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SHIP CONTRIBUTION TO AIR POLLUTION IN DENMARK – AN ASSESSMENT UTILISING AIS DATA

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Abstract: The paper describes a study to map the impact of ships on air pollution in Denmark. Recently, data from the Automatic Identification System (AIS) which logs ship activities have become available, enabling much more detailed ship emission inventories than previously to be produced. The study makes use of such data and demonstrates that the use of AIS data is recommendable as future practice. The Baltic Sea and the North Sea have been appointed Sulphur Emission Control Areas by the International Maritime Organisation (IMO). Furthermore, it is expected that the Baltic Sea will also become a Nitrogen Emission Control Area. The consequences of this are investigated for a 2020 scenario. Model calculations were carried out with the air pollution model DEHM (Danish Eulerian Hemispheric Model). Results concerning the concentration levels and the fraction that can be attributed to ship traffic are presented.

Key words: AIS, Automatic Identification System, ship emissions, DEHM, SECA.

INTRODUCTION

In Denmark, no location is more than 100 km away from the sea. Thus, pollution from ships plays a substantial role for air pollution in Denmark.

Previous estimates for the contribution from ships to concentrations in air over Denmark have been quite crude, because they were based on available emission inventories for ships, which have a low geographical resolution for emissions at sea. Furthermore, they were based on simplifying assumptions.

However, since 2006 the so-called *Automatic Identification System* (AIS) has registered ship activities in Danish marine waters. All ships larger than 300 GT (Gross Tonnage) are required to carry a transponder, which transmits information on the ship’s identity and position to land-based receiving stations. This information makes it possible to map ship emissions in much greater detail than previously feasible. In the present study this opportunity has been utilised to create a new emission inventory for ships in the Danish marine waters.

The new AIS-based inventory of ship emissions has been combined with other necessary data and used as basis for new model calculations of air quality in Denmark. A main objective of this work was to assess the contribution from ships to concentration levels of various pollutants. For the modelling of concentrations, a new version of the air pollution model DEHM (Danish Eulerian Hemispheric Model) has been applied – a version with a higher geographical resolution than the previous version.

The International Maritime Organisation (IMO) has adopted new regulations in order to reduce pollution from ships with sulphur dioxide (SO_2) and nitrogen oxides (NO_X) in the period until 2020. It is also the objective of the present work to investigate the effect of this regulation on air quality in Denmark. This is done through scenario calculations for air quality for 2020 based on expected emission reductions.

A detailed report on the study is available (Olesen *et al.*, 2009).

THE AIS-BASED EMISSION INVENTORY

Previously, emission inventories for ship emissions were retrieved from the EMEP data base (EMEP, 2008). These data had a geographical resolution of 50 x 50 km. An example is shown in Figure a.

The data underlying the EMEP emission inventory are based on various simplifying assumptions. However, with AIS technology it is possible to obtain much more accurate data. AIS data for a representative sample of days in 2007 were used to construct a detailed emission inventory for the ships in Danish waters.

For each single vessel in the AIS dataset, ship category, engine type, fuel type, main engine and auxiliary engine size were determined using the technical data from Lloyds' Register as well as various supplementary information. The vessel sailing speed is found between each AIS signal. Subsequently the instantaneous engine load is calculated, using main engine size and vessel sailing speed as input. Further, the fuel consumption and emissions from each vessel during the time between two consecutive AIS signals are calculated by combining engine size, engine load, time duration between the AIS signals, together with fuel consumption factors and emission factors corresponding to the vessel’s engine and fuel type.

The result is a detailed emission inventory as depicted in Figure 1b for the case of SO_2. It appears from the figure that the new AIS-based inventory in detail shows how the ship routes appear as well-defined 'roads' at sea, as opposed to the old method, which has grid cells extending over both sea and land, and thus places some emissions from ships over land. Other differences are less visible, but have consequences for the emissions: The previous inventory assumed that the engine load for ships was constant, whereas the new method takes account of differences in emissions, depending on the speed of the ship.

