Sustainable Shipping and Environment of the Baltic Sea region

Project acronym: **BONUS SHEBA**

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Scientific final report

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Introduction

The BONUS SHEBA project has ended its 40 months of duration in July and is now finalising its final reporting and scientific publications. The main goal of the BONUS SHEBA project (Sustainable Shipping and Environment of the Baltic Sea Region) has been a holistic assessment of ecological, economic and societal impacts of operational shipping on the environment of the Baltic Sea region. The project methodology was to develop a Driver-Pressure-State-Impact-Response (DPSIR) assessment framework including the currently most advanced tools and models for determination of environmental pressures from shipping which would, in combination with evaluation of different future scenarios, also enable possibilities to test options for regulations and other policy measures that aim at the reduction of pressures, improvements of the state and minimized impacts on human health and ecosystems.

To achieve the main goal, BONUS SHEBA calculated the current and future emissions to water, to air, and of underwater noise through analyses of the drivers for shipping and their impacts on future ship traffic volumes and emission factors, using and extending the currently most advanced emission model which is based on Automatic Identification System (AIS) ship movement data and state-of-the-art emission factors as well as new emission factors developed within the project. Atmospheric, oceanic and noise propagation models in combination with ecotoxicology studies have been employed to assess the spatio-temporal distributions, fates and effects of these stressors in the Baltic Sea region and also to evaluate impacts of different pollutants on the water quality indicators of the EU Marine Strategy Framework Directive (MSFD) and Water Framework Directive (WFD) and on air quality indicators. Further, the project has provided an integrated assessment of policy options to mitigate pressures linked to shipping by quantifying as far as possible anticipated changes in ecosystem services, compared to an established baseline, including an analysis of the efficiency of policy options to reduce environmental pressures from shipping based on the cost-benefit principle.

Key messages:

- The drivers of the shipping sector were analysed and reported in a comprehensive report ‘Drivers for the shipping sector’ which can be downloaded on BONUS SHEBA webpage www.sheba-project.eu/deliverables/index.php.en. This analysis is used in the scenario work in BONUS SHEBA and in the harmonized scenario work of the BONUS projects coordinated by BONUS BALTICAPP project
- The work on scenarios has produced predictions of emissions to air and water as well as underwater noise for present times, 2030 and 2040 for shipping in the Baltic Sea. Secondly, shipping activities in two additional cumulative scenarios used in climate research (Sustainability and Fragmentation) were analysed. These were also used to identify the gaps between what is expected from shipping in the future and what is needed for shipping to become sustainable.
- A completely new model was developed to describe small boats, The Boat Emissions and Activity siMulator (BEAM) and has been applied to the Baltic Sea. The contribution of boats to most air pollutants is negligible, but hydrocarbon and carbon monoxide emissions are high. Also, the combined wet surface area of boats is almost as large as the contribution of

big ships. This makes boats potentially a significant source of pollution considering the anti-fouling paint residues.

- The work package on air pollution (WP2) performed extensive atmospheric chemistry modelling of impact of the shipping in the Baltic Sea on air quality and on deposition of pollutants on the Baltic Sea as well as on coastal areas employing several atmospheric chemistry-transport models (CTMs) on both regional and urban scale. Three regional-scale CTMs were used in ensemble simulation of impact of year 2012 shipping emissions in the Baltic Sea region and three different future scenarios on Baltic Sea shipping in 2040 have been investigated with one of these models. Assessment of health impacts and impacts on coastal land ecosystems has been performed based on the model results. In addition, four port cities were studied employing 2 different urban-scale models. It could be shown that reduced fuel consumption achieved by efficiency increases together with strict regulations on sulphur and NOx emissions will lead to significant reductions of the impact of shipping on air pollution in the Baltic Sea area.
- Load factors of shipping-related water contaminants have been implemented into the Ship Traffic Emission Assessment Model (STEAM) and a spatio-temporally resolved emission inventory of pollutants for the entire Baltic Sea has been produced. This new model development will be applied in annual ship emission reporting for the benefit of HELCOM member states.
- Simulations with the coupled 3-d hydrodynamic-biogeochemical marine model GETM-ERGOM utilizing the spatial resolved emissions and deposition has been used to investigate 1) fate and effect of nutrient inputs (D3.4), 2) surface water pH change (D3.6), 3) distribution and viability of invasive species (D3.8) and PEC/PNEC ratios or the Sum of Toxic Units (STU) from shipping related top ranked contaminant input (D.3.5). Shipping related nano- and micro-particles are of emerging interest, but the yet too scarce data to allow for reliable modelling, led to a report on the topic. Results from BONUS SHEBA served as input to the 'Chemical risk assessment of contaminants in grey water from ships' of Swedish transport administration.
- The impact of shipping on the marine environment along five potential future scenarios were analysed in relation to the two EU Directives, Marine Strategy Framework Directive (MSFD) and Water Framework Directive (WFD), showing that some of the descriptors and quality elements in these directives are negatively affected by future shipping in the Baltic Sea.
- Project has finalized a field sampling campaign in the Baltic Sea shipping lanes, where both atmospheric and water pollutants were measured.
- The Wittekind model was implemented into the STEAM model which is now able to produce point sources of underwater noise emissions. The BONUS SHEBA approach calculates the noise energy (Joules) emitted from ships at specific frequency bands. This additive quantity can be used not only as a noise map visualisations, but also as an indication of annual changes of shipping noise emissions in various parts of the Baltic Sea, which will be applied in annual ship emission reporting for the benefit of HELCOM member states. Based on the project results, containerships were identified as the largest contributor to shipping noise. However, considering the travelled distances, the noisiest vessels may be found in the RoPax class of ships.
- The experimental campaign concerning tracking of fish behaviour as a function of underwater noise level was completed during the summer 2016. Preliminary analysis

