and technical data of the vessel are known, an estimate of its level of main and auxiliary engine use is computed based on the functional dependence of the instantaneous speed and the design speed; the fuel consumption and exhaust emissions of the vessel are then calculated. These result in a ship-specific fuel and emission inventory.

The instantaneous power P is evaluated as a function of the velocity of the ship V (ITTC, 1999):

$$P = (CF + CR + CA + CAA)\left(\frac{1}{2}V^3 S\right)\frac{1}{\varepsilon_0} \tag{2}$$

where CF, CR, CA and CAA are the frictional resistance, residual resistance, appendage resistance and air resistance, respectively; ε_0 is the propulsive coefficient and S the wet surface of the ship. All values in Eq. (2) are in SI units. Normally the maximum power P_{max} is 80% of the total installed main engine power, which is assumed to represent the Maximum Continuous Rating (MCR) of the engine, when the vessel travels at its design speed. In this study, a safety margin of 0.257 m/s (0.5 knot) in design speed is used for all ships; the propelling power will suffice to move the ship at its design speed plus the safety margin when $P = P_{max}$.

Correlations describing these parameters (CF, CR, CA, CAA and ε_0) can be found in the literature, but they are typically functions of hull-specific parameters that cannot be found in available databases. A straightforward solution to this problem is to simplify Eq. (2) by assuming that CF, CR, CA, CAA, S and ε_0 are ship-specific constants. Then Eq. (2) can be written simply as:

$$P = kV^3 \tag{3}$$

and the problem reduces to finding the ship-specific parameter k.

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Different ship types have different ways of using their engines, especially during harbour visits; they may also use different fuel on the open sea and in harbours. The electricity requirements vary depending on the type of the ship. The model described in this paper uses different auxiliary engine profiles for various vessel types. For instance, the energy demand of a large cruise ship with more than a thousand air-conditioned cabins is considerably different from that of a bulk cargo carrier. Auxiliary engine use plays a predominant role in modelling the emissions in harbour areas, because auxiliary engines are used to generate electricity during stays in harbours, while main engines do not contribute to harbour emissions significantly during hotelling.

Current estimates for auxiliary engine use are based on ship-type specific profiles, depend on the operating mode of the ship and employ the following rules: 1) Passenger, RoPax and cruise ships use 4000 kW of auxiliary engine power regardless of the operation mode. This includes boilers, if any. 2) All other types of ships use 750 kW of auxiliary engine power during cruise, 1250 kW during port manoeuvers and 1000 kW during hotelling. 3) No more than 20% of the installed main engine power is allowed for auxiliary engine output. This restriction applies to ships for which auxiliary engine data is unavailable, constituting approximately 15% of the ~20 000 ships in the internal database. 4) Predicted transient auxiliary engine usage cannot exceed maximum installed auxiliary engine power. The operating modes are determined by the speed of the vessel. Fuel types, specific consumption, fuel sulphur content and measured emissions are taken into account, if the shipowner has made this data available.

2.1 Ship-specific validation material

The best method of verifying the predictions of emissions would be a direct comparison with the measurements of ship exhausts. However, this would require a large number of measurements for different ship types in various operating conditions. Instead, we have compared the predicted and reported fuel consumption. Fuel is a major item of expenditure; every commercially-operated ship therefore keeps at least monthly records. The fuel consumption and air emissions of any ship are calculated as a function of instantaneous engine power. Obtaining engine-specific fuel consumption data for quality control purposes necessitates continuous cooperation with the shipowners. The data collected from interviews with Finnish shipowners consist of the annual fuel consumption of six RoPax vessels, ranging from hourly to monthly fuel reports. The fuel consumption of main and auxiliary engines and boilers are reported separately, facilitating adjustments of ship-specific power profiles. Measured emissions of specific ships are used in the model calculations, if the shipowner has made this information available.

2.2 Effects of waves

Waves tend to increase the fuel consumption of ships. The model takes the effects of waves into account by applying additional power requirements in high sea states. The hourly significant wave heights and the mean wave direction data are obtained from the WAve Model (WAM) (Komen et al., 1994) and the increased power demand is subsequently modelled by the STEAM model, according to Townsin et al. (1993). The grid resolution of WAM was 0.2° lon by 0.1° lat and was forced with winds from the HIRLAM model. The implementation and performance of the model in the Baltic Sea is described in Tuomi (2008). Besides the sea state, the additional power requirement depends on parameters describing the wet surface and the three-dimensional structure of the hull (these are different, for example, for oil tankers and passenger ships), and the contact angle between the hull and waves.

The directional part of the speed penalty is given by

$$\mu = \begin{cases} 1.0, \theta \leq 30^\circ \\ \frac{1.7-0.03(BN-4)^2}{2}, 30 < \theta \leq 60 \\ \frac{0.9-0.03(BN-6)^2}{2}, 60 < \theta \leq 150 \\ \frac{1.7-0.03(BN-8)^2}{2}, \theta > 150 \end{cases} \tag{4}$$

Where θ is the contact angle between the wave direction and the ship (in degrees) and

BN is the effective Beaufort number (dimensionless) The evaluation of the increased power demand is dependent on *BN*; hence, the modelled significant wave height obtained from the WAM model for fully-developed waves needs to be converted to *BN*.