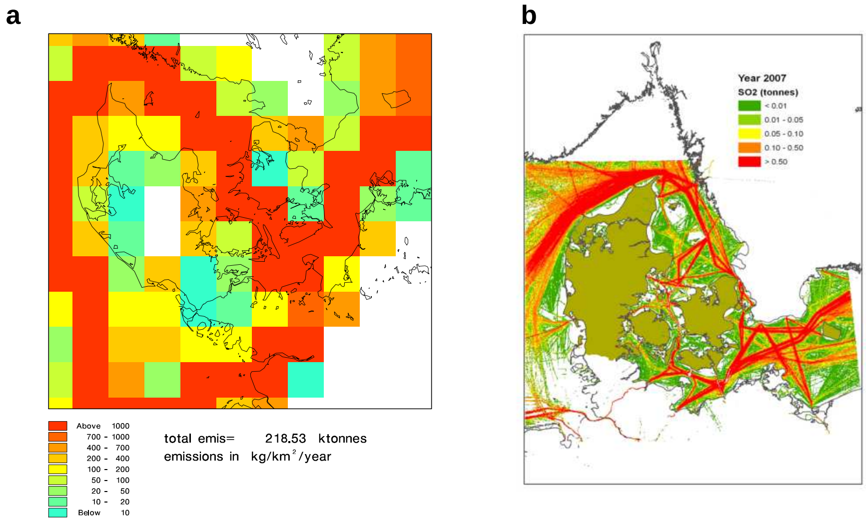

Figure 1. Ship emissions of SO_2 pr km_2. (a) The previously used inventory, where the emission is assigned to grid cells of size 50 x 50 km.
(b) Values from the new, AIS-based emission inventory with a resolution of 1 x 1 km.

Thus, an important outcome of the study is a new, AIS-based ship emission inventory for ship traffic in Danish waters. Other studies have also made use of AIS data, notably Jalkanen *et al.* (2009). It would be of great benefit to the modelling community if emission data based on AIS could be made generally accessible.

SCENARIOS

It is important to note that the seas around Denmark are appointed *Sulphur Emission Control Areas* (SECA's). Figure illustrates the requirements for sulphur content in heavy fuel oil, which is the most common marine fuel. The curve labelled Non-SECA represents the general requirements, applicable everywhere. In SECA's requirements are stricter. The Baltic Sea and the North Sea have been appointed SECA areas, implemented in 2006 and August 2007, respectively. Prior to 2006, the sulphur content in fuel used by ships in these areas has been assumed to be 2.7%, in accordance with Cofala *et al.* (2007).

The study has had to cope with the problem of combining several emission inventories: The detailed AIS-based inventory applies to the seas closest to Denmark, while for ship traffic farther away the available EMEP-based inventory has been used, combined with an assumption on sulphur content in fuel. For land-based sources and air traffic yet other inventories were used.

The year of 2007 was taken as a baseline scenario, while the study considered projections for two future scenarios: 2011 and 2020. For the future scenarios a number of assumptions had to be applied. It was assumed that:

- The IMO regulations for sulphur and NO_X will be implemented as planned. In particular, it is expected – and assumed – that the marine waters around Denmark will be designated a *NO_X Emission Control Area* (NECA) as defined by IMO. The status as NECA requires severe NO_X emission restrictions for new ships from 2016.
- Concerning the amount of ship traffic, an annual increase of 3.5 percent has been assumed for transport of goods from 2011 and onwards, while passenger traffic is assumed unchanged.
- Concerning land-based emissions, a specific set of assumptions have been used. It is expected that in the near future a new EU directive on national emission ceilings for 2020 (NEC directive) will be negotiated. However, there is not yet an official proposal for the directive. Therefore a scenario for emissions from land-based sources in Europe in 2020 has been set up, which is mainly based on emission scenarios for EU-27, prepared by the International Institute for Applied Systems Analysis (Amann *et al.*, 2008) as part of the preparatory work for a new NEC directive.

