

Dear Editor

Below follows a point-by-point reply to the comments raised in the review (answers to the comments in italics).

Comments to reviewer 1

1. The abstract must provide quantitative information. This concerns both the country averaged contributions from ships and the change of pollutant concentrations between 2016 and 2030.

We have added quantitative information for the contributions of Baltic Sea shipping to NO₂ and PM_{2.5} levels in the abstract.

The last part of the abstract now reads:

"From Baltic Sea shipping the largest contributions are calculated for NO₂ in air, accounting for more than 50% in central parts of the Baltic Sea. In coastal zones contributions to NO₂ and also nitrogen depositions can be of the order of 20% in some regions. Smaller effects, up to 5 – 10%, are seen for PM_{2.5} in coastal zones close to the main shipping lanes. 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 Baltic Sea shipping now have virtually no effects on PM_{2.5} concentrations and sulphur depositions in the Baltic Sea region.

Adding to the expected reductions of air pollutants and depositions following the projected reductions in European emissions, we expect that the contributions from Baltic Sea shipping to NO₂ and PM_{2.5} concentrations, and to depositions of nitrogen, will be reduced by 40 – 50% from 2016 to 2030 mainly as a result of the Baltic Sea being defined as a Nitrogen Emission Control Area from 2021. In most parts of the Baltic Sea region ozone levels are expected to decrease from 2016 to 2030. For the Baltic Sea shipping, titration, mainly in winter, and production, mainly in summer, partially compensate. As a result the effects of Baltic Sea shipping on ozone is similar in 2016 and 2030."

2. The global emission dataset ECLIPSE version 5a was used, which has a horizontal resolution of 0.5 x 0.5 degrees. It needs to be specified how these coarse emissions have been resampled to the EMEP model grid of 0.1 x 0.1 degrees for Europe. Which proxies were used or was the emission data simply interpolated, ignoring smaller urban areas? It should also be stated how emissions of large point sources were handled.

*We have added more information on the re-gridding of the Eclipse emissions:
"The ECLIPSE v5a emissions were re-gridded using the TNO-MACC-III 0.125x0.0625*

lon-lat emission distribution Kuenen et al. (2014) for year 2011. During the re-gridding process only the spatial distribution of the ECLIPSE v5a emissions was modified, while the national and sector totals remained unchanged. Where TNO-MACC-III emissions are not available (such as North-Africa) the gridded ECLIPSE v5a emissions were interpolated to the TNO-MACC grid resolution. Any missing sectors for countries which were included in the TNO-MACC-III emission data were also completed from the interpolated ECLIPSE v5a emissions.”

3. In the Conclusion (p.9, Line 24-27), a source-receptor calculation for secondary inorganic aerosol (SIA) is referred which was not presented in the paper. It needs to be clarified how the methodology of the present work (section 3.3) differs from the yearly reported source-receptor calculations in EMEP reports. Does the present study confirm the important contribution of the countries in the BAS region to levels of SIA (in PM_{2.5} and in PM₁₀) in the countries themselves and in Europe?

It should be noted that only the anthropogenic sources are considered in the source receptor calculations. We have included additional text here:

”EMEP source receptor calculations for the individual countries (see EMEP country reports for year 2016 (Klein et al. 2018)) show that, for many countries in the region, BAS shipping is among the 5 to 6 largest regions/countries contributing to SIA (Secondary Inorganic Aerosols). SIA is a major constituent of PM_{2.5} typically ranging from about 30 to 60% of PM_{2.5} mass in (scarce) measurements and in EMEP model calculations (Tsyro et al. 2018). Other constituents in PM_{2.5} include seasalt and organics (both natural and anthropogenic) with no or minor contributions from shipping as well as primary particles. As a result, the percentage contributions from BAS shipping to SIA is of the order of a factor of two higher than for PM_{2.5}. As the natural part of PM_{2.5} (and likewise PM₁₀) is not included in the EMEP source receptor calculations (EMEP 2018) they bears some resemblance to SIA. Thus the relative contributions from BAS shipping presented here is lower than the above source receptor calculations as it is compared to PM_{2.5} (and likewise PM₁₀) of both antropogenic and natural origin. In a global model calculation with ship emission from the BAS and NOS also provided by FMI, source receptor relationships are in the same range as the reported EMEP results for 2014 and 2016 (Jonson et al. 2018). It should however be noted that the EMEP source receptor relationships are calculated by perturbing the emissions by 15%, whereas in this study we have excluded the emissions altogether in the NoShip scenarios.”

