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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 NO_2 in air, but effects are also seen for $PM_{2.5}$ 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 $PM_{2.5}$ concentrations and sulphur depositions in the Baltic Sea region.

Following the expected reductions in European emissions, model calculated NO_2 and $PM_{2.5}$ 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 (Tista et al., 2018), 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

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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 (IMO, 2008). 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 (IMO, 2017). 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 (Corbett et al., 2007; Endresen et al., 2003; Eyring et al., 2007; Sofiev et al., 2018). In a global model calculation Jonson et al. (2018) 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. Jonson et al. (2015) 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 Karl et al. (2018). Brandt et al. (2013) 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. Karl et al. (2019) 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. Claremar et al. (2017) 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.

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

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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 (Barregård et al., 2019; Repka et al., 2019).

Experimental setup

1.1 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 regard to ship emissions in the BAS, we use emission data provided by FMI 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 (Johansson et al., 2017).

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 IHS Global (2017) constituted the most significant source for this information. The STEAM model is described in Jalkanen et al. (2009, 2012, 2016) and Johansson et al. (2013, 2017). Daily 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 2014 and 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.

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 Kalli et al. (2013), which goes beyond the Energy Efficiency Defined Index (EEDI) requirements of the IMO;
- 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.

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.

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1.2 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 Simpson et al. (2012) with later model updates being described in Simpson et al. (2018) 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 Gauss et al. (2016, 2017, 2018) 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 Colette et al. (2011, 2012); Angelbratt et al. (2011); Dore et al. (2015); Karl et al. (2019); Stjern et al. (2016); Jonson et al. (2018). Vivanco et al. (2018) 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.

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.

2 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

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the perturbation scenarios as described in Section 1.2. The impact on $PM_{2.5}$ 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 (Barregård et al., 2019) and assessing the environmental impacts, including the exceedances of critical loads from ship emissions in the BAS (Repka et al., 2019).

2.1 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 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 1 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 corresponding time series plots for NO_2 are shown in Appendix A. 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. The comparisons with measurements convincingly show that the measurements can only be reproduced when BAS ship emissions are included. The contributions to individual countries will be further discussed in a later section.

As shown in Table 1, measured SO_2 levels are relatively well reproduced by the model for the Present_Base calculation. The corresponding time series plots for SO_2 are shown in Appendix A. 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 1. This clearly illustrates the effects of the stricter SECA regulations - 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 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 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 1. 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. The model results underestimate the measurements at most of the sites listed.

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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 a later section.

2.2 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 (Repka et al., 2019). 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 2 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 (Present_Base – Present_NoShip). The effects of the stricter SECA regulations is demonstrated by an increase of about 9% in the calculated concentrations of oxidised sulphur in precipitation in the Present_HiSulphur scenario compared to the Present_Base calculation.

2.3 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 (Jonson et al., 2017, 2018). Irrespective of species and depositions, the largest contributions are seen for smaller countries with long coastlines exposed to the BAS as

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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 from BAS shipping is seen for NO_2 (Figure 3b), depositions of oxidised nitrogen (Figure 3d), 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 (Barregård et al., 2019), population weighted $PM_{2.5}$ concentrations are used.

Figure 4 shows calculated SOMO35 and the effect of BAS shipping on SOMO35 (left) [1] and the effects on annual average ozone (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 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 a combination of net ozone increases, mainly in the summer months, and ozone titration by NO, mainly in winter. In the BAS region net production and titration 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 expected emission reductions from 2016 to 2030 result in increased annual ozone levels in Germany. Even though annual ozone levels decrease, lower emissions will result in SOMO35 reductions in both these two cases as the titration events mainly occur in winter time when ozone levels are below 35 ppb.

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 Vinken et al. (2011); Huszar et al. (2010) have shown that this could lead to an overestimation of ozone formation. However, Vinken et al. (2011) 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

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3 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, emissions of non-sulphur particles from BAS shipping are 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 (Klein et al., 2018)). 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 (Barregård et al., 2019) 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 $PM_{2.5}$ 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. 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 Klein et al. (2018) 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.

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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Competing interests. There are no competing interests

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Table 1. Annual average measured (Obs) and model calculated concentrations (Calc) of NO_2, SO_2 and $PM_{2.5}$ for the present (2016) Base, NoShip, HiSulphur scenarios. Also listed are 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 correlations and RMS errors are not listed. The timeseries plots for the same sites are shown in appendix A. 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.

