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Interactive comment on "Effects of strengthening the Baltic Sea ECA regulations" *by* Jan Eiof Jonson et al.

Jan Eiof Jonson et al.

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We, the authors, thank the reviewers for constructive comments and suggestions

Below we list the comments from reviewer 1 followed by our reply reference to any changes made in the paper.

General comments

1) However, the paper falls short in precisely addressing the effects of the ECA regulations. The paper refers in many places to the use of the presented model results in upcoming studies that are in preparation. To improve the presentation, I recommend to better emphasize the objectives of this study and the value of the model calculations in itself by deriving recommendations for emission control policies.

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Answer: We have added new material to the conclusions reflecting these comments.

Presently there are no further emission mitigation regulations targeted for the Baltic Sea and the North Sea apart from the NECA regulation entering into force in 2021. This regulation is expected to result in gradual reductions in PM2.5 concentrations and in depositions of nitrogen from BAS shipping, as shown in our calculations for future versus present conditions. The relative reductions are largely comparable to the decrease from other anthropogenic sources in the region. However, according to IMO (2018) the target set by IMO is "to reduce CO2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008; and GHG emissions from international shipping to peak and decline as soon as possible and to reduce the total annual GHG emissions by at least 50 % by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the vision as a point on a pathway of CO2 emissions reduction consistent with the Paris Agreement temperature goals." It is unlikely that this goal can be reached without substantial penetration of zero emission ships resulting in reductions of all air pollutants beyond what is assumed in the Future_Base scenario in this paper.

2) The use of three years to compute an average of the present situation is not clear. Information regarding the averaging of computed years is given piecewise and the reader is left alone with finding out which emissions and meteorology of which years are used for the different scenario simulations and which output year is compared. Definitely, a table presenting this information in one place would be very helpful. Why was only one year (2016) compared with the future scenarios?

Answer: As suggested we have included a table listing what emissions have been used in the model scenarios. The effects of future scenarios were calculated for all three meteorological years.

3) The non-consistent numbering of sections adds to the confusion: section one starts

with the Introduction, followed by a section ‘Experimental Setup‘ which is not numbered and then beginning with 1.1 Emissions. This should probably be section two and renamed ‘Model Setup‘.

Answer: The section numbering has been changed.

4) Projections for the future ship emissions are not described and justified in the manuscript. How would the air quality change in future if a higher growth of the ship fleet or non-compliance to the stricter regulations are assumed?

Answer from Jukka Pekka Jalkanen:

We (Finnish Meteorological Inst.) are preparing a separate manuscript for scenario development and we wanted to keep this part of the manuscript relatively simple, because this is a long story of its own. The key idea is that a simple scaling up emissions with assumed annual growth rate will not work for future years if energy efficiency gains, future emission regulations, fleet technology developments and regional rules are not properly covered. In this regard, we have divided the scenario development in three parts, which will operate on different ship types in a different way. The three features listed in the manuscript involve a) energy efficiency developments, b) vessel size development and c) vessel numbers. These three contributions are used linking the shipping sector to global transport demand, which in turn is linked to annual GDP growth of various regions in the world.

Efficiency gains for various ship types are obtained from Kalli et al. (2013) (see reference in paper). Vessel numbers of each ship type are based on number of ships built each year. For some vessel types this is very challenging, like for the global containership sector, which has undergone a rapid growth since year 2000. The future shipping fleet is difficult to predict, because for example plotting the number of containerships built each year leads to almost exponential growth which cannot be followed for the next 30 years. In 2050, the number of containerships fleet is assumed to grow by 40%, to 6500 actively used ships. Also, the size development of vessels in various shipping sectors needs to be considered. The largest Triple E class of container ships in 2014 were able to carry over 18Âă000 TEUs, but 22Âă000 TEU capacity was nearly achieved in 2017. The triple E class has DWT/TEU ratio of almost 11 tons/TEU, which leads to significantly larger vessels if the current DWT growth trend continues. Containership which exceed 50Âă000 TEUs could be introduced to the fleet by 2050 with our assumptions, which is a decade sooner than anticipated in some recent estimates (McKinsey Group, 2017). These vessels will not be operated in the Baltic Sea because of several limitations.

Specific Comments:

1.) P. 2 line 30: Please add a discussion on emissions from open loop scrubbers to air and to water in the Introduction. Moreover, the different alternative fuels and control technologies to fulfil the stricter ECA regulations and their actual use by the BAS ship fleet needs to be addressed. From 2014 to 2016 only the sulphate fraction of PM was reduced accordingly whereas other components of PM were less affected.

Answer: This discussion is now included in the introduction.

2.) P.3 line 1-2: At the end of the Introduction, it is referred to two papers in preparation which are based on results of this study. This reference somehow weakens the scientific relevance of the present study. Either delete or move to the Conclusions.

Answer: These references have been moved to the conclusions

3.) P.3 line 8-9: ECLIPSEv5a: how high is the expected variability of land-based emissions between 2014 and 2016?

Answer:

In this paper we use the ECLIPSE emissions available only on 5 year intervals.We then apply the same Eclipse emissions for all three meteorological years. We use the ECLIPSE emissions in order to get consistent available emissions for both present and 2030 conditions.

However, annually reported emissions for all countries in Europe are listed in the EMEP reports (reference added in the paper). We have added the following text in the paper:

"In reality land based emissions will change between years. Annual emissions from year 2000 to 2016 for the European countries are listed in EMEP (2018). In the Baltic region reported changes in country emission are small with the exception of SOx emissions in Poland dropping almost 20% from 2014 to 2016."

In the paper we deliberately did not change land-based emissions from year to year in order to isolate the effect of the regulations on shipping.

4.) P.3 line 18: Which fraction of open loop scrubbers is assumed for BAS shipping emissions in 2014 and in 2016? What is assumed about primary particle emissions from open loop scrubbers?

Answer: This information is now included in the paper.

"Globally, during 2014 there were 77 vessels using a scrubber, of which 30% were of open loop, 48% of closed loop and 22% of hybrid type. By 2016 scrubber installations were doubled globally to 155 units. In the Baltic Sea area during 2016, there were 85 vessels operating a scrubber releasing 73 million tonnes of wash water to the sea. Almost all of this (99.8\%) discharge came from open loop operation of scrubbers. "

5.) P.3 line 19-21: Are the total BAS shipping emissions for all other pollutants unchanged between 2014 and 2016?

Answer: Ship emissions of other species differ between 2014 and 2016, but much less than for sulphur.

The following text is now included: "Ship emitted pollutants were modelled using AIS data for year 2014 and 2016. Any changes in vessel activity, fleet size and development will have an impact on energy use and all pollutant emissions. However, the sulphur rule was the only significant change which had a large impact on emitted pollutants. Both PM and SOx were reduced by this change, but only the sulphate fraction of PM was reduced accordingly whereas other components of PM were less affected."

6.) On P.3 line 17, daily emission grids are introduced. On the same page, line 30-31 it is stated that hourly data was aggregated into monthly ship emissions. The purpose of the daily emission grid remains unclear. How high is the uncertainty of monthly versus hourly emissions when considering the titration of ozone by ship emissions?

Answer: We have corrected the text from daily to hourly. Previously we have run the model with daily ship emissions resulting in only small changes hardly affecting the model validation at measurement sites.

7.) P.4 line 6-7: Add reference or delete the sentence on ecosystem specific deposition.

Answer: Moved to conclusions. References included here.

8.) P.5 line 16-23: What is the criterion in this study to conclude that measurements are reproduced by the model, either with or without including ship emissions in the model simulations? The present assessment could be strengthened by use of a quantitative indication for the match between model and measurements.

Answer: A quantitative indication is given in Table 1 in the form of correlation, rmse and now also bias. There is no commonly accepted threshold for when a model performs well, and it is clear that models (and also emission inventories) often have problems in reproducing a short-lived species such as NO2 correctly. But the point with this paragraph was that the (mainly negative) biases in the model become considerably worse (more negative) at all measurement sites when omitting the ship emission source. This is a clear indication of the importance of the ship emission source of NOx at these coastal sites. Likewise for SO2 the positive bias becomes very large for the sites listed when the 2016 emissions are replaced by 2014 emissions in the Baltic Sea. For secondary species (SO4 and PM2.5) and depositions of oxidized N and S the effects of shipping is smaller, and we can't draw any conclusions from the match between model and measurement alone with regard to the effects of Baltic Sea emissions.

9.) P. 6 line 1-2: What is the fraction of sulfate in the modelled PM2.5 in 2014 and 2016? If possible, add a comparison of measured and calculated SO4 at the monitoring stations in Table 1.

Answer: SO4 now included in Table 2

We have also included some additional text here to explain the results: In Table 2 we also show measured and model calculated concentrations of SO4. At the sites in Table 2 both the measured and model calculated fraction of SO4 in PM2.5 is about 0.15, and fraction increase only marginally with the Present_HiSulphur scenario.

10.) P. 7 line 1-2: The small national contribution of ship emissions in countries with large in-land area does not really reflect the local significance of this sector. It would be better to calculate the average value in the coastal zone of the countries.

Answer: In this paper we have used similar methodology as used in the source-receptor calculations in the annual EMEP reports (https://www.emep.int/mscw/mscw_publications.html). In the paper the effects along the Baltic Sea coast is also shown in Figures 1 and 2. In the Barregård et al. paper now submitted to IJERPH population weighted concentration are used.

11.) P. 8 line 8: Does the statement about unaffected emissions of non-sulphur particles hold in view of realistic emissions from open loop scrubbers and the PM emissions from burning ultra-low sulfur heavy fuel oil (HFO)? The use of scrubbers might capture a large fraction of PM, not only sulfate.