Table 1 shows the relation between *BN*, the corresponding wind speed ranges and significant wave heights given by Townsin et al. (1993), as well as the values for fully-developed waves predicted by the growth curves of Kahma (1986). The lower value of Kahma (1986) was used in this study. Based on the values in Table 1, an empirical expression was derived for the dependence of the effective *BN* on the significant wave height:

$$BN = 4.21794 * Hs^{0.31} \tag{5}$$

where Hs is the significant wave height (in metres). The performance penalties for tankers and other ships are (Townsin et al., 1993)

$$\frac{\Delta V}{V} 100\% = C * BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}} \quad \text{oil tankers} \tag{6a}$$

$$\frac{\Delta V}{V} 100\% = C * BN + \frac{BN^{6.5}}{22\nabla^{2/3}} \quad \text{other ships} \tag{6b}$$

where $\Delta V/V$ is the the speed penalty (in percents), ∇ is the displacement volume of the vessel (in m^3) and C is a dimensionless parameter; its value is 0.5 for tankers and 0.7 for other ships. The difference between laden tankers and those carrying ballast cargos was not used, since the effect is small. The performance penalty is given separately for oil tankers and for other ships due to the shape differences in hull cross-section.

The actual increase in the required engine power is obtained by multiplying Eq. (6a–b) with the appropriate μ from Eq. (4). Equation (4) is in a slightly modified form, compared with that presented by Townsin et al. (1993), as the original led to non-physical behaviour at high BN's. The speed penalty applied to any ship is restricted to

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a maximum of 50%, which would require a significant wave height of 5 m for oil tankers and 11 m for other ships.

2.3 Ship properties

In order to apply Eqs. (1–3), technical information about the ship is needed. The primary source of ship technical data is the internal database of vessels held by STEAM, consisting of details for approximately 20 000 ships and their engines. The internal database is a synthesis based on many data sources (Lloyds, shipowners and local maritime authorities) that contain measured emission factors for ships, but it also includes information of the abatement techniques installed in ships. If the vessel is not included in this database, the program queries the Lloyds ship register for necessary information.

It is possible to decrease the amount of NO_x and SO_x by technical measures, but curbing CO_2 emissions is more difficult. Currently, ten abatement techniques have been modelled, and emission reduction factors are assigned for each technique (ENTEC, 2005; Wahlström et al., 2006; Lövblad et al., 2006; DeMers et al., 2000). If emission certificates have been granted for a ship, the certified emission factors are used. Individual emission factors and fuel consumption values are assigned for engines. The emission inventories do not currently include the particulate matter (PM) emitted by ships. This is mainly due to insufficient data regarding the ash content and fuel types that are specific to those of the main and auxiliary engines in use in the Baltic Sea area, and to uncertainties regarding the size distributions and other properties of the emitted PM. The current procedure for determining emissions from a ship relies on detailed technical data of the engines. Only if the data are missing, are the average values for that specific ship type then used.

3 Results and discussion

Real-time reception of the AIS data flow enables real-time tracking of ship emissions, but significant amounts of data need to be analyzed. For example, the AIS position reports of the ships in the Baltic Sea area in 2007 consist of over 210 million individual messages. Counting the number of received AIS messages each hour revealed that in 2007 there were 146 h with no data, which corresponds to 98.3% availability for the AIS service. Our emission and fuel consumption values include all the ships in the Baltic Sea that have an active AIS transmitter, regardless of their destination or operating mode. Grid resolutions of the order of a few hundreds of metres (or even less) can be used, which facilitates detailed studies of emissions in port areas. In 2007, there were 9497 vessels carrying an active AIS transmitter in the Baltic Sea area. The primary means of identifying any ship is its IMO registry number. The secondary means of identification is the MMSI number (Maritime Mobile Service Identity) and the vessel name, which are used together. During the summer months, the number of unidentified vessels is at a maximum. If the vessel cannot be identified at all, it is then assumed to be a small craft. These cases, at a maximum, represent 10% of the vessels in the Baltic Sea during June, July and August.

In its current state, the STEAM model assumes a default sulphur mass-% of 1.5 for the main engine as required by the SO_x Emission Control Area regulations of the IMO. For auxiliary engine fuel, a 0.5 mass-% of sulphur is assumed. If the shipowner has reported a lower sulphur content for the vessels, the lower values are used. A specific fuel oil consumption of 200 g/kWh is used by default for all engines, although the STEAM model allows setting specific values for each of the engines, if these are known.

The contribution of vessels not equipped with the AIS system must be assessed using other methods, since there is no centralized registry of vessels or vessel movements. For example, the annual contribution to NO_x emissions from workboats, small fishing vessels and pleasure craft for Finland was estimated as 6 kilotons, concen-

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trated around active fishing areas and pleasure craft harbours (Mäkelä, 2007). However, these numbers are not included in the estimate reported here, since we are not aware of any corresponding information source that would cover the whole of the Baltic Sea area.

In the following, all emissions have been computed without the effects of waves, unless stated otherwise.