NO_2

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

SO_2

Station	Km Balt.	Obs	Calc	Corr.	RMS	Calc.	Corr	RMS	Calc	Corr.	RMS
Aspvreten	10	0.10	0.25	0.11	0.34	0.30	0.13	0.38	0.25	0.11	0.34
Råö	10	0.12	0.09	0.29	0.12	0.22	0.31	0.21	0.07	0.26	0.13
Hallahus	50	0.13	0.14	0.58	0.16	0.21	0.55	0.19	0.13	0.61	0.15
Utö	10	0.15	0.09	0.23	0.27	0.23	0.12	0.30	0.08	0.24	0.28
Anholt	10	0.10	0.10	0.72	0.08	0.28	0.61	0.30	0.07	0.66	0.08
Risø	10	0.13	0.19	0.59	0.18	0.26	0.64	0.23	0.17	0.59	0.17
Vilsandy	10	0.30	0.11	0.37	0.43	0.18	0.28	0.42	0.10	0.38	0.43
Zingst	10	0.29	0.27	0.74	0.30	0.40	0.71	0.33	0.25	0.74	0.31
Rucava	100	0.20	0.18	0.48	0.30	0.21	0.48	0.30	0.18	0.48	0.30

PM2.5

Station	Km Balt.	Obs	Calc	Corr.	RMS	Calc.	Corr	RMS	Calc	Corr.	RMS
Hallahus	50	6.04	5.90			6.08			5.46		
Aspvreten	10	4.39	3.63	0.57	3.08	3.77	0.57	3.07	3.45	0.57	3.09
Råö	10	3.77	4.26	0.43	3.40	4.44	0.42	3.48	3.93	0.45	3.03
Rucava	100	9.08	4.63	0.50	7.31	4.77	0.50	7.23	4.43	0.51	7.40
Vilsandy	10	4.38	3.43	0.67	3.00	3.63	0.67	2.94	3.21	0.67	3.07

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Table 2. 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 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.

Wet dep. oxN

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

Wet dep. oxS

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

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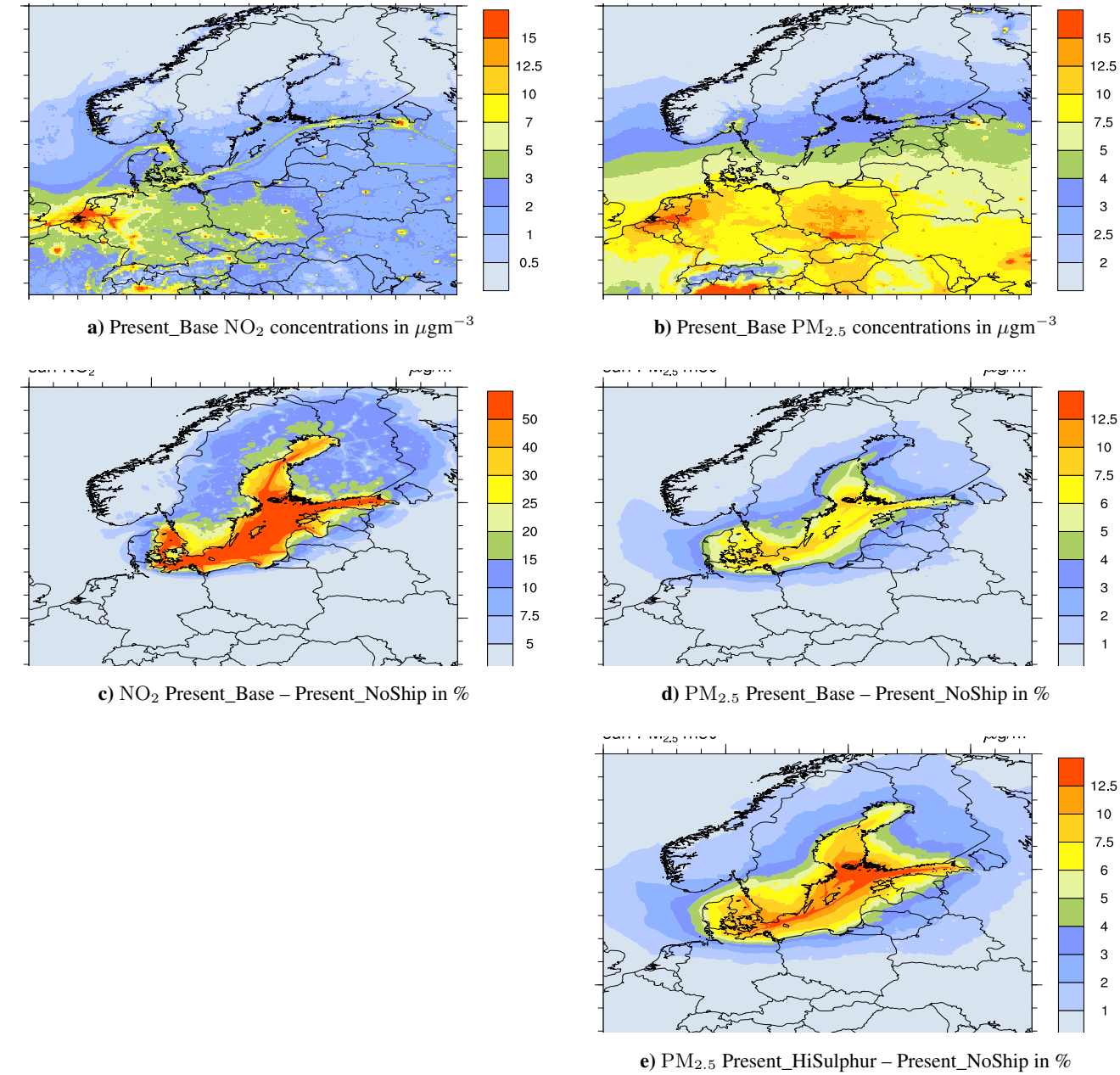