Answer: We have added a section in the conclusions discussing this:

"For other species of PM, like EC, OC and Ash, emission factors will be similar as with HFO and thus emissions of non-sulphur particles from BAS shipping are assumed to be virtually unaffected by the SECA regulations.

12.) P. 8 line 20: What is the health impact of negative SOMO35?

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Answer: Decreases in SOMO35 (caused by increased NOx resulting in ozone titration) should have a positive health impact. However, the corresponding increase in NOx will, as we demonstrate in the paper, increase PM2.5. As PM2.5 has larger effects on health than ozone the net health effects from NOx should still be negative.

Technical Corrections:

P. 5 line 6: The lifetime of NO2 is relatively short.

Answer: Changed to relatively short.

P. 7 line 19: Please replace “show” by “shown”.

Answer: This part of thext is changed as a result of comments from reviewer 3.

Figure 1 and Figure 2: Please add annotation of x- and y-axis (degrees longitude and latitude) around the concentration maps. The plot header lines are partly cut off and not visible.

Answer: Figures 1 and 2 changed as requested. Figure 2a showed total (oxidised + redused) depositions of N. Corrected to oxidised N.

Figure 3: For some countries the green and red bars are hardly visible. I suggest to add additional plots where the contributions from BAS and from high-sulphur fuel are enhanced.

Answer: Instead of making additional plots we have added the values for the small "Add Baltic" and "Add Baltic 2014" as numbers behind the bars. We have also changed the colour codes to make the text more visible. We believe that these changes make the charts more readable.

Figure 4: In figure part (a) cut the x-axis in the plot at 2000 ppb days and add the values for the bars above 2000 inside the plot.

Answer: We have added the values for the smaller red and blue bars inside the plot.

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We, the authors, thank the reviewers for constructive comments and suggestions

Below we list the comments from reviewer 1 followed by our reply reference to any changes made in the paper.

Specific comments: 1. Page 3, line 10: Please specify what FMI stands for.

Answer: Finish Meteorologcal Institute now included in brackets.

2. Page 3, line 17: Here the ship emissions in daily temporal scale was first introduced, but later in line 30, it was mentioned that ship emission data in hourly temporal resolution was aggregated into monthly resolution in the CTM. Please clarify the original

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temporal resolution of ship emissions and how it was implemented into the CTM.

Answer: The original temporal resolution is hourly. This is corrected in the text.

3. Page 3, line 18: What is the spatial resolution of ship emissions?

Answer: Spatial resolution for the ship emissions For the 2016 Baltic Sea emissions is about 0.034 x 0.018 degrees

For all other sea areas (2015) the spatial resolution is 0.09 x 0.089 degrees

The resolution of the ship emissions is finer than the model grid. Ship emissions are read into the model in the original spatial resolution and then interpolated to the model grid on the fly.

4. Page 3, line 24-29: The description of future emission projections for the year 2030 is not clear. Although it was mentioned some changes such as vessel size growth and fleet size increase, it will be helpful to include the exact or estimated percentage of ship size growth in 2030 compared to current ship size.

Answer: We now list the annual ship size growth used in the 2030 scenario compared to current ship size.

5. Page 4, line 18: I understand the authors mainly focused on the influence of ship emissions, so they presented their results by averaging the three meteorological years. However, some important messages were missing if they took this approach. For example, the changes of observed SO_2 and associated $PM_{2.5}$ species before and after stricter SECA regulation was applied, which is highly relevant to the title of this paper and has critical policy implication. I suggest the authors add the comparison of observation between years to the paragraphs where the Present_HiSulphur and Present_Base simulation was compared.

Answer: The comparisons of model calculations to observations are discussed in section 3.1, where also the Present_HiSulphur and Present_Base simulations are discussed.

6. Page 5, line 12: As it showed that the elevated PM2.5 by BAS shipping emissions are concentrated over the shipping routes and the coastal cities close to the routes, the location of the cities relative to major shipping routes is important. It will be helpful to include a map showing the geographic location of the sites in Table 1 and 2. Also a discussion about whether the sites close to major shipping route would have larger impact of ship emission can be included.

Answer: A map with the position of the measurement sites is now included in the appendix. In the text we also note that the sites close to major shipping routes (as Anholt and Raaoe) NO2 and SO2 measurements can only be reproduced in the Present_Base calculation.

7. Page 5, line 28: What are differences between your estimated contribution of PM2.5 by BAS shipping emissions and the estimation by Karl et al. (2019) that mentioned in page 2, line 24?8.

Answer: Unfortunately there is very little overlap in the stations (even though the AIRBASE dataset also includes the EMEP sites used in this publication. Although the model resolution is the same the Karl et al. calculations have been made with an older EMEP version. Furthermore also land based emissions are lower in 2016 compared to 2012, especially of SO2. In the present study there is a tendency for more underestimation of NO2 and comparable results for the other species.

Page 5, line 30: The results showed that ship emissions contributed more on PM2.5 concentrations when the ship emissions were assumed to be at 2014 levels. Does it imply the PM2.5 contribution in 2014 (before strict SECA) was mainly from SOx? What is the fraction of sulfate in the modeled PM2.5 in Present_HiSulphur and Base simulation? Do the ground observations of PM2.5 show higher fraction of sulfate in 2014 and decreased fraction of sulfate in 2016 after the strict SECA?

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Answer: measured and model calculated SO4 is now tabulated in the paper. The fraction of SO4 in PM2.5 was higher in 2014, but it was not the main component in PM2.5.

9. Page 5, line 32: Here you compared the differences between Present_Base and Present_Noship for NO2 and PM2.5 at the measurement sites. As the magnitude of NO2 and PM2.5 are different (it is not appropriate to compare their difference directly) and it is hard to tell the differences by eyeballing the numbers, I suggest to have barplots over a map (i.e. every site has its relative difference of Base and Noship (Base minus Noship divided by Noship) for PM2.5 and NO2 presented by a barplot), if it would not be too messy on a map.

Answer We have tried this, but given the format of the maps and the plotting software at hand it turned out not to be feasible without compromising readability.

10. Page 5, line 34 & Page 6, line 1-2: It was stated that the model results underestimate the measurement at most of the sites listed. What is the criterion of evaluating Base model performance?

Answer: The criterion is based on the comparison to measurements. This is discussed in more detail in the EMEP model validation report from 2018 https://emep.int/publ/reports/2018/sup_Status_Report_1_2018.pdf comparing EMEP model results to measurements for 2016. We have included a reference to this publication, and some accompanying text, just before section 3.1 (Se also reply to reviewer 1.)

11. Page 6, line 33: This discussion would benefit from a quantitative indication than just describing the largest contribution are seen for smaller countries with long coastline. I suggest to add a quantitative assessment like the contribution weighted by coastline length or weighted by distance-to-major-shipping-route to strengthen the statement here.

Answer: We agree that a quantitative assessment like the contribution weighted by coast-line length or weighted by distance-to-major-shipping-route would have strengthened the statement. We have considered this. The length of the coastline, and the coast/area ratios for countries are available from several sources such as Wikipedia and wold.by.map.org, all listing virtually identical numbers. We are however uncertain whether the methods calculating the length of the coastlines are comparable between countries. As an example all sources list the coastline of Estonia as being longer than both the coastlines of Sweden and Finland. This is most likely due to different measurement techniques. Basing our conclusions on data that are not comparable would not be scientifically sound. We have also considered using distance-to-major-shipping-route as a criteria, but found it hard to define and calculate in practice.

12. Page 7, line 6: Figure 3b shows the reduction of NO2 caused by ship emission in 2030 (i.e. For each country, the green bar along with blue bar is shorter than the green bar with black bar). As it is stated here, the improvement of the pollution levels is caused by reduction of BAS ship emissions. However, in page 3, line 24-29, you mentioned increase of ship size and fleets, and in page 4, line 23, the future scenario was assumed with NECA (and strict SECA?) applied. How the vessel size growth and fleet size increase, which would lead to more emissions, are balanced with strict regulations to have emission reduction in the future?

Answer: The future scenarios will either add or subtract vessel activity of the base year (2014), depending on the fleet size growth rate. If currently there were 100 containerships and an annual growth rate of one percent is applied, then 143 ship would exist in 2050. Adding 43 containerships to the fleet is done by replicating the activity of 43 randomly chosen containerships which exist in 2014. Introducing 43 new ships will need to comply with the existing year 2050 regulations, like Tier III limits, if the vessels were younger than 29 years. The changes in physical dimensions of future ships their impact on vessel speed/resistance curves is not considered, however.

13. Page 7, line 21: It was stated that increase of SOMO35 is more than annually

averaged ozone. The units of SOMO35 and annually averaged ozone are different. What is the comparing criterion in this statement?

Answer: We have added the word relative. This statement was based on considering percentage increases (which are not shown). Relatively speaking the changes in SOMO35 are more pronounced. This is not uncommon for a threshold indicator, where many areas are just below the threshold in the base case.

14. Page 7, line 23 & line 24: It was explained the changes in SOMO35 and annually averaged ozone by combination effect of ozone enhancement in the summer and decrease during the winter time. It would be supportive to add analysis of separating SOMO35 and ozone difference by two seasons into appendix and references to support the argument.

Answer: We have included figures of summer and winter SOMO35 and average ozone in the appendix and the discussion of the results for average ozone and SOMO35 is extended referring to these figures.

15. Page 7, line 25: There are some confusion for the discussion here. In Figure 4,both Germany and Denmark show decrease of annual mean ozone in 2030 (Present-2030, positive difference), but the statement here is “the additional emissions from BAS shipping lead to ‘reductions’ in annual ozone in Denmark. Furthermore,..... result in ‘increased’ annual ozone levels in Germany.” Conflict arises from the differences between discussion mentioned above and Figure 4.

