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Model calculations of the effects of present and future emissions of air pollutants from shipping in the Baltic Sea and the North Sea

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Abstract

Land-based emissions of air pollutants in Europe have steadily decreased over the past two decades, and this decrease is expected to continue. Within the same time span emissions from shipping have increased, although recently sulphur emissions, and subsequently particle emissions, have decreased in EU ports and in the Baltic Sea and the North Sea, defined as SECAs (Sulphur Emission Control Areas). The maximum allowed sulphur content in marine fuels in EU ports is now 0.1 %, as required by the European Union sulphur directive. In the SECAs the maximum fuel content of sulphur is currently 1 % (the global average is about 2.4 %). This will be reduced to 0.1 % from 2015, following the new IMO rules (International Maritime Organisation).

In order to assess the effects of ship emissions in and around the Baltic Sea and the North Sea, regional model calculations with the EMEP air pollution model have been made on a 1/4° longitude × 1/8° latitude resolution, using ship emissions in the Baltic Sea and the North Sea that are based on accurate ship positioning data. The effects on depositions and air pollution and the resulting number of years of life lost (YOLL) have been calculated by comparing model calculations with and without ship emissions in the two sea areas. The calculations have been made with emissions representative of 2009 and 2011, i.e. before and after the implementation of stricter controls on sulphur emissions from mid 2010. The calculations with present emissions show that per person, an additional 0.1–0.2 years of life lost is estimated in areas close to the major ship tracks with present emission levels. Comparisons of model calculations with emissions before and after the implementation of stricter emission control on sulphur show a general decrease in calculated particle concentration. At the same time, however, an increase in ship activity has resulted in higher emissions and subsequently air concentrations, in particular of NO_x, especially in and around several major ports.

Additional model calculations have been made with land based and ship emissions representative of year 2030. Following a decrease in emissions, air quality is expected to improve, and depositions to be reduced. Particles from shipping are expected to

decrease as a result of emission controls in the SECAs. Further controls of NO_x emissions from shipping are not decided, and calculations are presented with and without such controls.

1 Introduction

Maritime Transport is an important sector in Europe that enables trade and contacts between all the European nations. It ensures the security of supply of energy, food and commodities and provides the main vehicle for European imports and exports to the rest of the world. Compared to other modes of transport as trucks and air freight, shipping is far more energy efficient. Almost 90 % of the EU external freight trade is seaborne. Short sea shipping represents 40 % of intra-EU exchanges in terms of ton-kilometres. (http://ec.europa.eu/transport/modes/maritime/index_en.htm.)

During the last two decades emissions of air pollutants from other sources have been substantially reduced over Europe. Emissions of NO_x, CO and NMVOC (Non Methane Volatile Organic Carbon) have been reduced by about 50 %, and SO_x emissions have been reduced by about 75 % (Gauss et al., 2013). There are however large differences in the emission reductions between individual countries. As a result of the reductions in emissions, harmful effects of air pollution to the environment such as acidification and eutrophication, and health effects from particles and elevated ground level ozone events have been substantially reduced.

In the same time span modest regulations have been implemented for emissions from shipping. Both the North Sea and the Baltic Sea are defined by IMO (International Maritime Organisation) as SECAs (Sulphur Emission Control Areas). The most significant policy decisions affecting the ship emitted SO_x and PM are the revision IMO MARPOL Annex VI SO_x Emission Control Area requirements and the EU sulphur directive. The former restricts the marine fuel sulphur content in SECAs to 1.0 % as of July 2010 whereas the latter requires ships to use fuel with 0.1 % sulphur in harbour areas from January 2010. Further reductions to 0.1 % are decided in SECAs from January 2015.

Prior to July 2010 the maximum allowed sulphur content in SECAs was 1.5 %, as opposed to the global average of about 2.4 %, (IMO, 2010). Fuel sulphur reduction has a significant impact on emitted particulate matter (PM), which is commonly associated to detrimental effects on human health.

In sea areas outside the SECAs sulphur emissions have continued to increase. From 2020 the sulphur content in marine fuels outside SECAs should be reduced to 0.5 % globally, but depending on the outcome of a review to be concluded in 2018 as to the availability of the required fuel oil, this date could be deferred to 2025. However, EU sulphur directive obliges ship owners to use 0.5 % fuel in non-SECA EU sea areas starting from 1 January 2020 regardless of the outcome of the IMO review.

SO_x and PM emissions from North Sea and Baltic Sea shipping are decreasing, but it is noteworthy that there are some components of PM from shipping that are not affected by the fuel sulphur content. Thus the percentage decrease in PM emissions is not as large as for SO_x. The policy changes alone are not the only reason for the decrease of emitted pollutants. Also the recent decrease in overall economic activity have had an impact on ship emissions. The strong increase in the number of AIS transceivers installed in small vessels may have had some impact on estimated ship emissions.

For other species there has been a steady increase in the emissions in all sea areas in the last two decades. For NO_x IMO Tier I and Tier II limits apply globally, regardless of whether or not ECAs for NO_x will be established. The TIER I and TIER II requirements on new ships (or for major modifications on existing ships) where implemented in year 2000 and 2011 respectively. Tier I emission standards are up to 10 % stricter than for ships build before year 2000, and Tier II standards are up to 15 % stricter than Tier I, resulting in moderate reductions in NO_x emissions. The Tier standards are described in IMO (2007). This will happen even if the Baltic Sea, North Sea, and English channel would not be designated as NO_x Emission Control Area. The efficiency increase, and Tier II NO_x limit together outweigh the moderate traffic growth (Kalli et al., 2013).

Defining a NECA (Nitrogen Emission Control Area) for both the Baltic Sea and the North Sea will help to reduce the emissions of NO_x by as much as 80 % on new ships.

The Baltic Sea and the North Sea countries have already taken the first steps towards NECA but the decision regarding the formal submission of NECA IMO applications for the two sea areas will ultimately be political. Recent information (66th IMO MEPC meeting, March 2014) from IMO indicates that the entry date for NECAs, if implemented, will be left to the applicants to decide. The year 2016 is no longer strictly defined as an entry date, but some flexibility is allowed. The lower NO_x-emitting new engines installed on new ships will gradually replace old engines, but because of the long lifetime of ships, complete fleet renewal with Tier III compliant ships is not expected until about 30 years after the NECA entry date (Kalli et al., 2013).