3.1 Comparison of predicted and reported fuel consumption

The annual predictions for fuel consumption were compared with the actual consumption values obtained from the shipowners. A comparison presented here was performed for RoPax ships, as for this ship category the reported fuel consumption data were the most extensive.

The agreement between the predicted and reported fuel consumption data obtained from the shipowner for RoPax5 was fairly good; the average monthly difference was approximately 6%.

A comparison between the predicted and reported annual fuel consumption of six RoPax ships ranging from 10 000 to 60 000 GT is given in Fig. 3. The predicted fuel consumption of the main engines is well predicted for cases two, four and five, whereas cases one, three and six show larger errors. There are some gaps in the 2007 AIS data, ranging from 423 h (RoPax5) to 3632 h (RoPax6). RoPax6 left the Baltic Sea area several times during 2007, which decreases the reliability of the predicted fuel consumption. If gaps in the AIS data are continuous and longer than 72 h, neither emissions nor fuel consumption are interpolated over the gap. The large error in the predicted fuel consumption of RoPax1 underlines the importance of up-to-date technical data. In this case, the engine details of the database entry were incomplete, and ship-type specific average values were used. In most of the cases shown in Fig. 3, the consumption of the auxiliary engines is overestimated, because STEAM uses a constant kW value for the auxiliary engines of all six RoPax cases, regardless of their operation mode. The value depends on the installed auxiliary engine power, as described in Sect. 2.2.1. This feature could be improved by making the auxiliary engine use dependent on, for example, ship size or by using ship-specific power profiles obtained from the shipowners.

Figure 4 shows an example of significant wave height as given by the WAM model. The significant wave height varies on a scale of kilometres; there is also a significant temporal variation on a scale of hours.

An example of the predicted monthly fuel consumption of one particular ship, with and without the effects of waves, is presented in Fig. 5. There is only a minor difference between the two modelled consumptions. In this case, this difference was small on a daily basis, but waves can have a significant impact on hourly fuel consumption. Unfortunately, the lack of hourly and daily fuel consumption data for comparison from a large number of ships prevents drawing comprehensive conclusions about the effect of waves. The model predictions of the fuel consumption in October 2007 for RoPax2 were within 3% without and 6% with wave effects, if the two days 2 and the 20 are not included in the comparison because of data gaps in the AIS data. The annual fuel consumption (neglecting wave effects) is within 5% of the reported values for this specific ship in 2007. The effect of waves on the monthly total fuel consumption of ships in the Baltic Sea is of the order of 0–2%. However, for individual ships, the increase of hourly fuel consumption can be as high as 10–20%. Although waves may significantly affect the fuel consumption of a single ship , the effect is commonly fairly local and of a short duration.

3.2 Spatial and temporal distribution of annual total emissions

On the basis of an analysis of a full year of AIS data, the computation of the emissions results in 400 kilotons of NO_x emitted in the Baltic Sea area. This estimate of 400 kt NO_x is probably a lower limit, due to the various assumptions made in the modelling, such as the under-estimation of emissions from ships built before the year 2000, the neglecting of vessels that are not equipped with the AIS system, and the assumption that all unidentified ships were small craft. The annual estimates for SO_x (as SO_2)

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and CO_2 emissions during the year 2007 were 138 kt and 19 Mt, respectively. The estimated fuel consumption of Baltic Sea shipping in 2007 was 6205 kt, which corresponds to 265 PJ of energy consumed; these can be compared to the 5301 kt consumption and 215 PJ (Davies et al., 2000) projected for the year 2001.

The current estimates by EMEP of NO_x and SO_x emissions in the Baltic Sea area were not available, but in 2006 these were reported as 346.7 kt and 224.8 kt (Vestreng et al., 2004). The estimate of this study for the annual SO_x emission is considerably lower. The Sulphur Emission Control Area limitations became effective in the Baltic Sea area on 19 May 2006, which set the sulphur cap of fuel to 1.5 mass-% instead of the global average of 2.7 mass-% (Endresen et al., 2005). It is not stated, whether the values reported by EMEP include the influences of this change or not (EMEP, 2006).

The geographical distribution of annual NO_x emissions from ships in 2007 is presented in Fig. 6, where the main fairways are easily recognizable. The largest fairway NO_x emissions occur in the Southern Baltic, the Kiel Canal between Germany and Denmark and in the Gulf of Finland, where emissions of over 500 tons/grid cell can occur. This corresponds to over 6.3 g/m^2 of NO_x per year.

The emissions and the number of ships observed peak during the summer months, which can be attributed to the increased passenger traffic during that period. During June, July and August there were 4500 ships, while during February the number was 3700.

From Fig. 7 it can be seen that emissions of NO_x and SO_x are also highest during the summer months. The difference between the months with the highest (July) and lowest (February) predicted NO_x emissions was 20% in the Baltic Sea area in 2007. Globally, the seasonal variation of emissions is smaller (Corbett et al., 1999).

3.3 Classification of emissions by different categories

Ship-specific inventories allow for the classification of emissions according to various categories. For example, the largest contribution to annual NO_x (39%) and SO_x (43%) was from new ships, i.e., those built after 1.1.2000.