Answer: This part of the paper is re-written, See below

16. Page 7, line 27: It is not clear in the discussion here. Figure 4 shows that the-SOMO35 increases in the future (also stated in Page 7, line 21) for the two cases, but the statement here – “Even though annual ozone..... lower emissions will result in SOMO35 ‘reductions’ in both these two cases.....”. – you mentioned ‘reduction’ in SOMO35 instead. Additionally, I didn’t see the clear connection between SOMO35

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reduction and winter titration events.

Answer: We have now rewritten the text related to ozone and SOMO35. We have also included figures showing the winter and summer difference between the years 2030 and 2016 in ozone concentrations and SOMO35. We have have also added a reference corroborating our results.

Technical comments:

1. Page 7, line 9: It should be Figure 3e, instead of Figure 3d.2.

Answer: This is now fixed.

Page 7, line 19: Please rewrite the sentence, “Also show are the effects....”.3. Figure 1: Please add X-axis and Y-axis label of longitude and latitude and remove the remaining cut-off headers in the plots.

Answer: Regarding line 19, page 7. This part is rewritten, see answer to previous comments.

X and Y long and Lat labels are added and cut-off headers are removed.

Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-51, 2019.

Effects of strengthening the Baltic Sea ECA regulations

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Abstract.

Emissions of most land based air pollutants in western Europe have decreased in the last decades. Over the same period emissions from shipping have also decreased, but with large differences depending on species and sea area. At sea, sulphur emissions in the SECAs (Sulphur Emission Control Areas) have decreased following the implementation of a 0.1% limit on sulphur in marine fuels from 2015. In Europe the North Sea and the Baltic Sea are designated as SECAs by the International maritime Organisation (IMO).

Model calculations assuming present (2016) and future (2030) emissions have been made with the regional scale EMEP model covering Europe and the sea areas surrounding Europe including the North Atlantic east of 30 degrees west. The main focus in this paper is on the effects of ship emissions from the Baltic Sea. To reduce the influence of meteorological variability, all model calculations are presented as averages for 3 meteorological years (2014, 2015, 2016). For the Baltic Sea, model calculations have also been made with higher sulphur emissions representative of year 2014 emissions.

From Baltic Sea shipping the largest effects are calculated for $\mathrm{NO_2}$ in air, but effects are also seen for $\mathrm{PM_{2.5}}$ and depositions of oxidised nitrogen, mainly in coastal zones close to the main shipping lanes. As a result country averaged contributions from ships are small for large countries that extend far inland like Germany and Poland, and larger for smaller countries like Denmark and the Baltic states Estonia, Latvia and Lithuania, where ship emissions are among the largest contributors to concentrations and depositions of anthropogenic origin. Following the implementations of stricter SECA regulations, sulphur emissions from ships in the Baltic Sea shipping now have virtually no effects on $\mathrm{PM_{2.5}}$ concentrations and sulphur depositions in the Baltic Sea region.

Following the expected reductions in European emissions, model calculated $\mathrm{NO_2}$ and $\mathrm{PM_{2.5}}$ concentrations, depositions of oxidised nitrogen, and partially also surface ozone levels, in the Baltic Sea region are expected to decrease in the next decade. Parts of these reductions are caused by reductions in the Baltic Sea ship emissions mainly as a result of the Baltic Sea being defined as a Nitrogen Emission Control Area from 2021.

1 Introduction

Even though emissions of most air pollutants have decreased in the countries surrounding the Baltic Sea (BAS) in past decades (**?**), air pollution and atmospheric depositions affecting ecosystems remain a problem in the region. Significant contributions to the emissions also come from shipping, both inside and outside the region. Obtaining reliable data on emissions from international shipping has always been challenging, but in recent years ship emissions estimated based on AIS (Automatic Identification System) positioning data have become available, continuously tracking the position of the vessels, resulting in substantial improvements in the reliability of ship emissions data.

A number of IMO (International Maritime Organisation) and EU regulations have been implemented in the recent past, or will be implemented in the near future, affecting ship emissions in European waters. Most noteworthy are the SECA (Sulphur Emission Control Area) regulations, reducing the maximum sulphur content allowed in marine fuels from 1.0 to 0.1% from 1. January 2015 (**?**). Fuels with higher sulphur content may be used in combination with emission reduction technology reducing sulphur emission to levels equivalent to the use of compliant low-sulphur fuels. In European waters the North Sea (NOS) and BAS are designated as SECAs by the IMO. These two sea areas are also accepted as NECAs (NO_x Emission Control Areas) from 2021 (**?**). Reductions of NO_x emissions are expected to occur only gradually in the NECAs as these regulations only apply to new ships or when major modifications are made on existing ships. Furthermore, from 2020 a global cap on sulphur content in marine fuels of 0.5% will be implemented.

The global effects of international shipping on air pollution and depositions have been discussed in several papers (**????**). In a global model calculation **?** found that a large portion of the anthropogenic contributions to air pollution and nitrogen depositions in adjacent countries could be attributed to NOS and BAS ship emissions of NO_x and particles also after the introduction of stricter SECA regulations in 2015. In addition, several regional studies focusing on the effects of NOS and BAS ship emissions have been performed. **?** studied the effects of reducing the sulphur content in marine fuels from 1.5 to 1% in 2011 on air pollution, including also calculations of health effects as well as effects of future (2030) ship emissions. They found that the introduction of a NECA from 2016 (later postponed to 2021) would reduce the burden on health due to shipping in the BAS region. Reductions in future $PM_{2.5}$ (particulate matter with diameter less than 2.5μm) levels as a result of the 2021 NECA are also predicted by **?**. **?** calculated the effects of ship emission on Europe for the years 2000 and 2020. They found that the implementation of the stricter SECA regulations in the BAS and the NOS would result in substantial health improvements in Europe. **?** compared the effects of BAS shipping calculated by three different chemistry transport models using year 2012 emissions and meteorology. They found that in the entire BAS region the average contribution from ships to $PM_{2.5}$ is in the range of 4.3 - 6.5% for the three CTMs, and deposition of oxidised nitrogen to the Baltic Sea in the 20 - 24ktN per year range. **?** calculated the dispersion of air pollutants and depositions from NOS and BAS shipping for the period 2011 to 2050 with the main focus on sea-water acidity in BAS. They found that, also in the future, ship emissions could remain a major source of acidity, in particular when assuming high penetration of open loop scrubbers in combination with the use of high sulphur-content fuels.

SO_x removal by scrubbing the exhaust can significantly reduce both the gaseous sulphur compounds as well as particulate matter. Scrubbers may use seawater as a cleaning agent if the alkalinity of seawater is high enough and contains enough carbonates, bicarbonates and borates. However, in areas of low alkalinity, like the Bothnian Bay in the Baltic Sea, the required wash water volume becomes very large and chemicals, like caustic soda, are added to neutralize the acidic releases. The wash water may also contain other pollutants as heavy metals.

Ship owners can also comply with stringent sulphur rules by using LNG. However, during 2016 only about 0.8% of the energy need of the Baltic Sea fleet was produced with LNG. Use of renewable liquid fuels is rather limited because of high price and low availability. Liquid biofuels are not used by any ship in our modelling approach.

In this paper we have calculated the effects of ship emissions in the BAS on air pollution and depositions of oxidised sulphur and nitrogen in adjacent countries. Calculations have been made applying BAS emissions prior to (2014) and after (2016) the implementation of the stricter SECA regulations, which went into force on 1 January 2015. Furthermore, model calculations have been made with future (2030) land-based and ship emissions. ~~The health impacts of air pollutants and the increased depositions of acidifying and eutrophying species from BAS shipping based on these results will be discussed in two companion papers that are in preparation.~~ [1] [1]

~~**Experimental setup**~~

2 Experimental setup

2.1 Emissions

Land-based emissions have been provided by the International Institute for Applied Systems Analysis (IIASA) within the European FP7 project ECLIPSE. In this study we use version 5a (hereafter 'ECLIPSEv5a'), a global emission data set on 0.5 x 0.5 degree resolution, which has been widely used in recent years by the scientific community (http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5.html, Last accessed: 27 February 2019). ECLIPSEv5a is available in 5-year intervals from 2005 onwards, and in this study we have chosen data for 2015 and 2030. In reality land based emissions will change between years. Annual emissions from year 2000 to 2016 for the European countries are listed in **?**. In the Baltic region reported changes in country emission are small with the exception of SO_x emissions in Poland dropping almost 20% from 2014 to 2016.

In regard to ship emissions in the BAS, we use emission data as provided by FMI (Finish Meteorological Institute) for the year 2014 (i.e. with 1% maximum sulphur content in fuels in the SECA) and 2016 (maximum sulphur content reduced to 0.1% in the SECA). For the remaining sea areas, ship emissions for year 2015 are used from a previous global data set (**?**).

The emissions from shipping have been calculated with the Ship Traffic Emission Assessment Model (STEAM) based on ship movements from the automatic identification system (AIS) which provides real time information on ship positions. The model requires as input detailed technical specifications of all onboard fuel-consuming systems and other relevant technical details for all ships considered. The data from **?** constituted the most significant source for this information. The STEAM model is described in **???** and **??**. ~~Daily~~ Hourly emission grids for Baltic Sea ship emissions were produced based on vessel-specific modelling, considering the changes in fuel sulphur content that occurred between 2014 and 2016. ~~Differences between~~

[1] ~~Barregård et al. (2019), in preparation~~

[1] ~~Repka et al. (2019), in preparation~~

In STEAM scrubbers can operate in closed or open loop mode, depending on the equipment installed. If a hybrid scrubber system is known to be installed, it is assumed to operate in open loop mode when the vessel operates in an area where open loop systems are feasible. Closed loop mode of a hybrid scrubber is assumed in the Bothnian Bay and restricted zones, like German waters. If a vessel has open loop scrubber installed and it enters a restriction zone, the model assumes a fuel switch to low sulphur fuels. Emission modelling uses scrubber equipment type (closed/open/hybrid), vessel identity and installation date as input to emission modelling. All future scrubber scenarios introduce hybrid scrubbers to the fleet.