Currently NECAs exist only along the North American coastline. The North American NECA was adopted in 2010, entered into force in 2011, and the implementation began in 2012. The implementation of the Caribbean NECA (Costa Rica and US Virgin Islands) began in 1 January 2014.

Several previous model calculations of the effects of ship emissions have been made both on global as well as regional scales. On a global scale both the climate effects and air pollution have been studied (Corbett et al., 1999, 2007; Endresen et al., 2003; Eyring et al., 2007; Fuglestvedt et al., 2010). In addition several regional studies have addressed the regional impacts of ship emissions in Europe (Jonson et al., 2000, 2009; Andersson et al., 2007). Tuovinen et al. (2013) looked at the effect of increased shipping in the Arctic sea-lanes on nitrogen deposition and ozone uptake by vegetation. The Evaluation of the effects of ship emissions in the North Sea (Hammingh et al., 2012) was an environmental impact assessment commissioned by the coastal countries around the North Sea in support of the decision making process concerning the possible application to the IMO to designate the North Sea as a NECA. The regional studies point to ship emissions as major source of air pollution in Europe, in particular in coastal, often densely populated, areas.

The novelty of this study is the use of high resolution emission data, based on precise positioning data, for 2009 and 2011, i.e. before and after the revision of the EU sulphur directive and the IMO regulation of 2010. In addition a future scenario has been investigated to look at changes to be expected with and without further regulation. The following section describes the experimental setup, while Sect. 3 describes results for the present-day situation as well as the future.

2 EMEP model runs – model setup

When calculating the effects of present and future emissions of air pollutants we have used the EMEP chemistry transport model (Simpson et al., 2012), version rv4beta20, hereafter referred to as the EMEP model. The EMEP model can be run on a wide range of scales, and for global to local applications. In this study the model is run on a regional European domain with an approximate 14 km ($1/4^\circ$ longitude × $1/8^\circ$ latitude) resolution. In the vertical, the model extends from ground level to 100 hPa (tropopause or higher). Lateral boundary concentrations are provided by a combination of measurements and global model results. For ozone the lateral boundary concentrations are based on ozone climatology scaled by measurements from the clean sector, unaffected by European emissions, at Mace Head, Ireland. A detailed description of the model can be found in Simpson et al. (2012) and references therein. The meteorological data for 2010 are from ECMWF (European Centre for Medium-Range Weather Forecasts). The EMEP model is available as open source code. The latest version can be obtained from https://wiki.met.no/emep/page1/unimodopensource2011. The EMEP model is regularly evaluated against measurements in the EMEP annual reports, see http://emep.int/mscw/mscw_publications.html. Model calculations with the EMEP model are included in several recent publications comparing model results with measurements and calculations with other models (Jonson et al., 2010; Colette et al., 2011, 2012; Angelbratt et al., 2011).

2.1 Present and future emissions

With the exception of ship emissions in the Baltic Sea and the North Sea the emissions of air pollutants are based on the EC4MACS Interim Assessment of “Greenhouse gases and air pollutants in the European Union: baseline projections up to 2030” (Amann et al., 2012). Here we are using year 2010 emissions to represent present conditions, and year 2030 for future projections. The gridding of the emission data was done in the EU FP7 project TRANSPHORM http://www.transphorm.eu. Ship emissions in the Baltic Sea and the North Sea are described below.

2.1.1 Ship emissions in the Baltic Sea and the North Sea

The emissions for the Baltic Sea and the North Sea areas were obtained with the Ship Traffic Emission Assessment Model (STEAM) (Jalkanen et al., 2009, 2012). In this model actual ship movements of individual ships collected from the national Automatic Identification System (AIS) base station networks are used. Combined with the characteristics of each ship and engine type, the emissions from each individual ship could then be calculated. The emission modelling is based on over 550 (2009) and 600 (2011) million automatic updates of vessel positions.

The model requires as input a detailed technical specification of all fuel consuming systems onboard and other relevant technical details for all ships considered. Such technical specifications were therefore collected from various sources and archived for over 45 000 ships. The data from IHS Fairplay (2012) constituted the most significant source. The STEAM model is then used to combine the AIS-based information with the detailed technical knowledge of the individual ships. The model then evaluates instantaneous fuel consumption and emissions of NO_x, SO_x, CO, CO_2 and PM.

The temporal dimension of emissions is retained, and daily updates of ship emissions were provided for air quality studies. The emissions were allocated to a geographical grid of approximately $0.03^\circ \times 0.06^\circ$ longitude latitude. Emissions are calculated for the years 2009 and 2011 to assess the impacts of already agreed policy options (SECA, EU sulphur directive).

Daily (or finer) emissions reflect ship operational differences caused by ice conditions, meteorological conditions etc. which will differ between years. The traffic pattern changes caused by the meteorological phenomena were included, but the impact of these to vessel power requirement to maintain a specific speed was not included in this study. This way, impact of weather as a source of additional fuel consumption was left out. In this study we have compared the effects of emissions from 2009 and 2011, in addition to future projections. As none of these years coincide with the meteorological year (2010) used for the model runs, we have aggregated the emissions to monthly totals so that day-to-day operational fluctuations will cancel out. The total emissions in both sea areas are listed in Table 1 for the years 2009 and 2011, along with the projections for 2030. The geographical distribution of the emissions is illustrated by the SO_x emissions for year 2009 in Fig. 1. High emissions are in particular seen along the main shipping routes in the North Sea (and in particular in the English Channel), and also in the Baltic Sea. Note that sulphur emissions are reduced significantly from 2009 to 2011 as a result of stricter regulations. Emissions of other species are stable or increase slightly. Emissions of organic and elemental carbon and ash also increase as they are assumed to be unaffected by the fuel type (Johansson et al., 2013). The Baltic Sea and North Sea ship emissions for 2030 are based on projections from Kalli et al. (2013) and are listed in Table 1. The emissions are calculated by scaling the gridded 2009 emissions by the expected overall changes in emissions from 2009 to 2030 for the two sea areas as calculated by Kalli et al. (2013), taking into account changes in regulations, fleet renewal rates (in particular affecting NO_x emissions, as Tier II are replacing Tier I) and expected changes in traffic volumes and ship efficiency.