4. Figure 3c shows that only a very small fraction of PM_{2.5} is from ships. What is the contribution of ships to SIA in the countries of the BAS region and how high is it in the coastal zones?

See discussion regarding point 3.

Comments to reviewer 3

1. Page 6, line 30-34: The results showed that the measured and modeled fraction

of SO₄ in PM_{2.5} only increase slightly with the Present_HiSulphur scenario. I suggest the authors provide possible explanations for the linkage between the SECA regulation and changes of SO₄ and PM_{2.5} (Present_HiSulphur-Present_Base).

We have included additional text here:

"Continuing a downward trend from the late 1980s, land-based sulphur emissions have decreased by more than 50%, i.e. more than for any other of the major air pollutants (Tista et al. 2018) and thus the importance of sulphur in particle formation has thus decreased relative to other anthropogenic emitted species and natural sources. In the SECAs the sulphur content in marine fuels has decreased from the global average of about 2.5% to 1% in 2011 and finally to 0.1% in 2015. As a result of these large emission reductions the fraction of SO₄ in PM_{2.5} in the BAS region has decreased even further here. At the sites in Table 2 both the measured and model calculated fraction of SO₄ in PM_{2.5} is about 0.15. As SO₄ make up a morerate portion of the PM_{2.5} composition this fraction increase only by a small amount with the Present_HiSulphur scenario."

2. Page 8, line 28-31: The statement In summer the increase caused by titration around the English channel..dominates the annual values. is confusing, as NO_x titration leads to ozone reduction. Is the increase of SOMO35 and annual ozone over English Channel contrast to decrease of ozone for the rest BAS caused by reduction of titration? If it is what the authors mean, it would be helpful to clearly state the increase of ozone (SOMO35 and annual averaged ozone) and reduction of titration.

We have added the word less. "... the increase caused by less titration around the English channel .."

3. Page 8, line 31-34 & Page 9, line 1-2:

(1) It would be helpful to remind reader by referring the figure in detail for better understanding the discussion. For example, for the paragraph As shown in Figure 4.are higher in 2030 (but SOMO35 is reduced), you can add (green bar) to specifically refer the bar in Figure 4.

We have added (green bars) when referring to Figure 4 here.

(2) The statement In 2030 the additional emissions from BAS shipping..except Denmark does not match what Figure 4 shows. This sentence seems to discuss the blue bar (contributions from BAS in 2030) in Figure 4 but all the countries have increased SOMO35 and annually average ozone due to BAS ship emissions in the future, including Denmark. Also, the following sentence Here average ozone decreases (in contrast to the case in 2016, where SOMO35 increases when adding the emissions from BAS shipping) is not clear either.

The reviewer is right in pointing out an error here. We have deleted the above mentioned sentence. This part now reads:

"In 2030 the additional emissions from BAS shipping result in increased SOMO35 and annually average ozone in all countries. (blue bars in Figure 4)."

4. Page 10, line 19-25: The authors discussed whether the target set by IMO could be achieved in the future based on the results of this paper. Here the connections between the IMO target and the results of this paper are not clear, given the IMO target described here mainly focus on CO₂ emissions and GHG emissions from shipping, while this paper focused on NO_x, SO₂, and PM_{2.5}. The linkages between IMO target and the findings in this study can be stated more clearly.

We have tried to make the meaning more clear.

"It is unlikely that this goal can be reached without substantial penetration of zero emission ships. If a portion of these zero emission ships run on electricity or hydrogen in 2030 they will be zero emission also for sulphur, nitrogen and PM_{2.5} (in addition to CO₂), potentially resulting in reductions of these air pollutants beyond what is assumed in the Future_Base scenario in this paper."

Technical comments

1. Page 3, line 1: Please specify what LNG stands for.

Added in brackets (Liquefied Natural Gas)

2. Page 17, Table2: The Base-model calculated values of NO₂ and SO₂ for the site Uto are negative.

Corrected. (Calc. and NMB had swapped places)

3. Page 18, Table2: The HiSulphur-model calculated value of SO₄ for the site Rao is negative.

Corrected (Calc. and NMB had swapped places)

3. Page 23, Figure 4: The figure descriptions and legends are not consistent (green bar should be Present_Base Future_Base; blue bar should be Future_Base Future_NoShip).

Corrected. We changed the colours in the plot to enhance readability of the text in figure a. Unfortunately we did not change the legend.