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According to Fig. 8, one quarter of the NO_x was emitted by ships built in the 1990's and almost one fifth by ships from the 1980's. The emissions of older ships are probably underestimated, as all ships are assumed to obey the IMO NO_x curve, which has not, however, been a requirement for older ships. The ships in the three of the youngest groups constitute 60% of all the ships. The fourth age group is considerably smaller, referring to that the life cycle of a ship in the Baltic Sea area is around 30 years.

Classification of emissions in terms of the ship type shows that the exhaust emissions of certain types of ships are substantially higher than their relative proportion of all the ships.

In Fig. 9 a comparison of the different ship types is presented. The blue bar shows the percentage of ships in each type. The black, yellow and green bars show the relative emissions of NO_x, SO_x and CO_2, respectively. While RoRo/Passenger ships (RoPax) represent less than 5% of all ships, their emission was over 25% of the total NO_x, SO_x and CO_2 in 2007. Emissions of container ships (8%) are larger than their share of total number of ships (4%). The study of De Meyer (De Meyer et al., 2008) showed that container ships are a significant source of air emissions, despite their small share of the total number of ships. Container ships and RoRo cargo/RoPax ships usually have large engines, and work to a tight schedule. Pushing engines to their limits rapidly increases the fuel consumption and exhaust emissions. Excess engine heat can be harnessed to heat the service water, but in most cases the electricity for air conditioning cannot be obtained this way.

Classification of emissions in terms of the flag state was done based on the country codes of the Mobile Maritime Service Identity numbers (MMSI codes).

Half of the NO_x emissions originated from ships registered in the riparian states of the Baltic Sea (Fig. 10), almost one third came from ships registered to a country outside the European Union and the rest from ships in other EU member states.

A further division into individual flag states is given in Fig. 11. The comparisons only show the flag state of the emission source. Clearly, the shipowner can reside in one country, while his ship may sail under a different flag. This is particularly true for ships sailing under a flag of convenience, like Liberia, Bahamas and Panama. Nordic countries (except Iceland) are at the top of this list along with Germany. About 89% of export and ~76% of import (in tons) in Finland takes place by sea (Finnish National Board of Customs, 2008). Clearly, almost all the major harbors of Sweden, Finland and Denmark are found on the coast of the Baltic Sea, while Russia and Germany can use harbours outside the Baltic Sea area.

4 Conclusions

The objectives of this study were to develop flexible and versatile assessment tools for investigating the characteristics of shipping emissions. In addition to the temporal variations and geographical distribution of the shipping emissions, it is possible to classify them according to a variety of criteria. The model developed also makes it possible to study traffic flows in specific regions. The effects of waves can also be included using information on the significant wave height in the study area. A finer spatial and temporal resolution can be used to study, for example, the detailed properties of shipping within harbours or in the vicinity of nature conservation areas. The spatial and temporal resolutions are limited only by the accuracy of the GPS equipment on board the ships.

Clearly, the STEAM model also has several inherent limitations. The model determines the NO_x emission factors based on engine speed and the IMO NO_x curve. This assumption was necessary to cope with the insufficient emission data for older engines. However, just this assumption may be inaccurate for older engines, those constructed prior to the year 2000, as these engines were not subject to the more stringent regulations of MARPOL Annex VI (IMO, 1973) in 2007. Currently, no single information source can provide for all the input data required by the STEAM model: this encourages us to improve both the internal ship database and the STEAM model itself. For example, the details regarding the installed auxiliary engines, emission abatement techniques and shaft generators can be difficult to obtain otherwise than by directly contacting the shipowners.

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The STEAM model does not currently contain treatments for the effects of sea ice on thrust requirements, shallow water phenomena (squat), hull fouling or sea currents. All vessels are handled as single-propeller and single-hull ships; catamaran and trimaran structures or hydrofoil designs are not modelled. These approximations probably have a negligible effect on the overall accuracy of the emission inventories, but they may substantially affect ship-specific emissions. The STEAM model can treat mathematically short gaps of information in AIS data (<72 h); however, long-lasting gaps between position reports may lead to inaccurate predictions. In this study we have computed the numerical results neglecting the effect of waves, partly as experimental data for evaluating that section of the model is scarce. Non-AIS marine traffic is not included either, as it was not possible to evaluate the emissions of the smallest craft, except for Finland, due to lack of vessel movement data. Clearly, including the effects of sea ice, waves and non-AIS traffic would increase the predicted values of emissions of NO_x, SO_x and CO_2, and that of fuel consumption, compared with the values reported in this paper.

The evaluations for the annual emissions of NO_x, SO_x and CO_2 without the effects of waves in the Baltic Sea area in 2007 were 400 kt, 138 kt and 19 Mt, respectively. The predicted fuel consumption of Baltic Sea shipping was 6205 kt, which corresponds to an energy consumption of 265 PJ . Half of the exhaust emissions arising from Baltic Sea shipping originated from vessels registered to a Baltic Sea riparian state. The IMO has set new emission limits for NO_x and SO_x in its upcoming revision of MARPOL Annex VI (IMO, 1973), which allows for the setting of regional NO_x emission caps, and aims at switching to sulphur-free fuel globally by the end of 2020.