Kalli et al. (2013) report bulk emissions for particles, including sulphate, OC, EC and ash. Here we assume that sulphate emissions between 2009 and 2030 will be reduced with the same rate as for SO_2. As a result the corresponding percentage reductions in OC, EC and ash emissions are smaller than the reductions in total particle emissions estimated by Kalli et al. (2013) in order to match their estimate of total particle emissions in 2030.

It is uncertain when, or if, the two areas will be designated as NECAs. If so, ships built after NECA designation date will be Tier III compliant, gradually phasing out the Tier I and Tier II ships. As this is still uncertain, NO_x emissions for year 2030 are listed with and without a NECA, assuming entry date of 2016. Even if it is approved, the implementation of the NECA may be delayed, as agreed in the 66th meeting of the IMO MEPC. As the NECA applies to new ships only, this delay will result in higher 2030 NO_x emissions in the NECA than indicated in Table 1. A complete fleet renewal can be expected about 30 years from the NECA entry date.

3 Model results

In order to calculate the effects of ship emissions in the Baltic Sea and the North Sea, several model runs have been made with the EMEP model. A first set of model runs has been made comparing model runs excluding the 2009 ship emissions in the North Sea and the Baltic Sea to a reference model run that included all emissions.

A second set of model runs has been made to look at the effects of the changes in ship emissions from 2009 to 2011. The main motivation for this is to see the effects of the decrease in the maximum sulphur content in marine fuels from 1.5 to 1 % effective from 1 July 2010.

A third set of model runs has been made to assess the impact of projected future (2030) emissions from shipping in the Baltic Sea and the North Sea. Calculations for 2030 are made with and without the effects of future NECA regulations.

3.1 Present situation

Figure 2 shows the annually averaged concentrations of PM_{10}, $PM_{2.5}$ and daily maximum ozone. Also shown is the total deposition (wet and dry) of nitrogen from the reference model run.

Concentrations of PM largely reflect the emissions, with high PM levels throughout much of Europe. Of particular interest here are the high PM levels in the coastal regions around the North Sea and the English channel and (to a lesser extent) the Baltic Sea. The EU annual limit values of $40\,\mu g\,m^{-3}$ for PM_{10} and $25\,\mu g\,m^{-3}$ for $PM_{2.5}$ are not exceeded in the calculations. However, the WHO guidelines of 20 and $10\,\mu g\,m^{-3}$ for annually averaged PM_{10} and $PM_{2.5}$, respectively, are exceeded in limited parts of the model domain, including also areas/cities along the coast of the Baltic Sea and the North Seas.

In Figure 3 the YOLL (Years Of Lives Lost), calculated based on the 2010 $PM_{2.5}$ levels, are shown. YOLL is the average statistical loss in life expectancy of the population above the age of 30 due to exposure to $PM_{2.5}$ concentrations. The calculations of YOLL are based on the RAINS methodology (Amann et al., 2004). A risk factor of 6 % change in mortality hazards per $10\,\mu g\,m^{-3}$ annual average change in $PM_{2.5}$ as recommended by WHO (WMO, 2006) is assumed. The Norwegian Meteorological Institute applied these assumptions in the calculations made for the EuroDelta project (http://aqm.jrc.ec.europa.eu/eurodelta/). Of particular relevance to this paper are the regions along the southern coastlines of the two sea areas with calculated YOLL per person of 0.2 years or more. The accumulated YOLL per country (in thousands), as listed in Table 2, is the total number of statistical life years lost over the lifetime of the population above the age of 30 for selected countries adjacent to the two sea areas. As an example we calculate about 18 million YOLL for Poland, which over a population of about 40 million means roughly half a year of reduced life expectancy per person on average. As the Baltic Sea and the North Sea ship emissions are representative of 2009 rather than 2010, the 2010 YOLL is labelled as 2009 in the table.

Modelled concentrations of daily maximum ozone (Fig. 2c) in 2010 generally increase from north to south. In the high NO_x emitting areas around the North Sea ozone levels are particularly low as a result of NO_x titration. Figure 3b shows the annually accumulated SOMO35. SOMO35 is an indicator for health impacts for ozone recommended by WHO and is defined as the yearly sum of the daily maximum of 8 h running average ozone over 35 ppb. As for ozone, high SOMO35 levels are in particular calculated in and around the Mediterranean countries. SOMO35 levels are relatively low around the Baltic Sea and the North Sea.

Figure 2d shows the calculated deposition of total nitrogen. Large depositions of nitrogen are calculated for the North Sea region where there are both major land-based sources and ship emissions. The atmospheric deposition of nitrogen to the North Sea has remained static at about 300 $\mathrm{Gg\,yr^{-1}}$. The relative portions of nitrogen input for riverine, atmospheric and direct inputs are about 10 : 3 : 1 (OSPAR Commission, 2000). For the Baltic Sea the atmospheric deposition of nitrogen contributes about one quarter to the total nitrogen load. It originates from emissions both inside and outside the Baltic catchment area, with shipping being the most important, and continuously increasing, source (Pawlak et al., 2009). The total depositions of oxidised nitrogen and sulphur calculated with 2010 land-based emissions are listed for the Baltic Sea and the North Sea and for a selection of countries close to these sea areas in Tables 3 and 4. The tabulated depositions for 2010 have been calculated with the ship emissions for 2009 as listed in Table 1.

3.2 Effects of North Sea and Baltic Sea 2009 ship emissions

In addition to the reference model run, model perturbation runs have been made excluding all ship emissions from the Baltic Sea and the North Sea. Figure 4 shows the contributions from Baltic Sea and North Sea ship emissions to $PM_{2.5}$ concentrations and depositions of nitrogen in the region. The contributions are shown in percent and as concentrations of $PM_{2.5}$ and deposited mass of nitrogen. The calculated effects on PM_{10} (not shown) are very similar to the effects on $PM_{2.5}$.