a) Present_Base NO_2 concentrations in μgm^{-3}

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.

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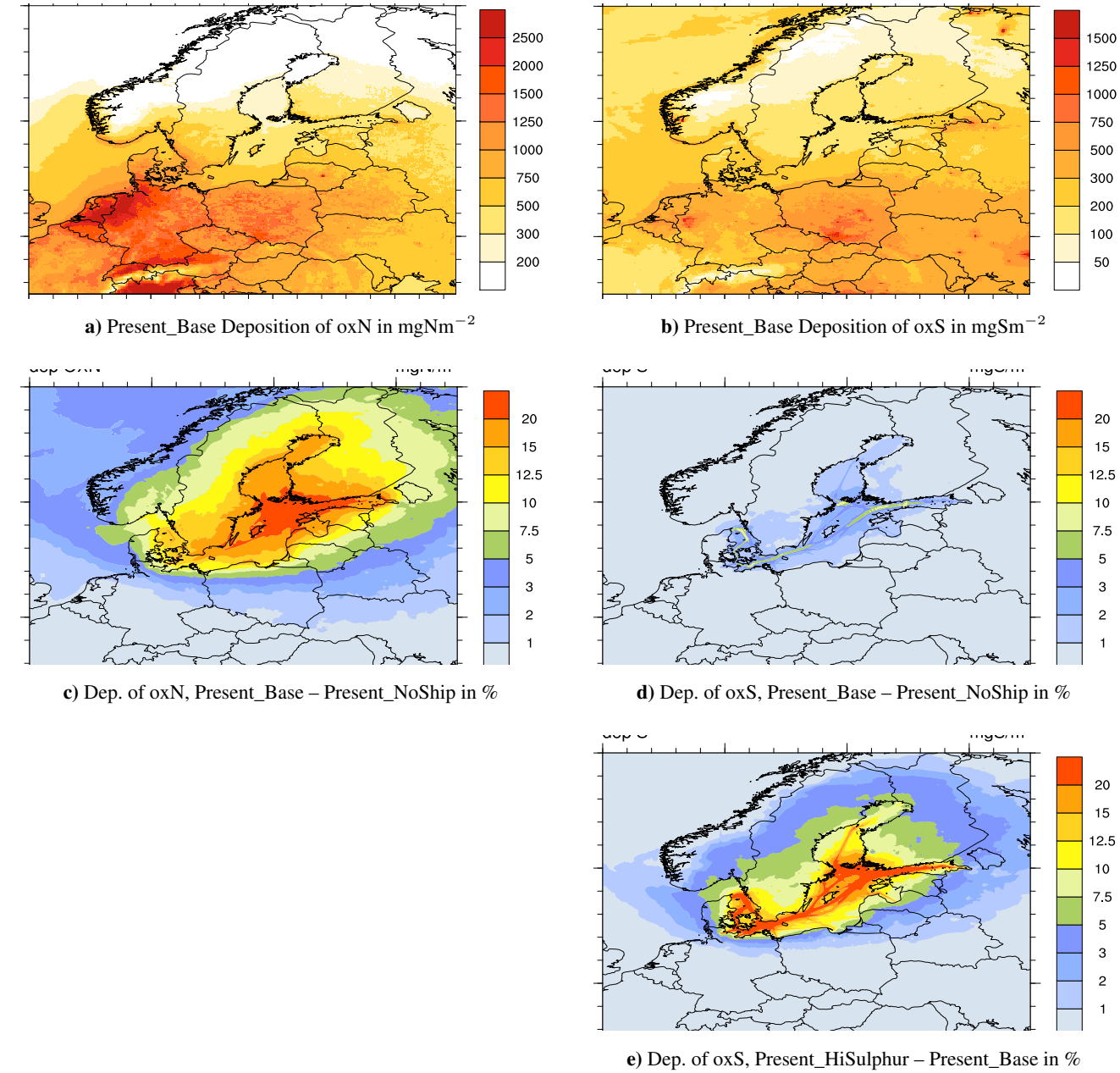

a) Present_Base Deposition of oxN in $mgNm^{-2}$

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.