The fuel consumption data provided by the shipowners is valuable for the model evaluation, but substantially more data is needed regarding the power profiles of various ship types during various operating modes. Direct emission measurements are required, especially for ships built before the year 2000. The AIS data-based computation of the ship emissions also allows the determination of vessel-specific emission inventories. The emission data produced by the STEAM model can be used as input for studies of the regional and long-range transport of pollutants and their health effects, and, e.g., in the evaluation of the effects of various emission abatement measures and policies, such as the construction of emission-based fairway dues systems. The STEAM model presented in this study could also be used to evaluate shipping emissions anywhere in the world, provided that the AIS data from that area were available and the relevant ship databases were up to date.

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Table 1. Correspondence of significant wave height, wind speed and the Beaufort number.

Effective Beaufort number	Wind speed range 10 m above the surface (m/s)	Significant wave height range (m) (Kahma, 1986)	Significant wave height (m) (Townsin et al., 1993)	Significant wave height used in this work (m)
0	0.0–0.2	0.0	–	0.0
1	0.3–1.5	0.0–0.1	–	0.0
2	1.6–3.3	0.1–0.3	–	0.1
3	3.4–5.4	0.3–0.8	–	0.3
4	5.5–7.9	0.8–1.7	–	0.8
5	8.0–10.7	1.7–3.1	–	1.7
6	10.8–13.8	3.2–5.2	2.8	3.2
7	13.9–17.1	5.2–7.9	4.8	5.2
8	17.2–20.7	8.0–11.6	7.6	8.0
9	20.8–24.4	11.7–16.1	11.3	11.7
10	24.5–28.4	16.2–21.8	15.8	16.2
11	28.5–32.6	22.0–28.7	–	22.0

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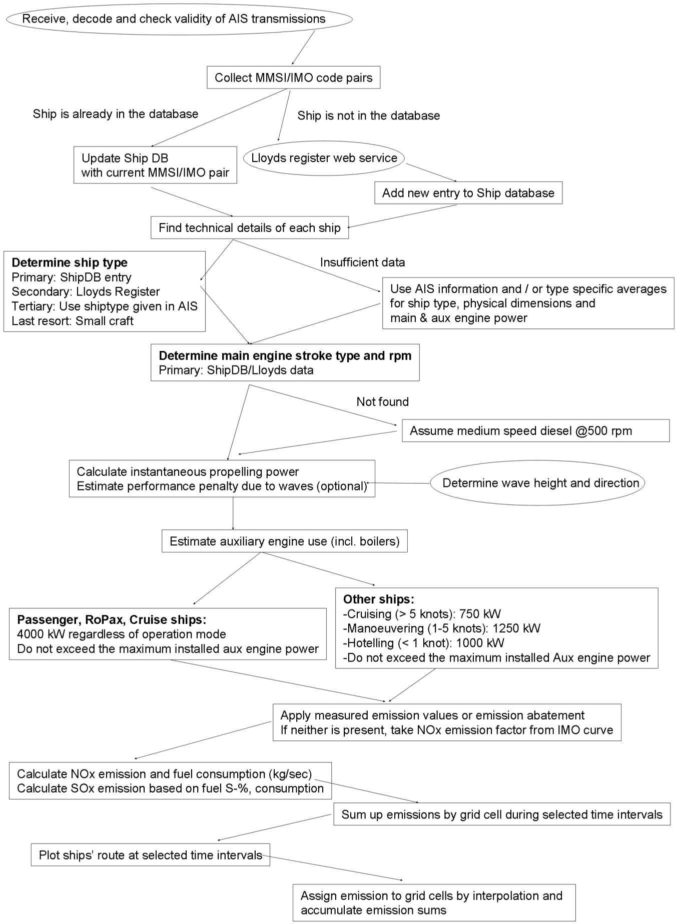

Fig. 1. A schemic presentation of the main algorithms of the STEAM model. The lines indicate the flow of information, from top to bottom. Input data has been shown with ellipsoids. RoPax=RoRo/Passenger ship, MMSI=Maritime Mobile Service Identity.

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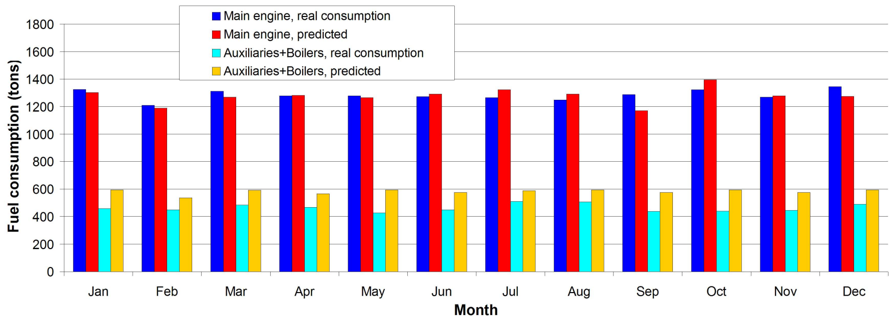

Fig. 2. A comparison between predicted and observed fuel consumption of a RoPax ship (RoPax5) with a gross tonnage of 58 000 in 2007. Modelled and reported fuel consumption of main engines is shown in red and blue. Modelled and reported consumption of auxiliary engines and boilers are shown in orange and cyan, respectively. Consumption is given in tons of fuel, without the effect of waves.