As shown in Fig. 4a and b, a significant part of the calculated $PM_{2.5}$ in land areas close to the Baltic Sea and the North Sea can be attributed to shipping. As a result the calculated area with $PM_{2.5}$ concentrations exceeding the maximum $PM_{2.5}$ (see Fig. 2b) of $10\,\mu g\,m^{-3}$ recommended by WHO is substantially lower in Belgium, the Netherlands and Luxembourg when calculated without ship emissions in the two sea areas. Consequently the calculated YOLL is also reduced when ship emissions are excluded (Fig. 5a) and Table 2. Based on our model results, shipping was responsible for about 10 % (range: 6–12 %) of calculated YOLL in the small and medium sized countries bordering the North Sea. In general contributions to countries around the Baltic sea are smaller than around the North Sea because ship emissions are lower here. Where the ship tracks are close to the shore there are, however, marked contributions also around the Baltic Sea. It should also be noted that the effects of elevated emissions in ports are poorly resolved in the dispersion calculations, and the effects there are likely to be higher than shown in this study.

The effects of total depositions of nitrogen (wet and dry) from ship emissions are shown both as contributions in $mg\,(N)\,m^{-2}$ (Fig. 4c), and as a percentage of total depositions (Fig. 4d). Depositions of nitrogen from ships are high in and around the sea areas, often peaking along the shorelines as a result of high precipitation rates here. The percentage contributions differ from the contributions in $mg\,(N)\,m^{-2}$ because relatively high contributions, around 10 % or more, are seen over widespread areas in the Nordic countries and the Eastern Atlantic as a larger fraction of the nitrogen depositions here originates from long-range transport rather than local emissions. The calculated contributions to depositions of oxidised nitrogen and oxidised sulphur from ship emissions in the Baltic Sea and the North Seas to the two sea areas, and to selected countries close to these sea areas, are listed in Tables 3 and 4. The contribution is significant for all the countries listed in the tables, and in particular for countries where a large portion of the landmasses are close to the sea as is the case for Denmark, the Netherlands and Belgium. Larger countries, as Poland and Germany, are more affected by land based emissions as a large portion of the area lies far from the shore. Note that, whereas the percentage depositions of nitrogen in Fig. 4d include also reduced nitrogen, the numbers in Table 3 include oxidised nitrogen only, hence the larger relative contributions from shipping in the table.

Figure 5b shows the effects of emissions from the Baltic Sea and North Sea shipping on SOMO35. In general, emissions from shipping result in a slight increase in calculated SOMO35, but in and around the major shipping tracks calculated SOMO35 is reduced as a result of NO_x titration following the NO_x increase due to ships.

3.3 Calculated effects of changes in ship emissions from 2009 to 2011

Since July 2010 the maximum allowed content of sulphur in fuels has been 1 % in the Baltic Sea and the North Sea. In order to see the effects of emission changes, additional model calculations have been made with estimated ship emissions for 2011. As seen in Fig. 6a calculated concentrations of sulphate are reduced. As a result of the reductions in sulphur emissions concentrations of SIA (Secondary Inorganic Aerosols) (Fig. 6b) and $PM_{2.5}$ (Fig. 6c) in general decrease. There is however a local increase in and around German North Sea ports, reflecting an increase in particular in activity and emissions here as a result of a recovery from the recession in 2008/09. There is also a large reported increase in small vessel activity, but this should not affect SO_x since most small vessels use low sulphur fuel. Figure 6d shows the resulting differences in calculated YOLL, reflecting the changes in $PM_{2.5.}$ The calculated contributions from shipping to YOLL accumulated for selected countries near the two sea areas are also listed in Table 2. Following the implementation of the lower sulphur limits in the SECAs and in EU ports, the share of YOLL attributed to shipping has fallen in the surrounding countries (Table 2). On a country basis, the largest impacts of the sulphur reductions are calculated for Denmark, Norway and Sweden, with reduction in the share from shipping of 2–3 %.

In Tables 3 and 4 the contributions from the two sea areas calculated with 2009 and 2011 emissions to the depositions of oxidised sulphur and oxidised nitrogen are listed. Compared to depositions from shipping calculated with 2009 emissions there are marked decreases in the share of calculated sulphur depositions in both sea areas and in most countries listed as a result of the decrease in sulphur content from 1.5 to 1 % in marine fuels. The sulphur depositions decrease despite a general increase in ship activity.

As there has been only small changes in the NO_x emissions between 2009 and 2011, the contributions from shipping to the deposition of nitrogen change very little. The changes in depositions in Table 3 partly reflect regional changes in emissions.

3.4 Calculated effects of Baltic Sea and North Sea ship emissions in 2030

As explained in Sect. 2.1.1 emissions from shipping in the Baltic Sea and the North Sea will change, with substantial emission reductions in particular for sulphur, and partially also for particles. Emissions of NO_x may remain at approximately the same levels, but if the two sea areas are accepted as NECAs, NO_x emissions will be markedly reduced. Emissions of CO are expected to increase slightly. Modelled concentrations of $PM_{2.5}$, depositions of nitrogen, SOMO35 and YOLL for 2030 are shown in Fig. 7, and should be compared to the levels calculated for 2010 (Fig. 2). The calculations of YOLL has been made with the same population density distributions as in the calculations for 2010, and does not take into account changes in population density and the projected ageing of the European population. Using the same population density has the advantage that the calculations for 2030 and 2010 are directly comparable. YOLL and depositions of oxidised sulphur and oxidised nitrogen calculated for year 2030 are also shown for selected countries in the Tables 2, 3 and 4 respectively. The calculations show that the expected changes in emissions in Europe from 2010 to 2030 will have positive effects, with decreases in pollutant concentrations and depositions and subsequent environmental benefits and reductions in health indicators as SOMO35 and YOLL. Calculated depositions of nitrogen and sulphur are reduced by almost 40 % between 2010 and 2030 for the countries listed in Tables 3 and 4. For the same set of countries YOLL is reduced by an average of about 25 % (Table 2), but with a considerable spread, as there are also large natural contributions to $PM_{2.5}$.

Figure 8 shows the effects of ship emissions from the Baltic Sea and the North Sea in 2030 on $PM_{2.5}$ concentrations and nitrogen depositions. Compared to the contributions in 2010 (Fig. 4) the effects of ship emissions on $PM_{2.5}$ levels are expected to decrease substantially because of the sulphur reduction requirements which have already been agreed by the IMO. Furthermore depositions of sulphur to the sea areas and to the neighbouring countries will become very small (Table 4).