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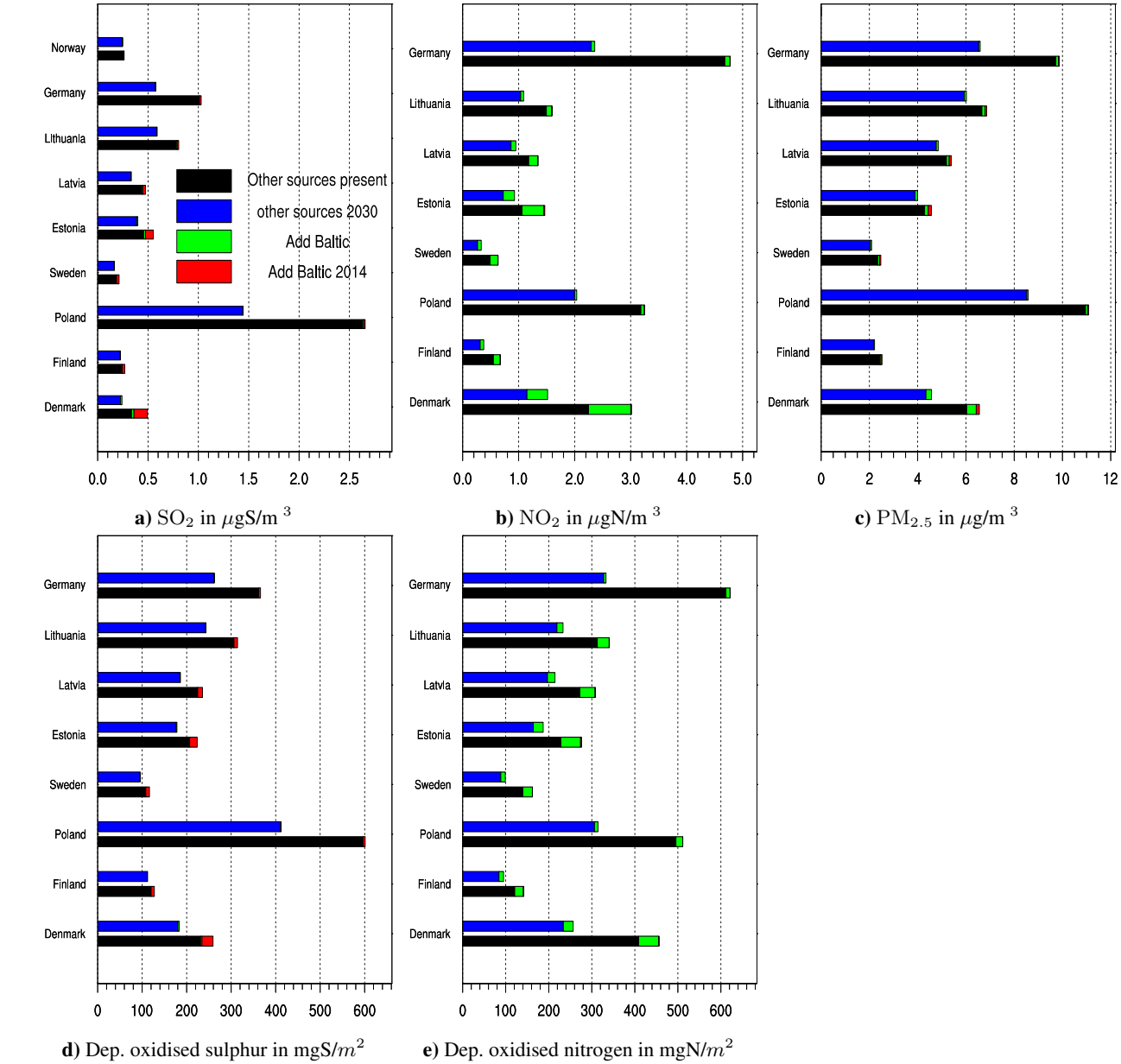

a) SO_2 in μgS/m ^{3} **b)** NO_2 in μgN/m ^{3} **c)** $PM_{2.5}$ in μg/m ^{3}

d) Dep. oxidised sulphur in mgS/m^2 **e)** Dep. oxidised nitrogen in mgN/m^2

Figure 3. For each country, the upper bar shows the present case and the lower bar the future 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 bars represent the Present_NoShip and Future_NoShip calculations respectively. The additional contributions from BAS are shown in green and the additional effect assuming high sulphur fuel emissions in red.