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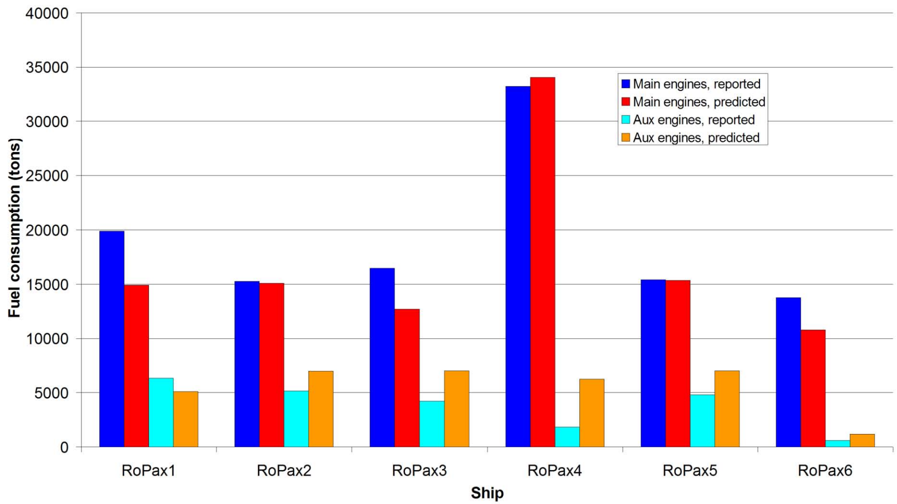

Fig. 3. Comparison of predicted and reported annual fuel consumption of six RoPax ships in 2007.

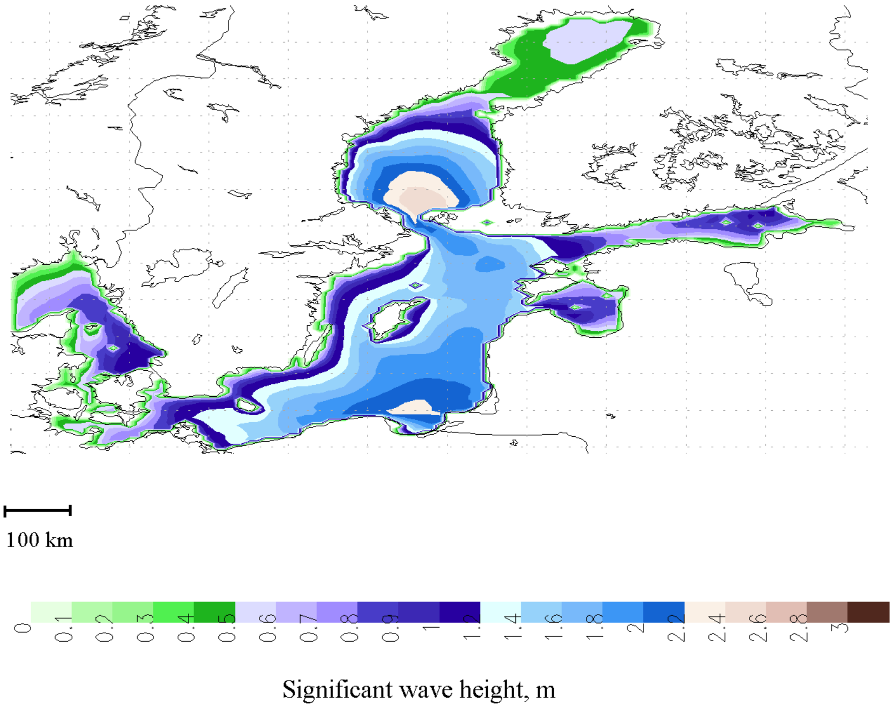

Fig. 4. An example of the significant wave height in the Baltic Sea at 22:00 UTC on 7 October 2007, as predicted by the WAM model.

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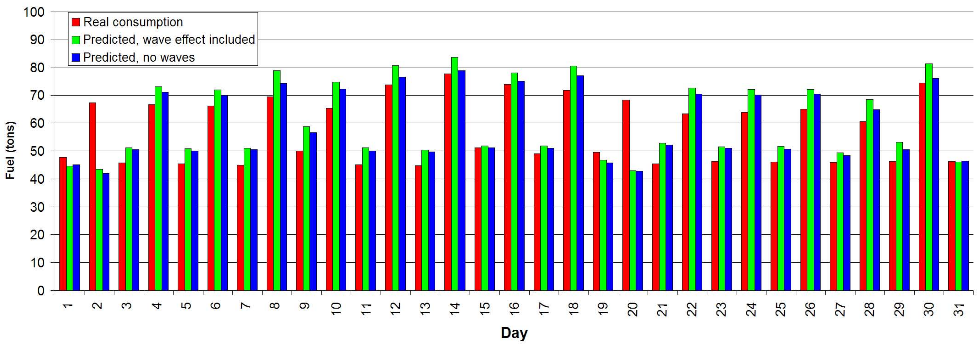

Fig. 5. Comparison of daily fuel consumption of a RoPax ship with a gross tonnage of 58 000, in October 2007. The red bars show the fuel consumption as reported by the shipowner. The green and blue bars show the predicted fuel consumption with and without the effect of waves.