Globally, during 2014 ~~and~~ there were 77 vessels using a scrubber, of which 30% were of open loop, 48% of closed loop and 22% of hybrid type. By 2016 ~~emission data also include changes in ship activity and routing, but on a regional scale these effects are assumed to be small, so that the modelled difference in air pollution and deposition mainly reflects the change in sulphur content in ship fuel.~~ scrubber installations were doubled globally to 155 units. In the Baltic Sea area during 2016, there were 85 vessels operating a scrubber releasing 73 million tonnes of wash water to the sea. Almost all of this (99.8%) discharge came from open loop operation of scrubbers.

Ship emitted pollutants were modelled using AIS data for year 2014 and 2016. Any changes in vessel activity, fleet size and development will have an impact on energy use and all pollutant emissions. However, the sulphur rule was the only significant change which had a large impact on emitted pollutants. Both PM and SO_x were reduced by this change, but only the sulphate fraction of PM was reduced accordingly whereas other components of PM were less affected.

From 2021 onward, NO_x emissions for new ships have to comply with IMO Tier 3 regulations. These contributions were taken into account in the emission modelling. Future emission projections for the year 2030 also include changes in:

- energy efficiency improvements, modelled following the method of **?**, which goes beyond the Energy Efficiency Defined Index (EEDI) requirements of the IMO;
- fleet size increase.
- vessel size growth, assuming a linear annual growth dependent on ship types;
- ~~fleet size increase.~~

Annual growth rates in fleet size are implemented as percentage increase per type of ship: For example, if the annual percentage growth is n% for container ships we duplicate n% of the container ships in the current fleet in the following year. The following growth rates are assumed for vessel DWT: Vehicle carriers and RoRo: 1.25% per annum; Dry cargo: 0.4% per annum; Container carriers: 1.2% per annum; Liquid cargo: 2.0% per annum; Passenger vessels, ferries, High-speed craft: 0.3% per annum; Cruise ships: 0.3% per annum; Fishing vessels: 0.3% per annum. Vessel size growth for other types were set to zero. For those vessels, the vessels size remains at 2014 level.

As the ship emission data are used for multiple meteorological years (see next section), we did not retain the high (hourly) temporal resolution in the data but rather aggregated them to monthly resolution before use in the chemistry transport model.

2.2 Model calculations of air pollutants and depositions

Concentrations of air pollutants and depositions of sulphur and nitrogen have been calculated with the EMEP MSC-W model (hereafter 'EMEP model'), version rv4.14, on 0.1 x 0.1 degrees resolution for the domain between 30 degrees W and 45 degrees E and between 30 and 75 degrees N. ~~The calculations of dry depositions are made separately for each sub-grid landcover classification. These sub-grid estimates are aggregated to provide output deposition estimates for broader ecosystem categories as deciduous and coniferous forests. The ecosystem specific depositions are not shown here, but will be used in a companion paper when calculating exceedances of critical loads for acidification and eutrophication.~~

A detailed description of the EMEP model can be found in **?** with later model updates being described in **?** and references therein. The EMEP model is available as Open Source (see https://github.com/metno/emep-ctm, Last accessed: 27 February 2019), and is regularly evaluated against measurements as part of the EMEP status reports. See **???** for evaluations of the meteorological years 2014, 2015 and 2016, respectively. In addition, the EMEP model has successfully participated in model inter-comparisons and model evaluations presented in a number of peer-reviewed publications **???????**. **?** evaluated depositions of sulphur and nitrogen species in Europe calculated by 14 regional models, showing good results for the EMEP model.

In the present study the model is driven by meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF) based on the CY40R1 version of their IFS (Integrated Forecast System) model. All simulations for this paper have been run for the three meteorological years 2014, 2015 and 2016, and then averaged, in order to cancel out meteorological variability. The simulations are:

- Present_Base: Base case with ship emissions of 2016. Land-based emissions for 2015 (from ECLIPSEv5);
- Present_NoShip: As Present_Base, but without ship emissions in the BAS;
- Present_HiSulphur: As Present_Base, but with ship emissions of 2014 (i.e high sulphur content) in the BAS;
- Future_Base: Ship emissions of 2030 (assuming NECA and business as usual development) and land-based emissions of 2030 (from ECLIPSEv5);
- Future_NoShip: As Future_Base, but without ship emissions in the BAS.

The emissions are also summarised in Table 1. In the future scenarios it is assumed that ships that are in compliance with the NECA regulations will operate the equipment (i.e. be compliant) also when sailing outside the NECA.

3 Model results

In this section model results for parts of Europe centred around the BAS are shown. Concentrations and depositions are shown as averages for three meteorological years for Present_Base and Future_Base and for differences between the two Base runs and the perturbation scenarios as described in Section 2.2. The impact on $\mathrm{PM}_{2.5}$ levels and on the depositions of oxidised nitrogen and sulphur species derived from the perturbation model runs presented here, forms the basis for coming papers discussing the effects on human health [1] (?) and assessing the environmental impacts, including the exceedances of critical loads from ship emissions in the BAS ~~.~~[1] (?).

In ? the EMEP model results for 2016 compared to measurements are discussed in detail. Although the model setup is not completely identical the results are qualitatively very similar. The model underestimates NO_2. Measured $PM_{2.5}$ is also underestimated, and results for the individual $PM_{2.5}$ components are mixed, with SO_4 underestimated, whereas other components are overestimated compared to measurements.

3.1 Air pollution due to Baltic Sea shipping

Concentrations of NO_2 for Present_Base are shown in Figure 1a. The lifetime of NO_2 is relatively short, and as a result the concentrations largely reflect the locations of the main source areas. Concentrations of NO_2 are high in Central Europe and in and around the English Channel with markedly lower concentrations north and east of the BAS. In the NOS and the BAS the major ship tracks are clearly visible. Figure 1c shows the difference between the Present_Base and the Present_NoShip scenarios The calculations show that ship emissions account for more than 50% of NO_2 in central parts of the BAS and for a substantial percentage also in coastal zones, in particular in Denmark, southern parts of Sweden and Finland and the Baltic states (Estonia, Latvia and Lithuania). This is also illustrated in Table 2 where measured NO_2 at sites located in the BAS coastal regions are compared to the Present_Base, Present_NoShip and Present_HiSulphur model calculations ~~. The~~ calculated with 2016 meteorology. The position of the measurement sites and the corresponding time series plots for NO_2 are shown in Appendix **??**. In the Present_NoShip case NO_2 levels are clearly underestimated and correlations and RMS errors deteriorated compared to the Present_Base calculation, ~~demonstrating the impact of ship emissions in many coastal areas~~in particular for those sites located very close to major shipping routes. The comparisons with measurements convincingly show that ~~the~~ these measurements can only be reproduced when BAS ship emissions are included. The contributions to individual countries will be further discussed in ~~Section 3.3.~~ a later section.

As shown in Table 2, measured SO_2 levels for 2016 are relatively well reproduced by the model for the Present_Base calculation. The position of the measurement sites and the corresponding time series plots for SO_2 are shown in Appendix **??**. The effects of excluding the BAS ship emissions in the Present_NoShip scenario have only minor effects on the SO_2 levels. Replacing 2016 BAS emissions with 2014 (Present_HiSulphur) has much larger effects, resulting in an overestimation of SO_2 levels at most of the sites listed in Table 2, and in particular so for Anholt and Råö, located very close to the shipping routes. This clearly illustrates the effects of the stricter SECA regulations~~, with~~. With the high ship emissions of 2014, the measurements for 2016 can not be reproduced. This is also a strong indication that the ships are largely in compliance with the SECA regulations. As for NO_2, the contributions to individual countries are discussed further in ~~Section 3.3.~~ a later section

$PM_{2.5}$ in the atmosphere is a mixture of many chemical species of both natural and anthropogenic origins. It is emitted both as a primary pollutant and formed as a secondary pollutant in the atmosphere. As a result $PM_{2.5}$ concentrations are more spread out compared to NO_2. Concentrations decrease from south to north from a maximum in central Europe. As shown in

[1] ~~Barregård et al. (2019), in preparation~~

[1] ~~Repka et al. (2019), in preparation~~

Figure 1d the percentage contributions from BAS shipping, calculated as Present_Base – Present_NoShip, are much smaller for $PM_{2.5}$ than for NO_2 but with noticeable contributions in coastal zones, in particular in parts of Denmark, Sweden and Finland. Figure 1e shows higher contributions when assuming BAS shipping at 2014 levels (Present_HiSulphur), prior to the implementation of the stricter SECA regulations. These results are also illustrated in the comparisons of model scenario calculations at the measurement sites located in BAS coastal regions as listed in Table 2. The position of the measurement sites and the corresponding time series plots for $PM_{2.5}$ are shown in Appendix **??**. For $PM_{2.5}$ differences between the Present_Base and the Present_NoShip cases are much smaller than for NO_2. Likewise, differences are smaller than for SO_2 between Present_Base and Present_HiSulphur. In Table 2 we also show measured and model calculated concentrations of SO_4. At the sites in Table 2 both the measured and model calculated fraction of SO_4 in $PM_{2.5}$ is about 0.15, and fraction increase only marginally with the Present_HiSulphur scenario.

The model results underestimate the measurements at most of the sites listed. Based only on the comparisons between measurements and the different model scenarios for $PM_{2.5}$ one can not conclude that the Present_Base scenario is more realistic than the other two. As for NO_2 and SO_2, the contributions to individual countries are discussed further in ~~Section 3.3.~~ a later section.