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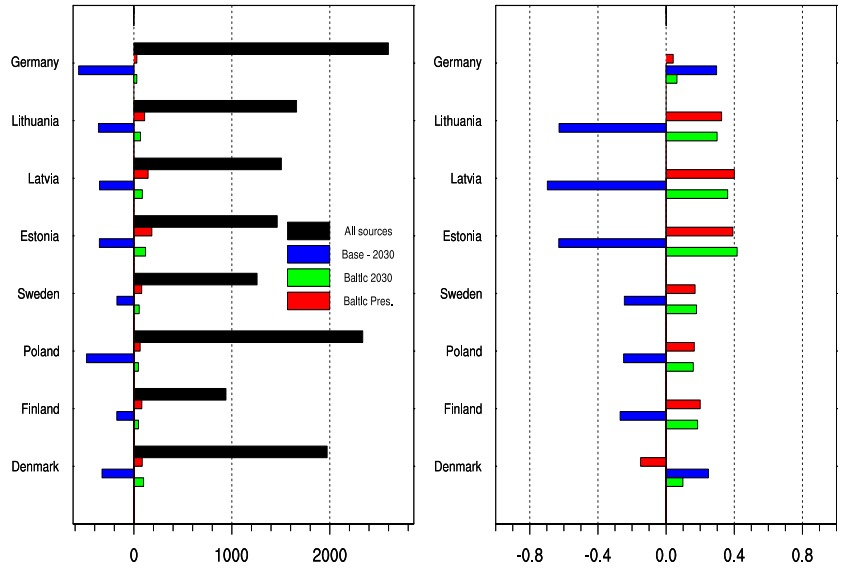

a) SOMO35 in ppb days **b)** ozone differences in ppb

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).

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Appendix A

This appendix contains time series plots for NO_2, SO_2 and $PM_{2.5}$ for the meteorological year 2016. Measured and model calculated annual average concentrations, correlations and RMS errors are listed in Table 1 in the main text. For many sites the timeseries for the different model scenarios are virtually identical, and the HiSulphur and NoShip scenarios are masked by the Base scenario.

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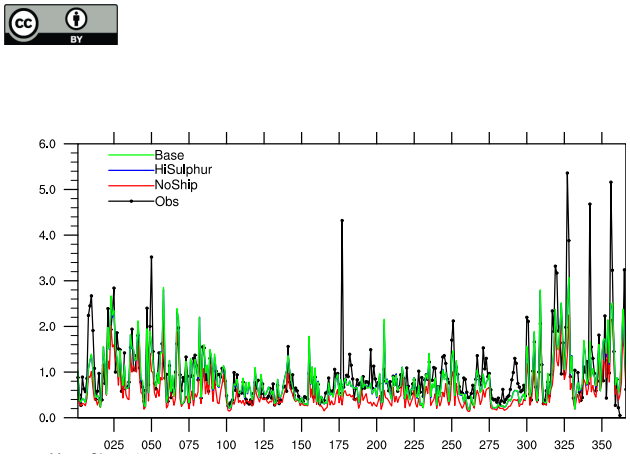
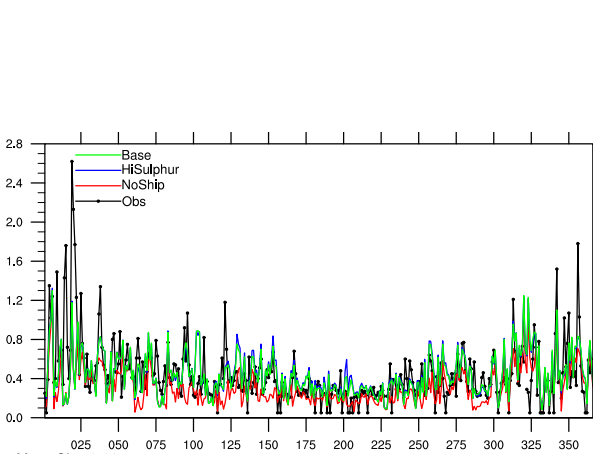
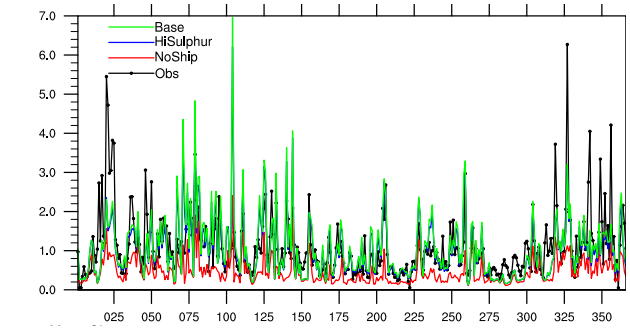