If the Baltic Sea and the North Sea are not accepted as NECAs, emissions of NO_x from the Baltic Sea and the North Sea are likely to remain close to present levels. As a result, depositions of nitrogen in 2030, as shown in Fig. 8c, will be virtually unchanged from their present (2010) levels (Fig. 4c.) As the land based NO_x emissions are projected to decrease substantially over the same time span, the percentage contribution from ship emissions will increase, as can be seen by comparing Fig. 8d to Fig. 4d. This is also illustrated by comparing the shares from shipping in 2010 and 2030 in Table 3.

If the two sea areas are accepted as NECAs from 2016, a substantial part of the fleet will be replaced by ships with TIER III technology by 2030. As a result, marked reductions in NO_x emissions will be achieved by 2030 (see Table 1). Postponing the requirements for Tier III to 2021 will delay the reductions in NO_x emissions. Tables 2 and 3 list the contributions to accumulated YOLL and depositions of oxidised nitrogen for selected countries from shipping in the two sea areas assuming that the NECAs are implemented from year 2016. The resulting fractional reductions in nitrogen depositions and YOLL are roughly in the same range as the emission reductions. With the low sulphur and PM emissions from shipping after the implementation of the SECAs, NO_x will be the dominant source of PM from shipping.

4 Conclusions

As a result of recently implemented measures, emissions of sulphur from shipping in the Baltic Sea and the North Sea have been reduced. Our model calculations show that these emission reductions already have had positive effects on air pollution and deposition. From 2015 the regulations will be further strengthened, and, provided the ships comply to the rules, significant further improvements in air quality as well as deposition of (acidifying) sulphur will result for land areas bordering the two sea areas. As the regulations are primarily linked to fuel use, these improvements will have immediate effects. So far there are no plans for additional European sea areas being defined as SECA in the foreseaable future.

The transition to TIER II on new ships will help stabilise NO_x emissions from shipping. Given a moderate increase in ship activity, NO_x emissions in the Baltic Sea and the North Sea will be virtually unchanged from 2010 to 2030, if NECAs are not implemented. The main contribution to $PM_{2.5}$ from shipping will then be from NO_x emissions. If, however, the two sea areas are accepted as NECAs, NO_x emissions in 2030 will be significantly lower, thereby reducing the burden on health and the environment from shipping.

There are several risk factors that can affect the foreseen improvements in the effects of ship emissions. The implementation of SECAs will most likely result in a substantial increase in the price of marine fuels (or alternatively, other approved technological methods with comparable reductions in sulphur emissions). The use of low sulphur fuel (0.1 %) or the use of alternative fuels or scrubbers are expected to increase fuel costs by 30–80 % compared to marine distillates with 1.5 % sulphur content. The fuel cost increase depends strongly on the future price development of marine fuels and the SO_x scrubber usage. With moderate (50 %) fuel price premium and wide adoption (all vessels over 4000 ton annual fuel consumption in SECAs) of scrubbers, the fuel cost increase can be as low as 30 %. However, in case of high price (100 %) premium for the low sulphur fuel and no exhaust scrubber installations, the cost increase can be as high as 80 % when compared to 2009 (1.5 % S) situation (Johansson et al., 2013). Notteboom et al. (2010) has estimated an increase of 25 % in freight rates, and for a number of routes the cost increase may reach 40 %. Such an increase in freight rates could result in a modal shift from sea transport to road transport (Notteboom et al., 2010). For several intra-Europe shipping routes the cost of shipping is already comparable

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to the cost of road transport. Also Johansson et al. (2013) note that further increases in the cost of shipping could result in a modal shift from ships to roads, potentially undermining the expected environmental and health related benefits associated with reduced marine emissions. The large expected increase in the cost in marine fuels will make it tempting to use high sulphur fuels also in the SECA areas. A system for compliance monitoring should therefore be put in place to ensure level competition and the obeyance of rules protecting human health and the environment.

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Table 1. Emissions from shipping in the Baltic (BS) and North (NS) Seas in Gg yr^{-1}. SO_x emissions as SO_2 and NO_x emissions as NO_2.

	SO_x		NO_x		SO4		EC		OC		Ash	
	BS	NS	BS	NS	BS	NS	BS	NS	BS	NS	BS	NS
2009	90	230	314	662	7.7	19.7	2.3	3.8	5.5	9.6	1.6	2.8
2011	80	155	337	677	6.8	13.2	2.2	4.2	5.6	10.8	1.6	3.1
2030 no NECA	8	21	293	642	0.7	1.8	1.5	2.5	3.7	6.4	1.1	1.9
2030 NECA	8	21	217	457	0.7	1.8	1.5	2.5	3.7	6.4	1.1	1.9

Table 2. The first row gives the total number of Years Of Life Lost (YOLL) summed up per country calculated with 2010 emissions (ship emissions in the Baltic Sea and the North Sea for 2009). Also listed are the percentage reductions from 2010 to 2030 under current regulation (second row), and the share from shipping calculated with ship emissions for 2009 and 2011 relative to the 2010 land based emissions (under "From Ships"). The percentage contribution from shipping in 2030 is listed both with and without a NECA implemented in the two sea areas (last two rows). Reductions in YOLL from shipping are mainly caused by stricter controls of ship emissions of SO_x.

Country[a]	BE	NL	DE	GB	DK	NO	SE	FI	PL	LV	LT	EE
YOLL[b] in 2010	4061	4665	26 071	11 716	660	657	928	629	18 085	562	986	169
Change, 2010 to 2030	−26 %	−31 %	−31 %	−31 %	−32 %	−12 %	−22 %	−16 %	−28 %	22 %	−20 %	−17 %
From Ships												
in 2009	6.5 %	9.7 %	3.8 %	6.3 %	11.7 %	6.5 %	10.0 %	4.9 %	1.6 %	3.1 %	2.9 %	5.0 %
in 2011	6.2 %	8.7 %	3.8 %	5.5 %	9.5 %	4.1 %	8.0 %	4.2 %	1.4 %	2.7 %	2.7 %	4.4 %
In 2030 No NECA	5.5 %	7.9 %	3.6 %	6.0 %	9.2 %	3.2 %	6.7 %	3.0 %	1.4 %	2.4 %	2.3 %	3.3 %
In 2030 with NECA	4.4 %	6.5 %	2.7 %	4.8 %	7.5 %	2.8 %	5.5 %	2.5 %	1.1 %	1.9 %	1.7 %	2.7 %

[a] BE: Belgium, NL Netherlands, DE: Germany, GB: Great Britain, DK: Denmark, NO: Norway, SE: Sweden, FI: Finland, PL: Poland, LV: Latvia, LT: Lithuania, EE: Estonia.