3.2 Depositions of sulphur and nitrogen from Baltic Sea shipping

Total depositions (wet and dry) of oxidised sulphur and nitrogen for Present_Base are shown in Figure 2a,b. The highest depositions of both sulphur and nitrogen are seen over Central Europe. For nitrogen, high levels of depositions also extend into northern Germany and Denmark. Based on the difference between Present_Base and Present_NoShip a significant amount of the nitrogen depositions can be attributed to BAS shipping (Figure 2c), contributing to more than 15% of the total nitrogen depositions in major parts of the BAS and also in parts of Sweden, Finland and the Baltic states (Estonia, Latvia and Lithuania). Dry deposition is parameterised as a function of sub grid-scale ecosystems and is typically higher than the grid average for forest ecosystems (both coniferous and deciduous). This will affect the calculations of critical loads for acidification and eutrophication as the sub grid-scale ecosystem depositions are used in the critical load calculations. Critical loads will be discussed in a companion paper [1] ~~.~~ (?). Figure 2d shows that the calculated contributions from BAS shipping in 2016 to depositions of sulphur are very low (Present_Base – Present_NoShip) and much lower than what has been calculated assuming 2014 emissions (Present_HiSulphur – Present_Base) as shown in Figure 2e, with percentage contributions exceeding 10% in many coastal zones.

These findings for the depositions of oxidised nitrogen and sulphur are also illustrated in Table 3 where measured concentrations in precipitation at sites located in the BAS coastal regions are compared to the Present_Base, Present_NoShip and Present_HiSulphur model calculations. Compared to Present_Base, averaged concentrations in precipitation are about 14% lower for oxidised nitrogen when BAS ship emissions are excluded ~~, and oxidised sulphur~~ (Present_Base – Present_NoShip). The effects of the stricter SECA regulations is demonstrated by an increase of about 9% ~~higher for when applying~~ in the

[1] ~~Repka et al. (2019), in preparation~~

calculated concentrations of oxidised sulphur in precipitation in the Present_HiSulphur ~~emissions~~scenario compared to the Present_Base calculation.

3.3 Contributions to individual countries from BAS shipping.

Figure 3 shows the concentrations of NO_2, SO_2, $PM_{2.5}$, and the depositions of oxidised sulphur and oxidised nitrogen averaged over the individual countries bordering the BAS. The black (Present) and blue (Future) bars represent contributions from all other sources (both anthropogenic and natural) than BAS shipping. The green part of the bars represents the (present and future) contributions from BAS shipping calculated as Base – NoShip where Base can be either Present_Base or Future_Base and NoShip can be either Present_NoShip or Future_NoShip. The sum of the black or blue and the green parts of the bars then adds up to the total concentrations and depositions averaged over the individual countries bordering the BAS for the Present_Base and the Future_Base scenarios. The red part is the additional BAS contributions assuming BAS ship emissions at 2014 levels calculated as Present_HiSulphur – Present_Base. The calculations are made assuming linearity. Previous calculations, adding up contributions from different sources, have shown that this assumption is reasonable (**??**). Irrespective of species and depositions, the largest contributions are seen for smaller countries with long coastlines exposed to the BAS as Denmark and the Baltic States, and the least for large countries as Germany and Poland with major parts of their areas located far from the shipping routes.

Following the expected reductions between 2016 and 2030 in both land-based and ship emissions, calculated concentrations and depositions are reduced over the 2016 to 2030 time-span. For SO_2 and depositions of sulphur, BAS shipping is already an insignificant source in 2016 and the differences between 2030 and 2016 are almost entirely caused by changes in land-based emissions. For NO_2 concentrations and depositions of oxidised nitrogen, reductions of land-based and BAS ship emissions both contribute to the improvements in pollution levels. In the BAS region the fractional reductions of future concentrations attributed to (mainly) land-based, and to BAS ship emissions are roughly in the same range.

The largest ~~contributions~~ contrilbutions from BAS shipping is seen for NO_2 (Figure 3b), depositions of oxidised nitrogen (Figure 3~~d~~c), and partially also for SO_2 (Figure 3a) when assuming 2014 emissions (Present_HISulphur). However, for SO_2 calculated contributions are insignificant following the implementation of the stricter SECA in 2015. The same conclusion also holds for sulphur depositions (Figure 3d). $PM_{2.5}$ contributions from BAS shipping are markedly smaller than for NO_2. Contributions are higher when assuming Present_HiSulphur emissions. After the implementation of stricter SECA regulations in 2015, $PM_{2.5}$ from shipping mainly originates from NO_2 and, in part, primary PM emissions. As shown in Figure 1d,e elevated $PM_{2.5}$ concentrations from BAS shipping are mainly seen in coastal zones close to shipping lanes. Much of these coastal zones are densely populated. When assessing the health effects of PM in a forthcoming companion paper [1]~~,~~ (**?**), population weighted $PM_{2.5}$ concentrations are used.

[1]~~Barregaard et al. (2019), in preparation~~

Figure 4 (left) shows calculated SOMO35[1] as an average for countries around the Baltic Sea and the effect of BAS shipping~~on SOMO35 (left)~~ [2] ~~and the~~. The effects on annual average ozone are shown in the same figure (right). For all countries annual averaged ozone is in the 33 - 37 ppb range. ~~Also show are the effects of the expected emission reductions in 2030 and contributions from BAS shipping for the same year.~~ For most countries both SOMO35 and annually averaged ozone increase only slightly as a result of BAS shipping, and relatively more so for SOMO35 than for annually averaged ozone. ~~For most countries the expected emission reductions from year 2016 to 2030 results in reductions in the ozone levels. However, changes in SOMO35 and annually averaged ozone are~~ However, in Denmark emissions from BAS shipping result in a decrease in annually averaged ozone with present emissions.

Changes in ozone are caused by a combination of ~~net ozone increases~~ozone production, mainly in the summer months, and ozone titration by NO, mainly in winter. In ~~the BAS region net~~ winter reductions in NO_x emissions (including reductions in emissions from ships) result in a decrease in ozone titration and subsequently higher ozone levels. This is illustrated in Figure **??**a with ozone winter levels in 2030 higher than in 2016 throughout northern and central Europe. Ozone production dominates in the summer months (Figure **??**b) and with the exception of a region around the English channel, the expected reductions in the emissions of ozone precursors result in lower ozone ozone levels. For SOMO35 (Figure **??**c,d) the relative increase in winter is much smaller as ozone is largely below the 35 ppb threshold. In summer the increase caused by titration around the English channel is confined to a much smaller area. As a result annually average ozone production and titration in the BAS region partially cancel out, and for some regions and countries titration dominates ~~. As a result, the additional emissions from BAS shipping lead to reductions in annual ozone in Denmark. Furthermore,~~ the annual values. As shown in Figure 4 the expected emission reductions ~~from~~ (land based and from ships) from year 2016 to 2030 result in ~~increased annual ozone levels in Germany . Even though annual ozone levels decrease, lower emissions will result in~~ overall reductions in ozone levels (both annually averaged ozone and SOMO35~~reductions in both these two cases as the titration events mainly occur in winter time when ozone levels are below 35 ppb~~) for all countries except Germany and Denmark, where calculated average ozone levels are higher in 2030 (but SOMO35 is reduced). In 2030 the additional emissions from BAS shipping result in increased SOMO35 and annually average ozone in all countries except Denmark. Here average ozone decreases (in contrast to the case in 2016, where SOMO35 increases when adding the emissions fram BAS shipping). These results are in good agreement with detailed model calculations with projected emission changes, demonstrating a future transition from NMVOC[2]-limited to NO_x-limited regimes in large parts of Europe north of the Alps (**?**).

It has to be noted that in our model calculations the ship emissions are instantly diluted throughout the model grid cell where the emissions occur. Previous studies **??** have shown that this could lead to an overestimation of ozone formation. However, **?** found that the overestimation caused by instant dilution was small in polluted regions, such as the central parts of the BAS.

[1]SOMO35 is the indicator for health impacts recommended by WHO calculated as the daily maximum of 8-hour running ozone maximum over 35 ppb

[2]~~SOMO35 is the indicator for health impacts recommended by WHO calculated as the daily maximum of 8-hour running ozone maximum over 35 ppb~~

[2]NMVOC - Non Methane Volatile Organic Compounds

4 Conclusions

Our calculations clearly show that, following the stricter SECA regulations from 1 January 2015, sulphur emissions from BAS shipping now contribute little to depositions of oxidised sulphur and $PM_{2.5}$ concentrations in air. This is in contrast to pre-2015 conditions when less stringent sulphur regulations were in place, and even more compared to pre-2011 conditions when up to 1.5% sulphur were allowed in marine fuels in the SECAs.

Still, emissions of NO_x and particles from BAS shipping continue to be high, causing health problems and other detrimental impacts on the environment in the BAS region. At present emission levels, particles originating from BAS shipping are mainly formed from NO_x emissions ~~. In addition,~~ and partially by primary particles other than SO_4.

Currently very little openly available emission factor data exist for marine diesels using Ultra-low sulphur heavy fuel oil and covering the whole engine load range from zero to 100 percent. Hypothetically, with these cases STEAM calculates the SO_x emission factor based on available sulphur in the fuel. If this was close to zero, then the SO_x emission factor is very small. The conversion of fuel sulphur to sulphate has a similar mechanism and only a small fraction of available sulphur is converted to SO_4. Again, the emission factor for SO_4 would be very small if the fuel sulphur content is close to zero. For other species of PM, like EC, OC and Ash, emission factors will be similar as with HFO and thus emissions of non-sulphur particles from BAS shipping are assumed to be virtually unaffected by the SECA regulations.