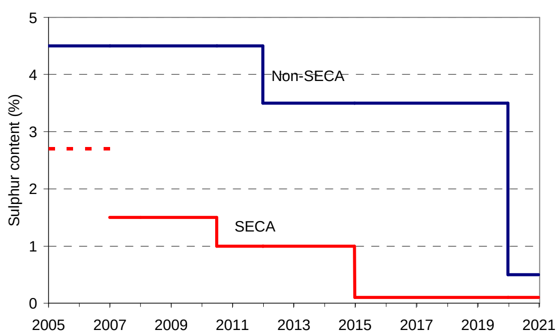

Figure 2. Limit to sulphur content in heavy fuel oil, according to IMO regulations. The SECA regulations were implemented in the Baltic Sea in 2006 and in the North Sea in August 2007. The broken line indicates 2.7% which was the assumed level prior to 2007.

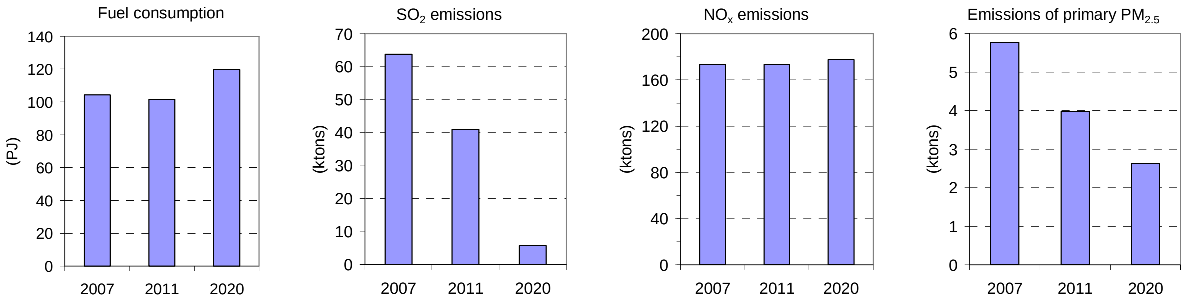

Figure 3. Fuel consumption (Petajoule) and emissions from ship traffic (ktons) in the waters around Denmark for the three scenario years 2007, 2011 and 2020.

The emission calculations predict a 15% increase in fuel consumption from 2007 to 2020 as a result of increased traffic (36% increase for freight ships and unchanged passenger traffic), combined with increased efficiency for ship engines.

For emissions of nitrogen oxides (NO_X) there is an expected growth of 2% between 2007 and 2020. Without stricter emission requirements the increase would have corresponded to the increase in fuel consumption.

For sulphur dioxide (SO_2) a reduction of 91% is envisaged between 2007 and 2020, while for primary $PM_{2.5}$ the reduction is 54%. Primary particles account for only a minor fraction of the total amount of particles found in ambient air.

THE DEHM MODEL

The model calculations to assess air pollution concentration levels have been carried out with the Danish Eulerian Hemispheric Model (DEHM) which was developed at NERI (Christensen, 1997). DEHM is a Eulerian model that calculates emissions, transport, chemical and physical processes and deposition of air pollution in a three dimensional grid. The DEHM model is used in a new version with four nested grids, the finest of which has a geographical resolution of 6 x 6 km. Emissions are added to the model in the lowest layers of grid cells in the model. The emissions from ships have been added to the bottom layers with an even distribution from the surface and up to 170 m height. This simple approach has been taken because of lack of more detailed information on the effective height of ship emissions.

MODEL RUNS

Several sets of model calculations were carried out in order to investigate the effect of using different emission inventories. For each emission inventory, two model calculations were carried out. One model calculation uses all the emissions, while the other is carried out with a 15 % reduction in all the ship emissions. The difference between these two model calculations makes it possible to estimate the amount of air pollution originating from the ship emissions. This methodology has been preferred over another that might seem natural: To use a model run without any ship emissions as a reference. Such an approach would, however, involve an unrealistic chemical regime, and its results could easily be misleading.