[b] YOLL in thousands

Table 3. Depositions of oxidized nitrogen with units 100 Mg of N calculated with 2010 land based emissions and ship emissions in the Baltic Sea and the North Sea for 2009. The change in depositions between 2010 (2009 ship emissions) and 2030 is given in percent. The percentage contribitions from ships in 2009 and 2011 are calculated relative to the 2010 land based emissions. The share from shipping in 2030 are listed both with and without a NECA implemented in the two sea areas.

Country[a]	BAS	NOS	BE	NL	DE	GB	DK	NO	SE	FI	PL	LV	LT	EE
Dep. N (100 Mg), 2010	1153	1919	168	194	2028	627	184	403	833	614	1604	237	261	156
Change, 2010 to 2030	−38 %	−43 %	−45 %	−43 %	−50 %	−47 %	−42 %	−37 %	−37 %	−33 %	−42 %	−31 %	−33 %	−29 %
From ships														
in 2009	17 %	18 %	11 %	16 %	8 %	11 %	21 %	20 %	20 %	14 %	6 %	10 %	8 %	13 %
in 2011	17 %	17 %	12 %	16 %	8 %	11 %	20 %	17 %	19 %	15 %	6 %	11 %	8 %	14 %
in 2030 no NECA	25 %	29 %	22 %	29 %	15 %	21 %	35 %	29 %	29 %	19 %	10 %	13 %	11 %	17 %
2030 with NECA	19 %	24 %	17 %	24 %	11 %	16 %	28 %	23 %	23 %	14 %	7 %	10 %	8 %	12 %

[a] BAS: Baltic Sea, NOS: North Sea, BE: Belgium, NL Netherlands, DE: Germany, GB: Great Britain, DK: Denmark, NO: Norway, SE: Sweden, FI: Finland, PL: Poland, LV: Latvia, LT: Lithuania, EE: Estonia.

Table 4. Depositions of sulphur with units 100 Mg of S calculated with 2010 land based emissions and ship emissions in the Baltic Sea and the North Sea for 2009. The change in depositions between 2010 (2009 ship emissions) and 2030 is given in percent. The percentage contribitions from ships in 2009 and 2011 are calculated with 2010 land based emissions. Also listed are the percentage contributions from ship emissions in the two sea areas in 2030.

Country[a]	BAS	NOS	BE	NL	DE	GB	DK	NO	SE	FI	PL	LV	LT	EE
Dep. S (100 Mg), 2010	1314	2189	192	198	1725	766	143	394	653	540	2393	222	263	143
Change, 2010 to 2030	−44 %	−53 %	−29 %	−37 %	35 %	−48 %	−47 %	−25 %	−33 %	−27 %	−41 %	−35 %	−36 %	−33 %
From ships														
in 2009	21 %	26 %	8 %	17 %	5 %	7 %	25 %	12 %	15 %	8 %	1 %	4 %	3 %	8 %
in 2011	17 %	20 %	7 %	14 %	5 %	5 %	18 %	7 %	10 %	6 %	1 %	3 %	2 %	6 %
in 2030	3.4 %	4.7 %	0.9 %	2.3 %	0.7 %	1.2 %	4.2 %	1.5 %	2.1 %	1.0 %	0.2 %	0.7 %	0.5 %	1.1 %

[a] BAS: Baltic Sea, NOS: North Sea, BE: Belgium, NL Netherlands, DE: Germany, GB: Great Britain, DK: Denmark, NO: Norway, SE: Sweden, FI: Finland, PL: Poland, LV: Latvia, LT: Lithuania, EE: Estonia.

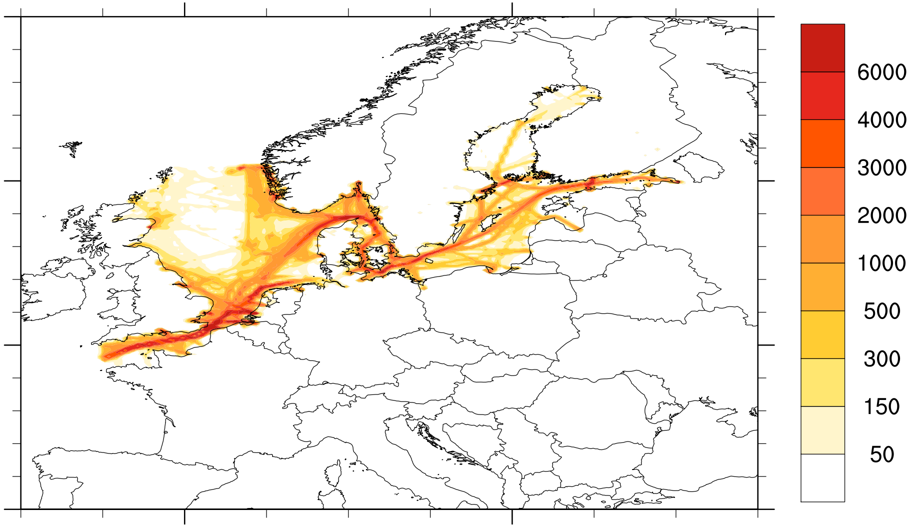
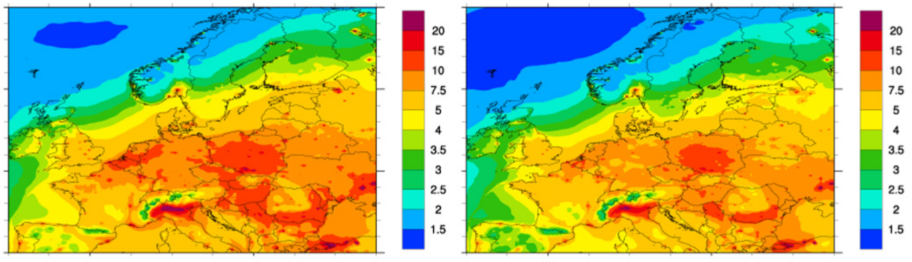
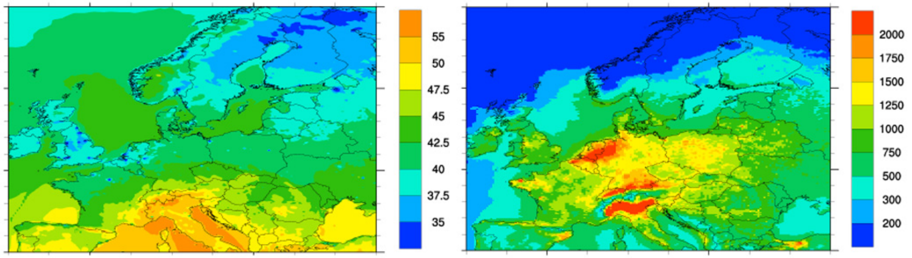