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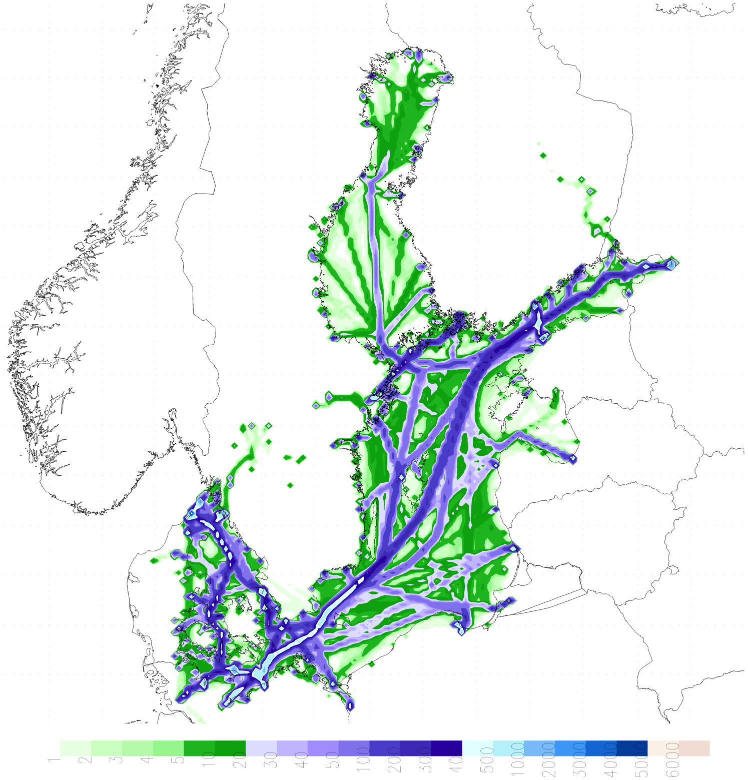

Fig. 6. Predicted annual sum of NO_x emission (as NO_2) due to Baltic Sea shipping in 2007. Emissions are given as tons/grid cell. The grid resolution is 0.08 degrees (~9 km by 9 km, rotated lon/lat grid). Values over 500 tons/cell (6.3 g m^{-2}) can easily occur on the heavily-frequented fairways of the southern Baltic Sea and between Sweden and Denmark.

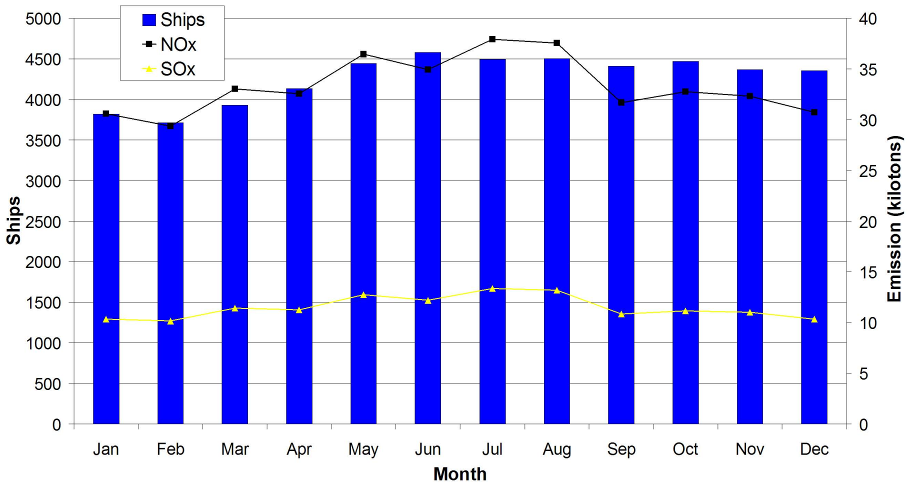

Fig. 7. The predicted seasonal variation of emissions of NO_x and SO_x from Baltic Sea shipping in 2007. The bars show the number of ships. The black line shows the monthly NO_x emissions and the red line the SO_x emission (in kilotons).