RESULTS IN TERMS OF CONCENTRATIONS

Concentrations of sulphur dioxide

Figure shows calculated concentrations of SO_2, referring to, respectively, 2007 (with 1.5% sulphur in fuel) and 2020. The requirement to sulphur content in 2020 is considerably more restrictive than now (max. 0.1% sulphur), and this is clearly reflected in computed concentrations for 2020.

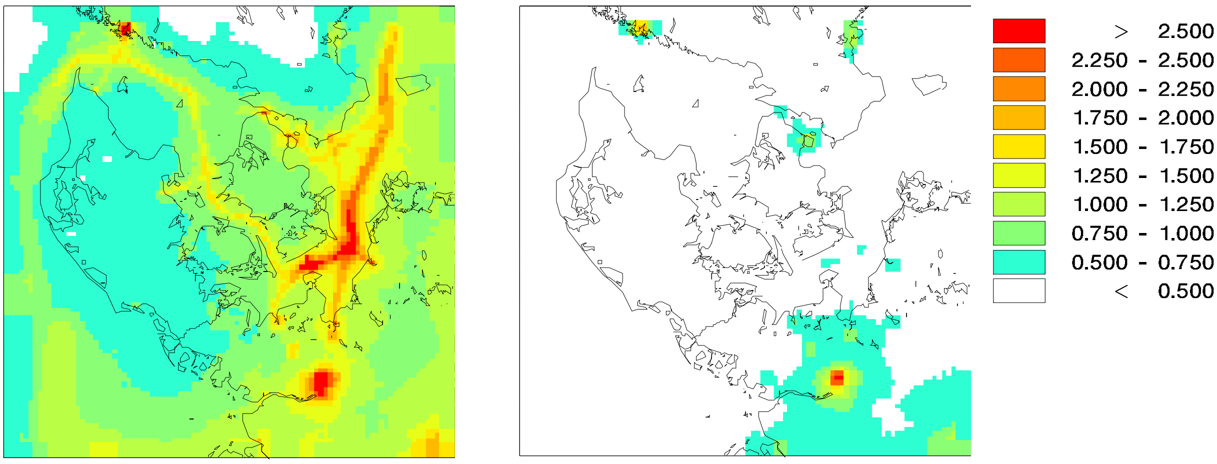

Figure 4. Calculated concentrations of SO_2 In $\mu g/m^3$. The left panel represents the situation in 2007, the right panel the situation in 2020. The impact of ship traffic is clear for 2007, while there is hardly any visible impact from ships in 2020.

Since 1990, SO_2 emissions from land-based sources have been substantially reduced, and in the years to come the reduction is expected to continue. Scenario calculations show that the SO_2 concentration level for Denmark will decrease considerably over the period up to 2020, so in 2020 it will reach a level of 0.3 $\mu g/m^3$. This is only 6% of what it was in 1990, and corresponds to 1.5% of the EU limit values.

Concentrations of nitrogen dioxide (NO_2)

IMO has adopted regulations of NO_X emissions. In the present study it is assumed that the marine waters around Denmark will become designated a so-called *NO_X Emission Control Area* as defined by IMO. This implies several restrictions on NO_X emissions, in particular for new ships from 2016, when an 80 percent reduction in NO_X emission is required. There are other, less demanding requirements to older ships.

However, at the same time an increase in ship traffic is foreseen. The reduction in emissions is not able to completely outbalance the expected increase in ship traffic, so the NO_X emission from ships will be slightly higher in 2020 than in 2007. It is likely that the IMO requirements will result in lower ship emissions after 2020, but this is not the case for 2020. On the other hand, according to the scenario for 2020 there are marked changes for land-based sources.

The result in terms of concentrations is seen in Figure . NO_X leads to formation of NO_2, for which health-related limit values exist. Figure shows model calculated concentrations of NO_2 for 2007 and 2020, respectively. The large shipping routes remain clearly visible, but inland concentrations decrease. The share from ships to the NO_2 concentration level is 21% in 2007, but increases to 34 % in 2020 – because the absolute contribution from other sources is reduced.