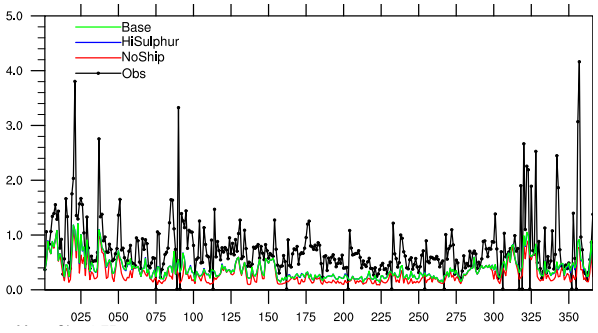
a) Hallahus NO_2 concentrations in μg(N)m^{-3}



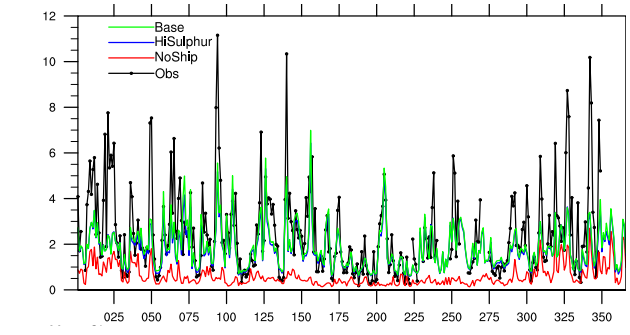
b) Aspvreten NO_2 concentrations in μg(N)m^{-3}



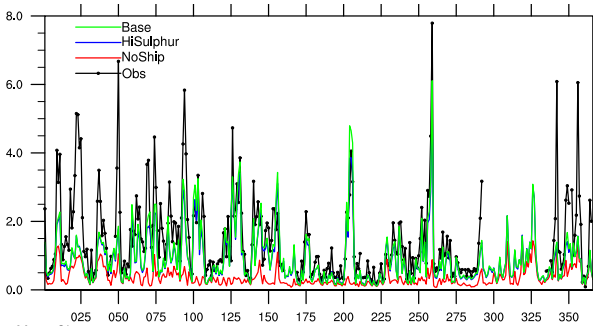
c) Raaö NO_2 concentrations in μg(N)m^{-3}



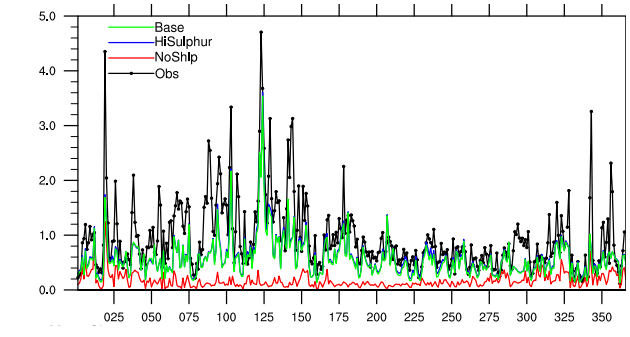
d) Rucava NO_2 concentrations in μg(N)m^{-3}



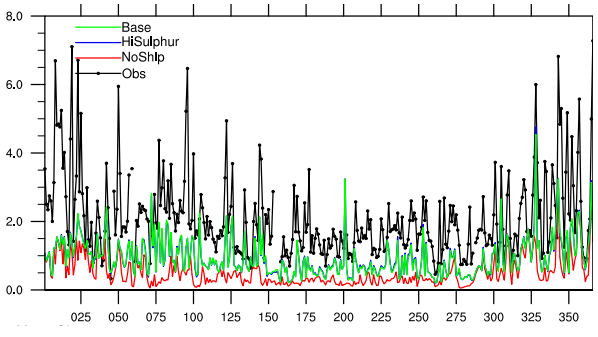
e) Keldsnor NO_2 concentrations in μg(N)m^{-3}



f) Anholt NO_2 concentrations in μg(N)m^{-3}



g) Ut ö NO_2 concentrations in μg(N)m^{-3}



h) Zingst NO_2 concentrations in μg(N)m^{-3}

Figure A1. Measured and model calculated present (2016) concentrations of NO_2. Present model calculated results are shown for the Base HiSulphur and the NoShip scenarios. The HiSulphur calculations are not visible as it is almost identical to Present_Base.