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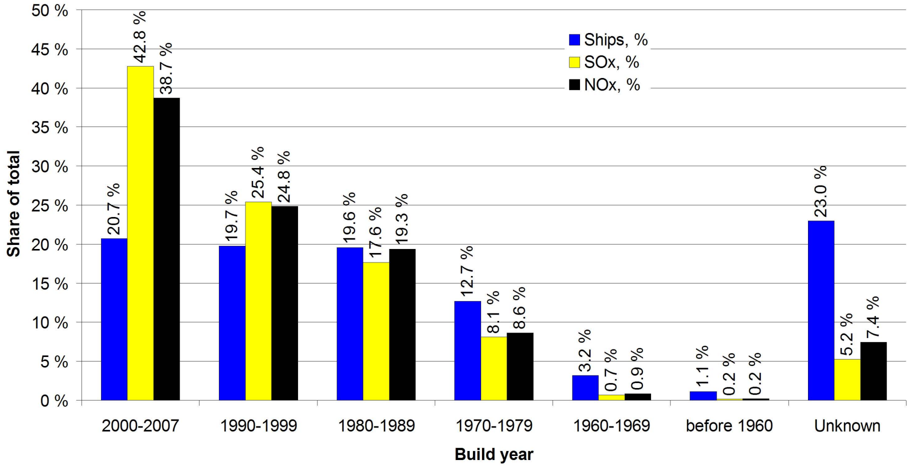

Fig. 8. Share of ships by age (blue) in the Baltic Sea area in 2007. The emission share of each age group of ships is shown with yellow (SO_x) and black (NO_x) bars.

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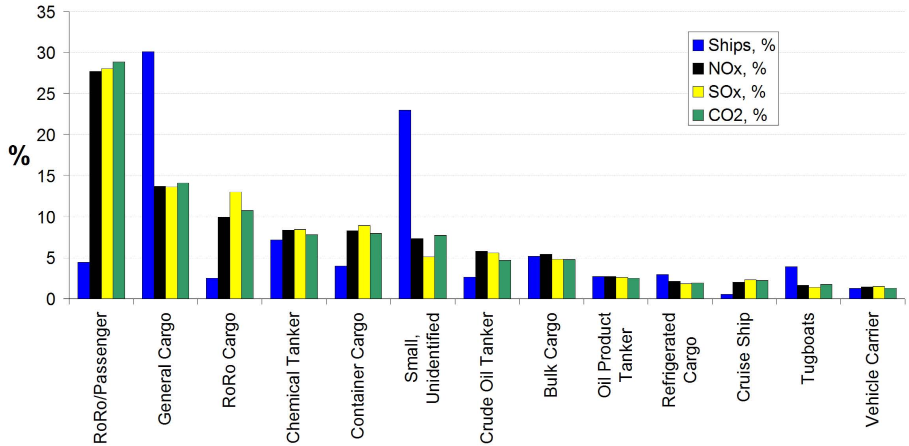

Fig. 9. Relative proportions of ship types and their emissions. Only ship types responsible for over 1% of NO_x emissions are shown. These 13 types are responsible for >96% of the total NO_x generated by Baltic Sea shipping during 2007. The blue bar shows the proportion of ships in each category, black, yellow and green bars the proportion of NO_x, SO_x and Co_2 produced by each of the ship types.

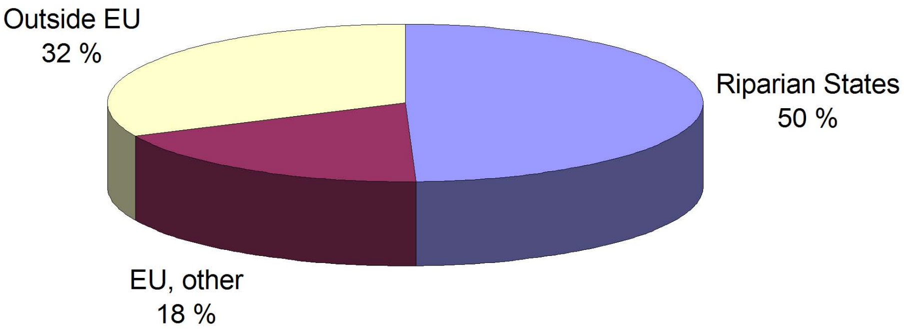

Fig. 10. NO_x emission by flag state, 2007.

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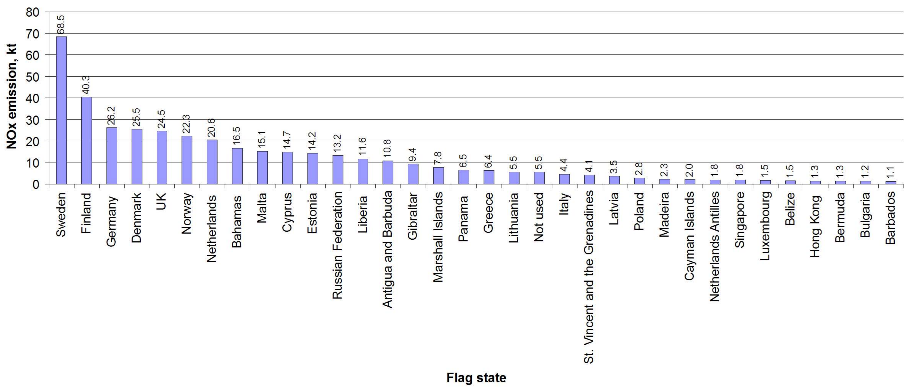

Fig. 11. NO_x emission in the Baltic Sea area by flag state, breakdown by country, 2007. NO_x emissions over 1 kiloton are shown, constituting ∼99% of the total NO_x emission. Note the entry "Not used", which indicates a country code that, according to the International Telecommunications Union, is not supposed to be used.