Our source-receptor calculations show that, for many countries in the BAS region, they are among the 5 to 6 largest regions/countries contributing to SIA (Secondary Inorganic Aerosols), which is a major constituent of $PM_{2.5}$ (see EMEP reports for the individual countries for year 2016 (**?**)). The largest contributions by far are calculated for the coastal zones. Many of the larger cities in the BAS region are located in the coastal zones. In the companion paper [3] (**?**) health effects from BAS shipping have been adjusted to the population density resulting in a proportionally higher contribution from shipping than presented here as area averaged concentrations.

~~The implementation of NECA regulations in the BAS (and also NOS) is expected to result in gradual reductions in from BAS shipping, as shown in our calculations for future conditions (Future_Base – Future_NoShip). In the future scenario this relative decrease is largely comparable to the decrease from other anthropogenic sources.~~

BAS ship emissions also affect the formation of ground level ozone. In much of the BAS region NO_2 levels are already influenced by large land-based sources, and additional contributions from BAS shipping to ozone and ozone metrics, exemplified by SOMO35, is moderate, and for several regions even negative. In this paper we have shown that for most countries future ozone and ozone metrics are expected to decrease from their present levels.

In addition to influencing particle formation and ozone levels, NO_x emissions also contribute to the depositions of oxidised nitrogen, causing exceedances of critical loads for acidification and in particular eutrophication. Depositions do however depend on the type of landcover. In the EMEP model the calculations of dry depositions are made separately for each sub-grid landcover classification. These sub-grid estimates are aggregated to provide output deposition estimates for broader ecosystem

[3] ~~Barregaard et al. (2019), in preparation~~

categories as deciduous and coniferous forests. The ecosystem specific depositions are not shown here, but will be used in a companion paper (?) when calculating exceedances of critical loads for acidification and eutrophication.

A significant portion of the depositions of oxidised nitrogen is due to BAS shipping. This is also corroborated by the source-receptor calculations for the individual countries in Europe for 2016, see **?** where they calculate that BAS shipping is the largest contributor to oxidised nitrogen deposition in Estonia (with 14%), and among the 3 to 5 largest contributors in several other countries in the region. As discussed above, these depositions are projected to be gradually reduced following the implementation of the NECA regulations, with relative reductions largely comparable to the decrease from other anthropogenic sources.

Presently there are no further emission mitigation regulations targeted for the Baltic Sea and the North Sea apart from the NECA regulation entering into force in 2021. This regulation is expected to result in gradual reductions in $PM_{2.5}$ concentrations and in depositions of nitrogen from BAS shipping, as shown in our calculations for future versus present conditions. The relative reductions are largely comparable to the decrease from other anthropogenic sources in the region. However, according to (?) the target set by IMO is "to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008; and GHG emissions from international shipping to peak and decline as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the vision as a point on a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals." It is unlikely that this goal can be reached without substantial penetration of zero emission ships resulting in reductions of all air pollutants beyond what is assumed in the Future_Base scenario in this paper.

Code availability. The EMEP model is available as Open Source (see https://github.com/metno/emep-ctm)

Data availability. Model output data available upon request to first author

Author contributions. JEJ has made the model calculations and has written most of the paper. MG has assisted in designing the model scenarios and in writing the paper. JPJ and LJ provided the ship emission data for both present and future scenarios. JPJ also assisted in the writing of the paper.

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Surface measurements have been made available through the EBAS web site, http://ebas.nilu.no/Default.aspx, last accessed 27 February 2019.

Competing interests. There are no competing interests

Table 1. All model scenarios have been calculated for the three meteorological years 2014, 2015 and 2016. In the comparisons to measurements in Table 2 only year 2016 model calculations are shown. The land based ECLIPSE emissions for 2016 have been interpolated between 2015 and 2020. SECA regulations for the North Sea are included in the Remaining seas ship emissions. The 2020 sulphur cap is included in the 2030 ship emissions outside the SECAS.

	Present_Base	Present_NoShip	Present_HiSulphur	Future_Base	Future_NoShip
Land Based emissions:	ECLIPSE 2016	ECLIPSE 2016	ECLIPSE 2016	ECLIPSE 2030	ECLIPSE 2030
Baltic Ship emissions:	2016	none	2014	2030	none
Remaining Ship emissions:	2015	2015	2015	2030	2030

Table 2. Annual average measured (Obs) and model calculated concentrations (Calc) of NO_2 ~~,~~ and SO_2 for the present (2016) Base, NoShip, HiSulphur scenarios. The figure continues on the next page with SO_4 and $PM_{2.5}$. Also listed are normalized mean bias (NMB), the daily correlations (Corr) and RMS errors (RMS) between model and measurements. For Hallahus there are $PM_{2.5}$ measurements only for parts of the year and bias, correlations and RMS errors are not listed. The timeseries plots for the same sites are shown in appendix **??**. Km Balt. is a classification of the distance in kilometres between the stations and the Baltic Sea coast. The distance is equal to or smaller than distance listed. The position of the measurement sites and the timeseries plots are shown in appendix **??**.

NO_2

			Base				HiSulphur				NoShip			
Station	Km Balt ~~,~~	Obs	Calc	NMB	Corr.	RMS	Calc.	NMB	Corr	RMS	Calc	NMB	Corr.	RMS
Aspvreten	10	0.44	0.44	0.00	0.50	0.28	0.44	0.00	0.48	0.28	0.31	-0.25	0.48	0.31
Råö	10	1.09	1.06	-0.03	0.58	0.73	0.99	-0.09	0.60	0.70	0.46	-0.48	0.60	0.91
Hallahus	50	0.96	0.85	-0.11	0.71	0.52	0.84	- 0.12	0.71	0.52	0.58	-0.40	0.70	0.64
Anholt	10	1.48	0.98	- 0.34	0.73	0.96	0.92	-0.38	0.76	0.99	0.35	-0.76	0.66	1.55
Keldsnor	10	2.47	1.89	-0.23	0.69	1.52	1.78	-0.28	0.72	1.55	0.58	-0.77	0.58	2.52
Rucava	100	0.75	0.38	-0.49	0.63	0.56	0.38	-0.49	0.63	0.56	0.30	-0.60	0.57	0.63
Zingst	10	2.10	0.96	-0.46	0.65	1.48	0.96	-0.46	0.65	1.48	0.52	-0.75	0.53	1.89
Utö	10	0.95	-0.40	0.57	0.76	0.58	0.59	-0.38	0.76	0.56	0.17	-0.82	0.25	1.00

SO_2

			Base				HiSulphur				NoShip			
Station	Km Balt.	Obs	Calc	NMB	Corr.	RMS	Calc.	NMB	Corr	RMS	Calc	NMB	Corr.	RMS
Aspvreten	10	0.10	1.50	0.25	0.11	0.34	0.30	2.00	0.13	0.38	0.25	1.50	0.11	0.34
Råö	10	0.12	0.09	-0.25	0.29	0.12	0.22	0.83	0.31	0.21	0.07	-0.42	0.26	0.13
Hallahus	50	0.13	0.08	0.14	0.58	0.16	0.21	0.62	0.55	0.19	0.13	0.00	0.61	0.15
Utö	10	0.15	-0.40	0.09	0.23	0.27	0.23	0.53	0.12	0.30	0.08	-0.47	0.24	0.28
Anholt	10	0.10	0.10	0.00	0.72	0.08	0.28	1.80	0.61	0.30	0.07	-0.30	0.66	0.08
Risø	10	0.13	0.19	0.37	0.59	0.18	0.26	1.00	0.64	0.23	0.17	0.13	0.59	0.17
~~Vilsandy~~ Vilsandi	10	0.30	0.11	-0.63	0.37	0.43	0.18	-0.40	0.28	0.42	0.10	-0.67	0.38	0.43
Zingst	10	0.29	0.27	-0.07	0.74	0.30	0.40	0.38	0.71	0.33	0.25	-0.14	0.74	0.31
Rucava	100	0.20	0.18	-0.10	0.48	0.30	0.21	0.05	0.48	0.30	0.18	-0.10	0.48	0.30

Table 2. continued from previous page.

SO_4

			Base				HiSulphur				NoShip			
Station	Km Balt.	Obs	Calc	NMB	Corr.	RMS	Calc.	NMB	Corr	RMS	Calc	NMB	Corr.	RMS
Aspvreten	10	0.71	0.56	-0.21	0.74	0.48	0.65	-0.08	0.72	0.49	0.56	-0.21	0.74	0.49
Råö	10	0.98	0.59	-0.40	0.53	0.71	-0.28	0.71	0.47	0.71	0.57	-0.42	0.53	0.72
Hallahus	50	0.87	0.76	-0.13	0.65	0.60	0.76	-0.13	0.62	0.63	0.76	-0.13	0.65	0.60
Anholt	10	1.58	0.60	-0.62	0.62	1.16	0.73	-0.54	0.58	1.08	0.59	-0.63	0.62	1.18
Risø	10	1.63	0.82	-0.50	0.69	1.13	0.94	-0.42	0.68	1.06	0.81	-0.50	0.69	1.14
Rucava	100	0.92	0.80	-0.13	0.71	0.64	0.88	-0.04	0.71	0.63	0.80	-0.13	0.71	0.65