It is an interesting result of the calculations that the concentration of NO_2 in urban background in Copenhagen is expected to be reduced by 7 $\mu g/m^3$ (from 16 to 9 $\mu g/m^3$) in the period up to 2020. In several highly trafficked streets in Copenhagen the EU limit value of 40 $\mu g/m^3$ is exceeded (Kemp *et al.*, 2008); this fact makes a large drop in background levels very interesting.

Concentrations of particles

Emissions of SO_2 and NO_X from ships contribute to the formation of secondary inorganic particles. The DEHM model which is used for calculations of concentrations takes account of the processes involved. However, there is insufficient knowledge to describe the formation of secondary *organic* particles, and DEHM does not account for these. Internationally, this is recognised as being *state-of-the-art* for most current models (see Yttri *et al.*, 2009). Accordingly, the DEHM model accounts only for a certain fraction of the particles found in the atmosphere, namely the primary and the secondary inorganic. This part is here designated *$mPM_{2.5}$* (modelled $PM_{2.5}$).

Figure shows calculated concentration levels of $mPM_{2.5}$. $PM_{2.5}$ can be transported over large distances, whereas SO_2 and NO_2 have a shorter atmospheric lifetime. This is the reason why the geographical pattern in Figure is very dissimilar to the previous figures. The pollution from ships is not visible, while it is a dominant feature that pollution from central Europe gradually declines over Denmark. The share of $mPM_{2.5}$ attributable to ship traffic is 18%, while in terms of *total* $PM_{2.5}$ the share from ships is considerably smaller. Relative to total $PM_{2.5}$ in Copenhagen, the share from ship traffic can be estimated to around 4-7%, depending on whether one considers the air in a highly trafficked street or in urban background (e.g. a park).

In the time up to 2020 a reduction of the general level of $mPM_{2.5}$ will take place, amounting to slightly more than 2 $\mu g/m^3$. This is mainly due to emission reductions for land-based sources.

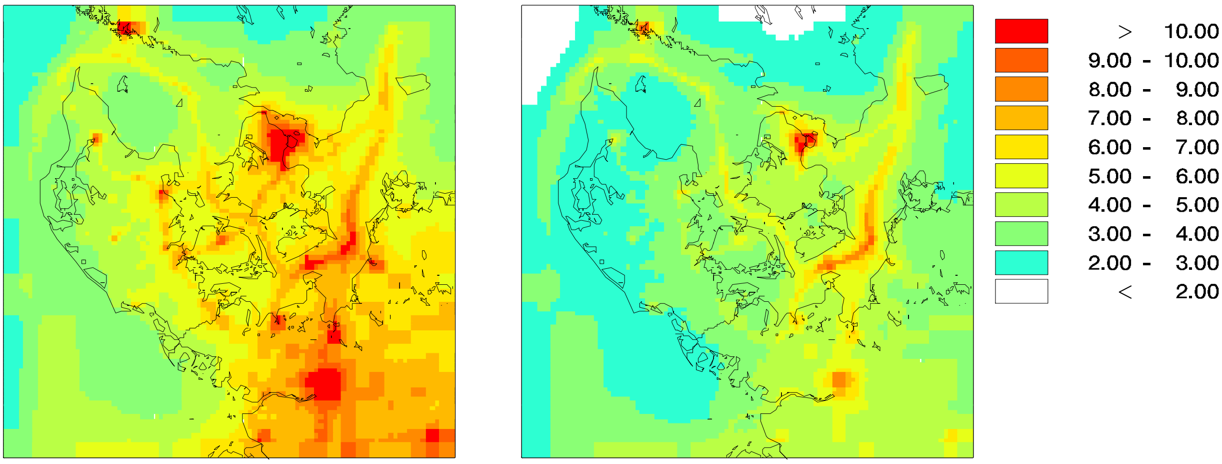

Figure 5. Calculated concentrations of NO_2 In $\mu g/m^3$. The left panel represents the situation in 2007, the right panel the situation in 2020. There is hardly any change in the emissions of NO_X from ship traffic between the two years, while there are large reductions for land-based sources.