Figure 1. Ship emissions of SO_x ($mg\,m^{-2}$) in the Baltic Sea and the North Sea in 2009.

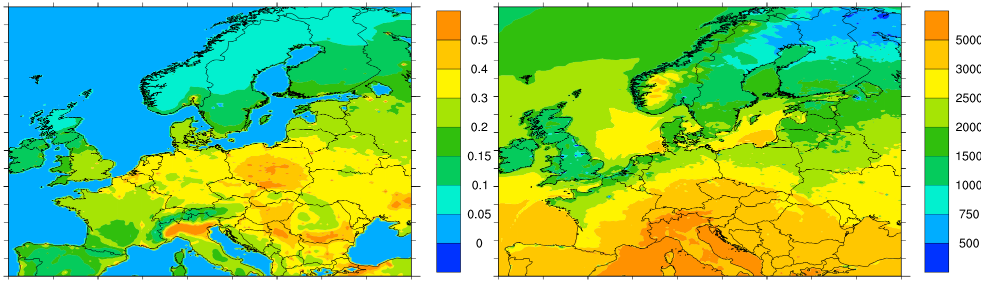


a) PM10 in μgm^{-3} **b)** PM2.5 in μgm^{-3}



c) Daily max. ozone in ppb_v **d)** Total Dep. of N in mgm^{-2}

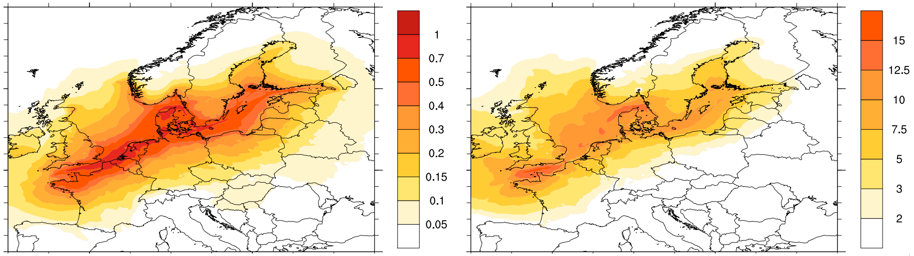
Figure 2. Modelled annual-mean concentrations of PM_{10} **(a)**, $PM_{2.5}$ **(b)**, daily maximum ozone **(d)**, and the total deposition of nitrogen **(d)**.



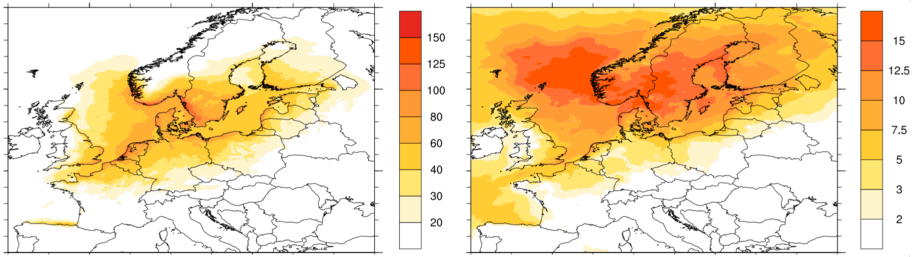
a) 2010 (2009 Ships) YOLL

b) SOMO35 in ppb days

Figure 3. Years Of Life Lost (YOLL) per person **(a)** and SOMO35 **(b)** as calculated from the reference model calculation.

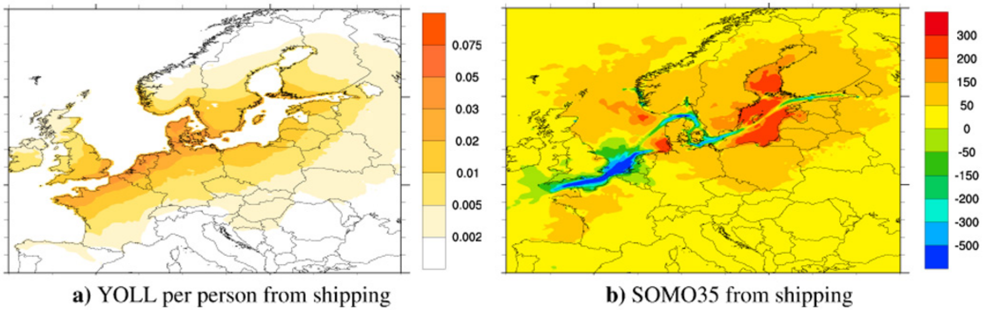


a) PM2.5 (μgm^{-3}) from shipping **b)** PM2.5 from shipping in percent



c) Total Dep. of N (mgm^{-2}) from shipping **d)** Total Dep. of N from shipping in percent