PM2.5

			Base				HiSulphur				NoShip			
Station	Km Balt.	Obs	Calc	NMB	Corr.	RMS	Calc.	NMB	Corr	RMS	Calc	NMB	Corr.	RMS
Hallahus	50	6.04	5.90	-0.02			6.08	0.01			5.46	-0.10		
Aspvreten	10	4.39	3.63	-0.17	0.57	3.08	3.77	-0.14	0.57	3.07	3.45	-0.21	0.57	3.09
Råö	10	3.77	4.26	0.13	0.43	3.40	4.44	0.18	0.42	3.48	3.93	0.04	0.45	3.03
Rucava	100	9.08	4.63	-0.49	0.50	7.31	4.77	-0.47	0.50	7.23	4.43	-0.51	0.51	7.40
~~Vilsandy~~ Vilsandi	10	4.38	3.43	-0.22	0.67	3.00	3.63	-0.17	0.67	2.94	3.21	-0.27	0.67	3.07

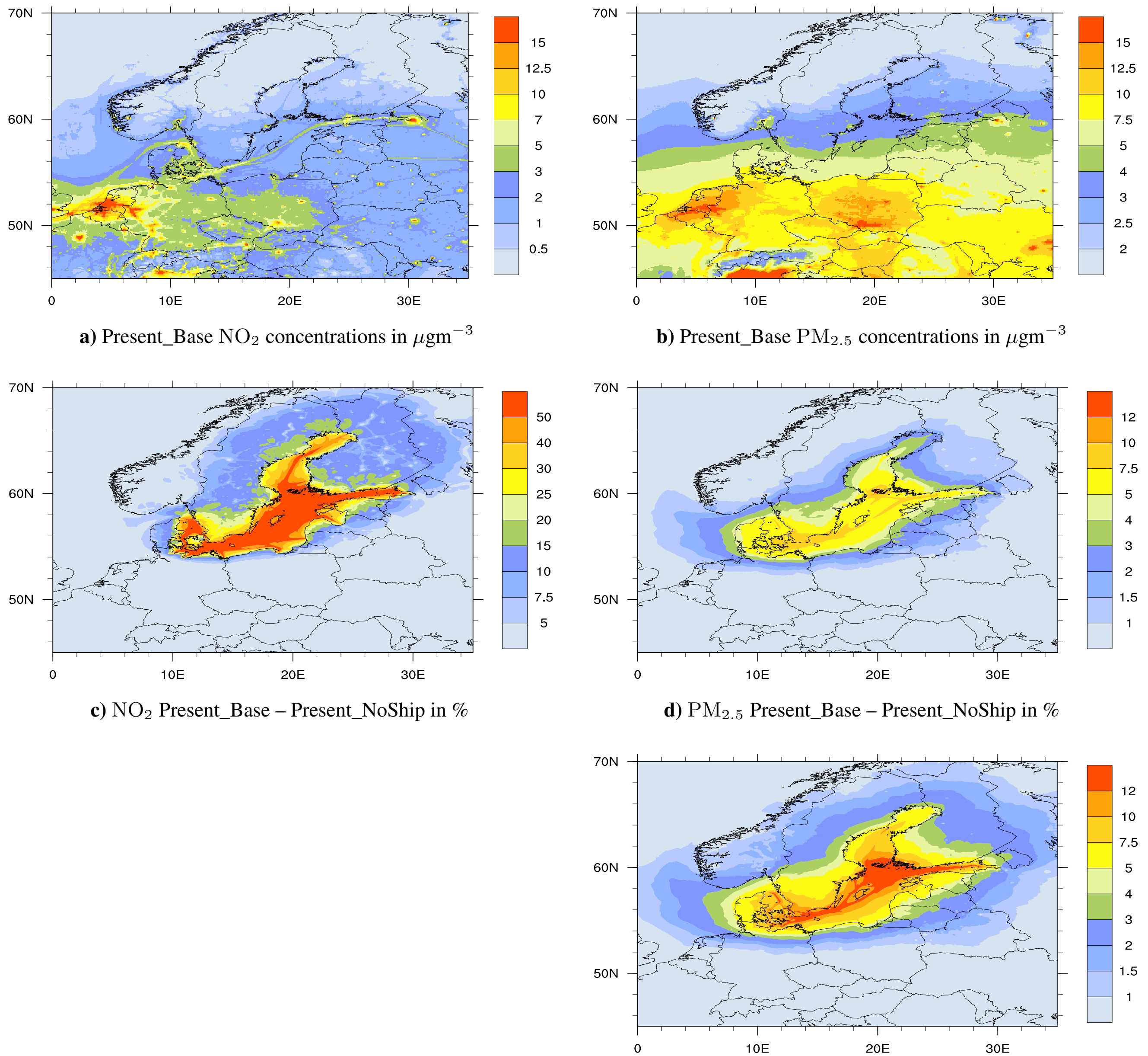
Table 3. Annual average measured (Obs) and model calculated concentrations (Calc) in precipitation of oxidised nitrogen in mg(N)l−1 and oxidised sulphur in mg(in S)l−1in 2016 for the present Base, NoShip, HiSulphur scenarios. Also listed are the normalized mean bias (NMB), the daily correlations (Corr) and RMS errors (RMS) between model and measurements. Km Balt. is a classification of the distance in kilometres between the stations and the Baltic Sea coast. The distance is equal to or smaller than distance listed. The position of the measurement sites and the timeseries plots are shown in appendix ??.

Wet dep. oxN

			Base				HiSulphur				NoShip			
Station	Km Balt.	Obs	Calc	NMB	Corr.	RMS	Calc.	NMB	Corr	RMS	Calc	NMB	Corr.	RMS
~~Brekaelen~~ Bredkälen	200	0.15	0.14	-0.07	0.63	0.38	0.14	-0.07	0.62	0.28	0.12	-0.20	0.61	0.27
Råö	10	0.55	0.80	0.45	0.57	1.21	0.80	0.45	0.57	1.21	0.72	0.31	0.57	1.15
Preila	10	0.65	0.76	0.17	0.38	1.62	0.76	0.17	0.38	1.62	0.65	0.00	0.36	1.65
Lahemaa	20	0.48	0.39	-0.19	0.16	0.95	0.39	-0.19	0.16	0.94	0.32	-0.33	0.16	0.94
Leba	10	0.73	0.78	0.07	0.59	1.05	0.78	0.07	0.59	1.04	0.67	-0.08	0.53	1.10

Wet dep. oxS

			Base				HiSulphur				NoShip			
Station	Km Balt.	Obs	Calc	NMB	Corr.	RMS	Calc.	NMB	Corr	RMS	Calc	NMB	Corr.	RMS
~~Brekaelen~~ Bredkälen	200	0.11	0.11	0.00	0.39	0.31	0.12	0.09	0.40	0.31	0.11	0.00	0.39	0.31
Råö	10	0.23	0.40	0.74	0.54	0.66	0.45	0.96	0.55	0.70	0.40	0.74	0.53	0.65
Preila	10	0.38	0.56	0.47	0.37	1.20	0.60	0.58	0.39	1.20	0.55	0.45	0.37	1.21
Leba	10	0.42	0.51	0.21	0.48	0.85	0.56	0.33	0.53	0.83	0.51	0.21	0.47	0.85



a) Present_Base NO_2 concentrations in μgm^{-3}

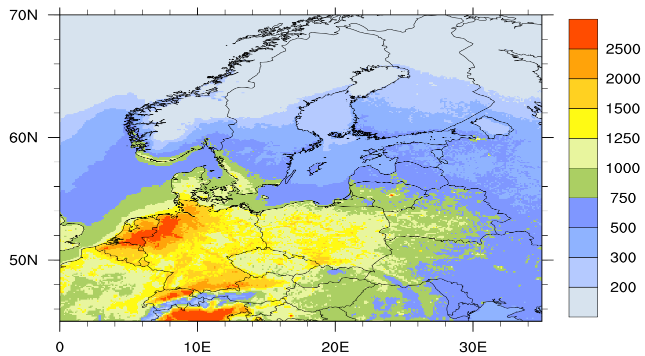
b) Present_Base $PM_{2.5}$ concentrations in μgm^{-3}

c) NO_2 Present_Base – Present_NoShip in %

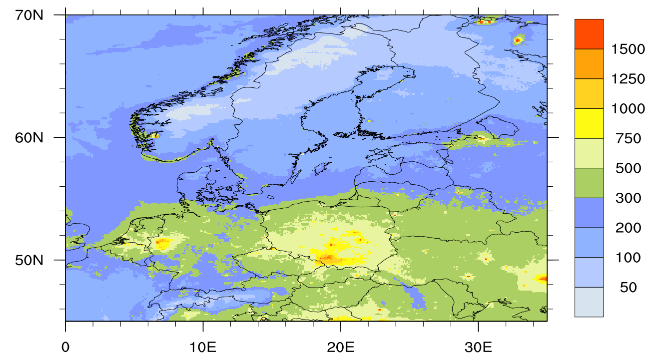
d) $PM_{2.5}$ Present_Base – Present_NoShip in %

e) $PM_{2.5}$ Present_HiSulphur – Present_NoShip in %

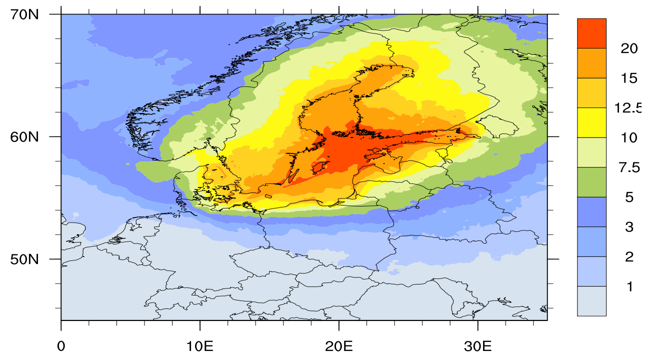
Figure 1. Top panels: concentrations of NO_2 and $PM_{2.5}$ in the Present_Base case. Middle panels: present percentage contribution from BAS ship emissions to NO_2 and $PM_{2.5}$ after the new sulphur regulations. Bottom panel: percentage contribution to $PM_{2.5}$ concentrations before the new sulphur regulations.