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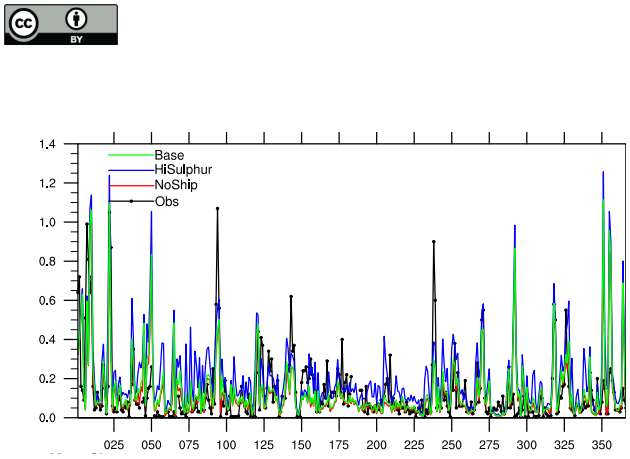
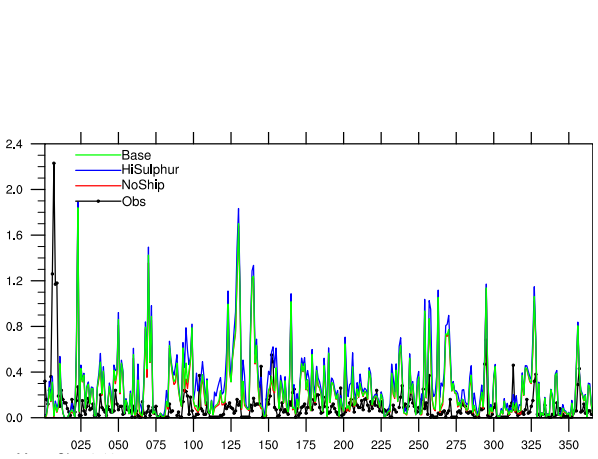
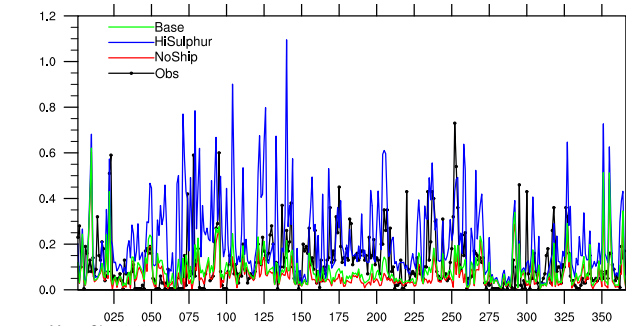


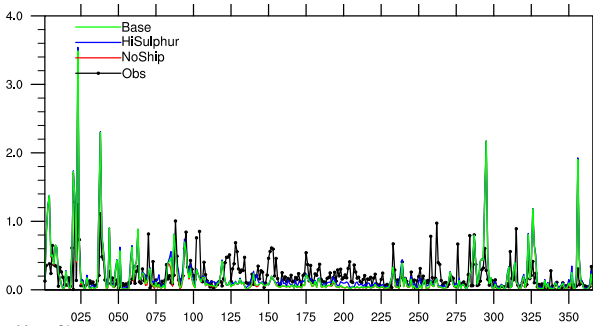
a) Hallahus SO_2 concentrations in $\mu g(S)m^{-3}$



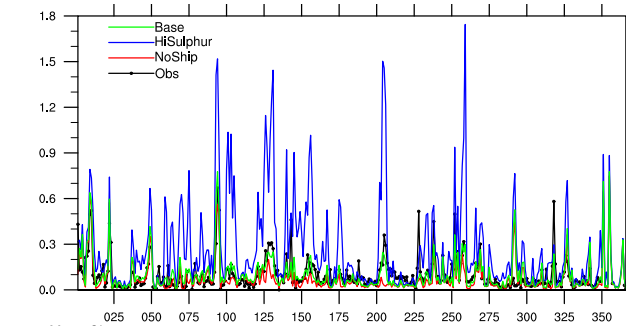
b) Aspvreten SO_2 concentrations in $\mu g(S)m^{-3}$



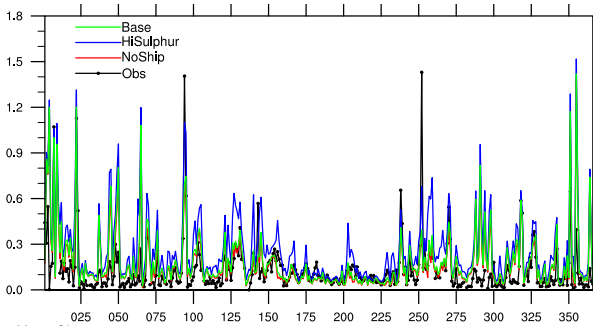
c) Raaö SO_2 concentrations in $\mu g(S)m^{-3}$



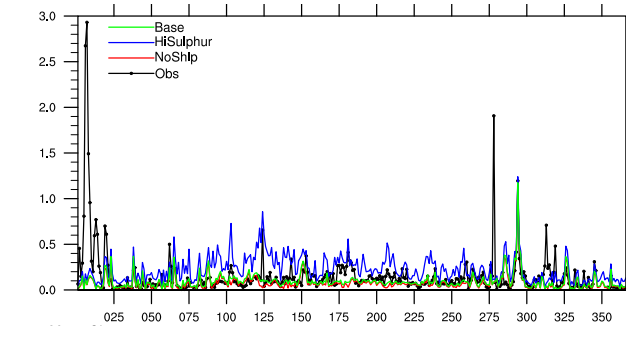
d) Rucava SO_2 concentrations in $\mu g(S)m^{-3}$