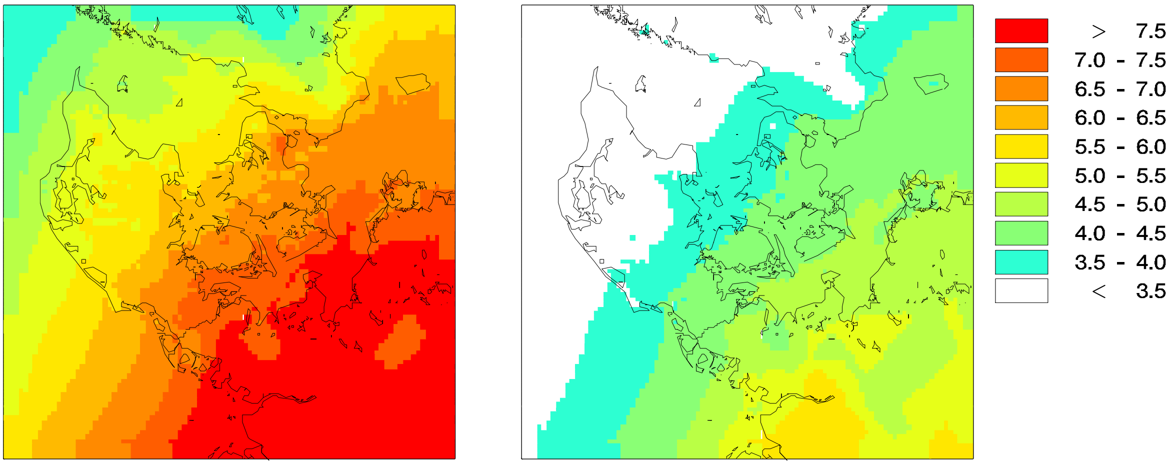

Figure 6. Calculated concentrations of $mPM_{2.5}$ in µg/m^3. $mPM_{2.5}$ is the fraction of particle mass that can be dealt with in the air pollution model. This is primary particles plus secondary inorganic particles. The left panel represents the situation in 2007, the right panel the situation in 2020.

CONCLUSIONS

One of the main results of the project is that a new, improved emission inventory for national and international ship emissions in Danish marine waters has been established. The inventory has a spatial resolution of 1 x 1 km. The inventory is based on AIS data. It is recommended that it becomes future practice to use AIS data for ship emissions.

Between 2007 and 2020 an emission reduction as large as 91% is envisaged in the marine waters around Denmark, in respect to sulphur dioxide from ship traffic – despite an increase of traffic. This is due to the IMO regulations. Within the same period a marginal increase is expected in total emissions of nitrogen oxides (NO_X) from ship traffic, namely by 2% from 2007 to 2020. The SO_2 concentration level as an average for Denmark will decrease considerably in the period up to 2020, so in 2020 it will reach a level of 0.3 µg/m^3, which corresponds to only 1.5% of the EU limit values.

The concentration of nitrogen dioxide (NO_2) in urban background air in Copenhagen is expected to be reduced from 16 to 9 µg/m^3 in the period up to 2020. The reduction is due to expected reductions in NO_X emissions from land-based sources. For ship traffic, however, the contribution is essentially unchanged, because increase in ship traffic and stricter emission requirements balance each other. For Denmark as a whole the NO_2 concentration level is considerably lower than in Copenhagen, and it will decrease from 5.5 to around 3.5 µg/m^3 from 2007 up to 2020. Presently, as an average for Denmark, 21% of NO_2 can be attributed to ship traffic, but the relative share from ships will increase in the years up to 2020 due to expected reductions for the land-based sources.

A considerable amount of fine particles ($PM_{2.5}$) is of unknown origin. Internationally, this is recognized as being *state-of-the-art*. The fraction that can be explained and modelled is here designated *$mPM_{2.5}$*. Around 1 µg/m^3 of the $mPM_{2.5}$ level can be attributed to ships, both in Copenhagen and generally in Denmark. Calculations point to a slight decrease by approximately 0.2 µg/m^3 during the period to 2020.

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