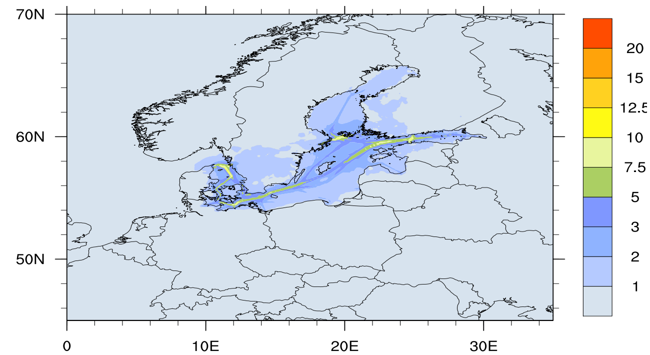
a) Present_Base Deposition of oxN in mgNm^{-2}



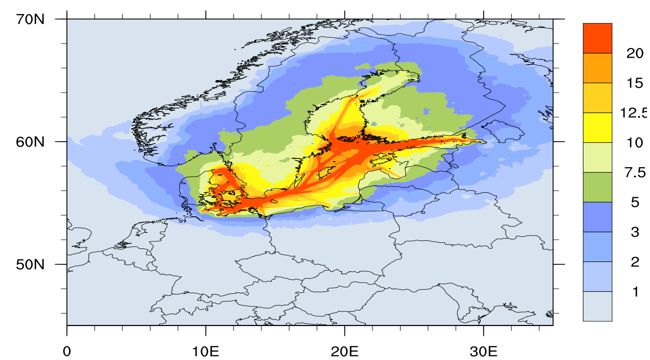
b) Present_Base Deposition of oxS in mgSm^{-2}



c) Dep. of oxN, Present_Base – Present_NoShip in %



d) Dep. of oxS, Present_Base – Present_NoShip in %



e) Dep. of oxS, Present_HiSulphur – Present_Base in %

Figure 2. Top panels: calculated depositions of oxidised nitrogen and sulphur. Middle panels: present percentage contributions from BAS ship emissions to depositions of oxidised nitrogen and oxidised sulphur with reference to Base 2016. Bottom panel: percentage contribution to depositions of oxidised sulphur with reference to 2014 BAS emissions.

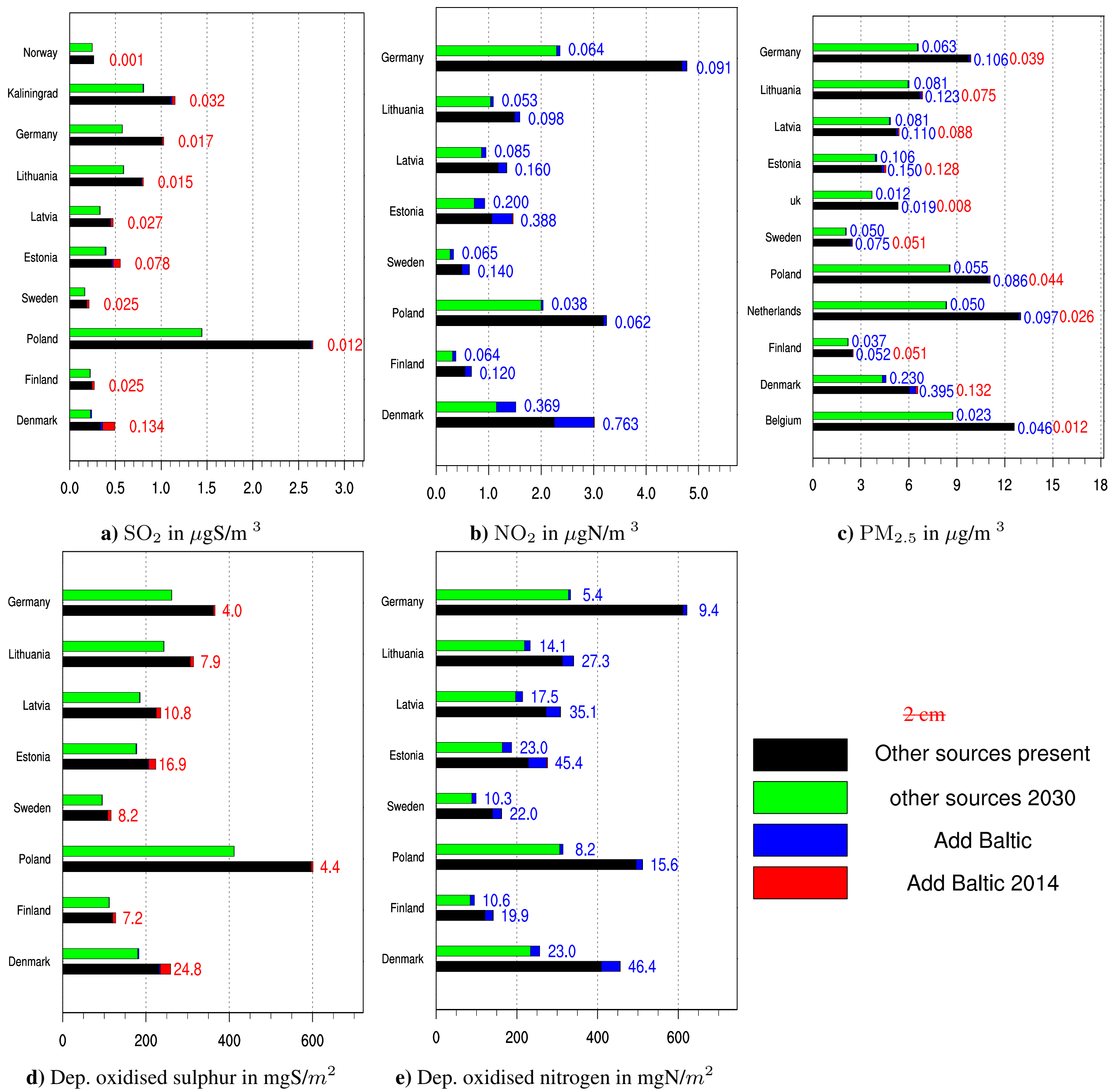
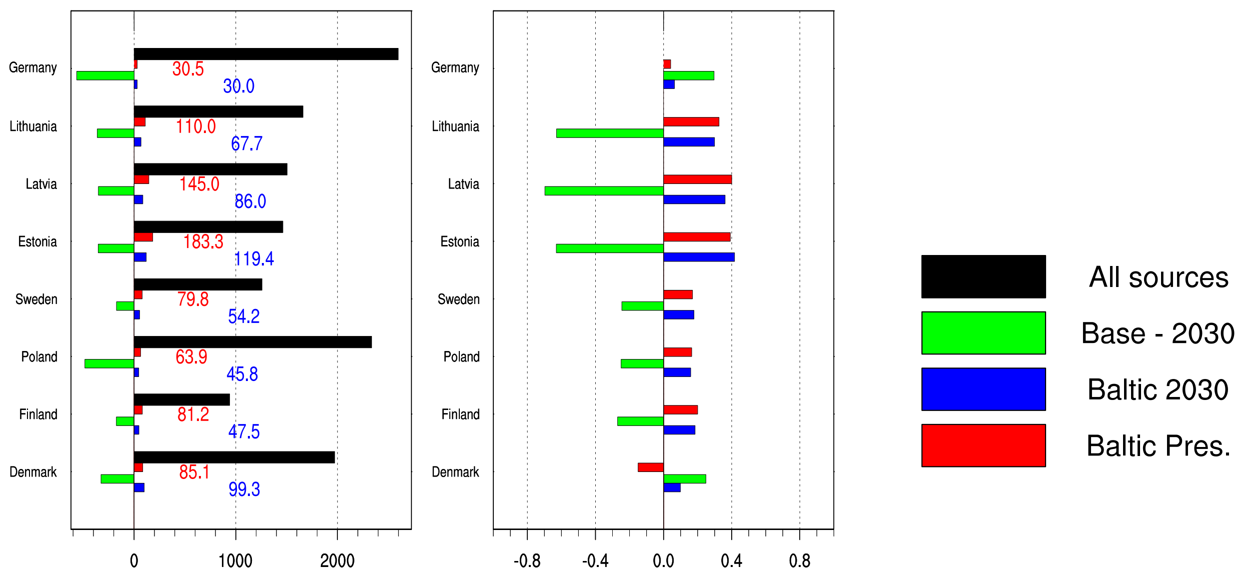


Figure 3. For each country, the upper bar shows the ~~present~~ future (2030) case and the lower bar the ~~future~~ present case country average concentration. a) SO_2, b) NO_2, c) $PM_{2.5}$, and depositions of oxidised sulphur (d) and oxidised nitrogen (e). The black and ~~blue~~ green bars represent the Present_NoShip and Future_NoShip calculations respectively. The additional contributions from BAS (Add Baltic) are shown in ~~green~~ blue and the additional effect assuming high sulphur fuel emissions (Add Baltic 2014) in red (These are also given as numbers. Numeric values for NO_2 Add Baltic and for SO_2 Add Baltic 2014 not given as they are very small).



a) SOMO35 in ppb days **b)** ozone differences in ppb ~~2 cm~~

Figure 4. Left, SOMO35 in ppb days where black bars represent Present_Base levels. Right, changes in annual ozone in ppb (annual average ozone is in the 30 - 35 ppb range in all countries). For both SOMO35 and annual ozone blue bars represent changes in levels from 2016 to 2030 (Present_Base – Future_Base), red bars: contributions from BAS (Present_Base – Present_NoShip) , green bars: contributions from BAS in 2030 (Future_Base – Future_NoShip).