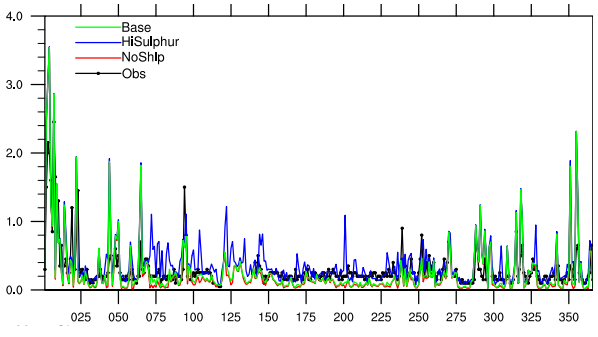
e) Anholt SO_2 concentrations in $\mu g(S)m^{-3}$



f) Risø SO_2 concentrations in μgm^{-3}



g) Utö SO_2 concentrations in μgm^{-3}



h) Zingst SO_2 concentrations in μgm^{-3}

Figure A2. Measured and model calculated present (2016) concentrations of SO_2. Present model calculated results are shown for the Base, HiSulphur and the NoShip scenarios.

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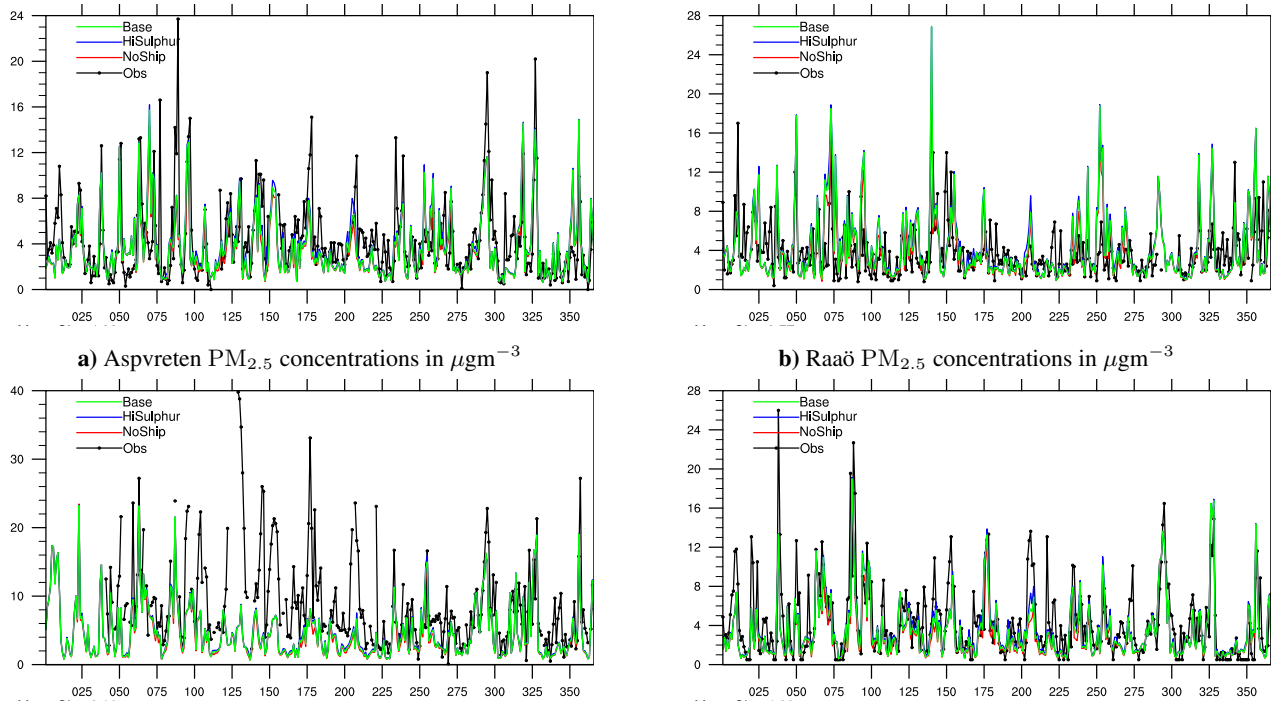

a) Aspvreten $PM_{2.5}$ concentrations in μgm^{-3}

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

c) Rucava $PM_{2.5}$ concentrations in μgm^{-3}

d) Vilsandy $PM_{2.5}$ concentrations in μgm^{-3}

Figure A3. Measured and model calculated present (2016) concentrations of $PM_{2.5}$. Present model calculated results are shown for the Base, HiSulphur and the NoShip scenarios.