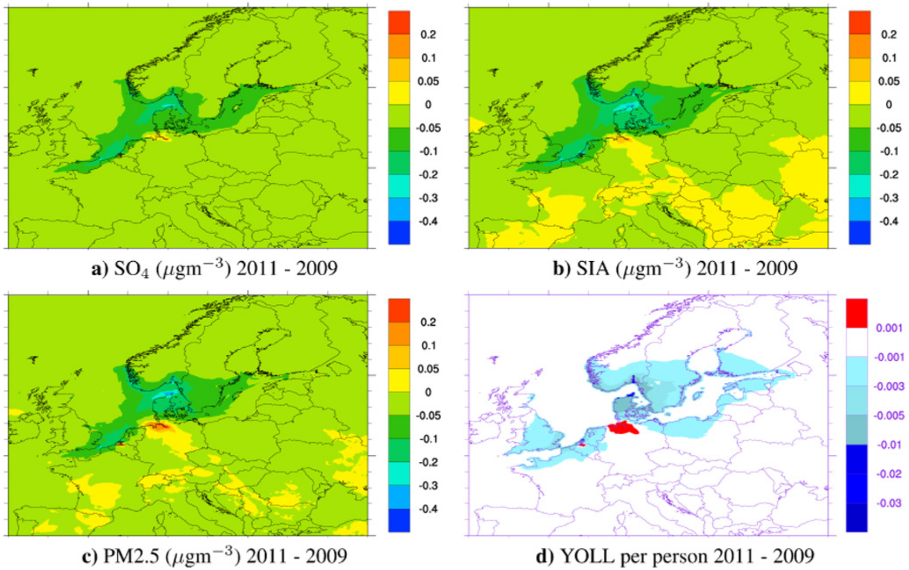
Figure 4. Contributions from year 2009 ship emissions in the Baltic Sea and the North Sea to $PM_{2.5}$ concentrations **(a)** and in percent **(b)**. Contributions to the total deposition of nitrogen in $mg\,m^{-2}$ **(c)** and in percent **(d)**.



a) YOLL per person from shipping

b) SOMO35 from shipping

Figure 5. YOLL per person (left) and SOMO35 (right) from year 2009 shipping in the Baltic Sea and the North Sea. Contributions from ship emissions are calculated as reference run minus the model run that excludes ship emissions.



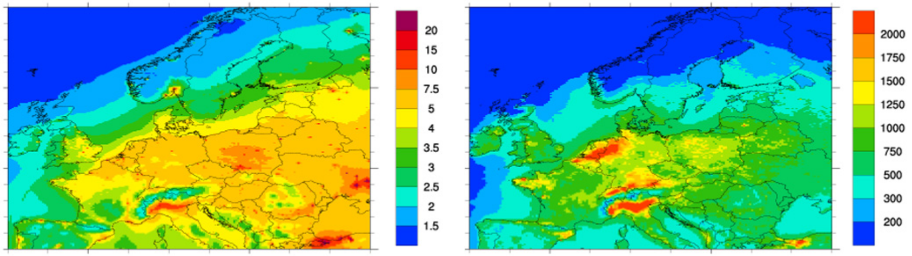
a) SO_4 (μgm^{-3}) 2011 - 2009

b) SIA (μgm^{-3}) 2011 - 2009

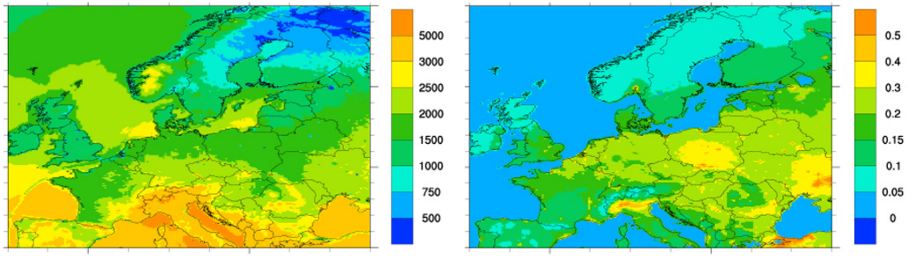
c) PM2.5 (μgm^{-3}) 2011 - 2009

d) YOLL per person 2011 - 2009

Figure 6. Model calculated difference, 2011 vs. 2009 ship emissions.

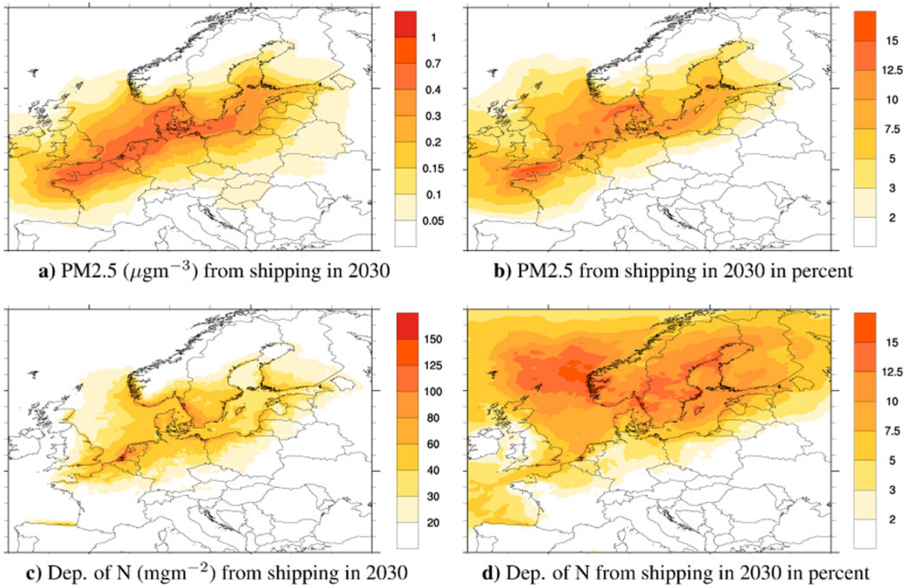


a) PM2.5 in μgm^{-3} b) Total Dep. of N in mgm^{-2}



c) SOMO23 in 2030 d) YOLLpp in 2030

Figure 7. Year 2030 model calculated annually averaged, **(a)**: $PM_{2.5}$ concentrations, **(b)**: deposition of nitrogen, **(c)**: SOMO35 and **(d)**: YOLLpp.



a) PM2.5 (μgm^{-3}) from shipping in 2030

b) PM2.5 from shipping in 2030 in percent

c) Dep. of N (mgm^{-2}) from shipping in 2030

d) Dep. of N from shipping in 2030 in percent

Figure 8. Contributions from ship emissions in the Baltic Sea and the North Sea in year 2030 to $PM_{2.5}$ concentrations **(a)** and in percent **(b)**. Contributions to the total deposition of nitrogen in $mg\,m^{-2}$ **(c)** and in percent **(d)**.