revealed that upon exposure to loud shipping noise, a cautious defensive reaction was observed. However, clear panic reaction or physical injury was not observed.

- Significantly more work is needed to gain a comprehensive view on noise impacts, for example monitoring network for noise needs to be established, before complete soundscape for the Baltic Sea area can be obtained.
- The work package on assessments and policies (WP 5) adapted existing DPSIR (Driver-Pressure-State-Impact-Response) frameworks to the Baltic Sea and shipping. The framework was developed to assess the linkages from the pressures of shipping in the Baltic Sea to its effects on ecosystem services and human wellbeing.
- 20 selected policy options reducing environmental pressures from shipping in the Baltic have been assessed. The evaluation of the 20 policy options is based on a developed multidimensional assessment framework using stakeholder consultation, expert judgement and literature review. The stakeholder consultation included sessions on two stakeholder workshops and a web-survey.
- BONUS SHEBA has established interaction with stakeholders on different levels. Stakeholders were consulted for dedicated topics in order to support especially the scenario building process of BONUS SHEBA in two stakeholder elicitation events and in a web questionnaire. The project organised a number of outreach activities oriented to different stakeholders, among these: 1. Exhibition and seminar of cluster of 5 BONUS shipping projects on Swedish politicians' week in Almedalen in 2016, 2. Several contributions to the "Forschung vor Anker" events of HZG at the Baltic coast, 3. A conference on "Shipping and the Environment", jointly organized with the project SOLAS (International Surface Ocean - Lower Atmosphere Study), brought together about 120 scientists and stakeholders of the shipping sector from all over the world.
- BONUS SHEBA has become a flagship project of the European Union Strategy for the Baltic Sea Region (EUSBSR) and throughout the duration of the project informed the international steering board of the EUSBSR Policy Area Ship on work progress of the project on their annual meetings. The project became a partner of starting-up the INTERREG Clean Shipping Project Platform CSHIPP. BONUS SHEBA has also become a part of the Baltic Earth (www.baltic-earth.eu).

1. Scientific results achieved during the project

1.1. WP1, Policies, activity data and scenarios

The objectives of WP1 were:

- Assess economic, environmental and societal drivers of change on the shipping activities taking into account relevant policy developments
- Update shipping activity data using AIS data from HELCOM and data on activity for pleasure boats.
- Develop scenarios for future shipping activities in the Baltic Sea for the years 2030 and 2040.

The report 'Drivers for the shipping sector' (D1.1) assessed the current policy and socioeconomic drivers affecting shipping and other vessels globally and in the Baltic Sea region. The report provided a 'baseline' reference of key policy and socioeconomic drivers against which potential future changes to vessel activity were assessed. There is a description on the key policies affecting shipping internationally (mainly IMO), from the EU and within the Baltic Sea region as well as national legislation within the Baltic Sea states (see Figure 1). In addition socio-economic drivers affecting shipping were described. The results of this report were used to help create the scenarios in Task 1.3 *Future scenarios*.

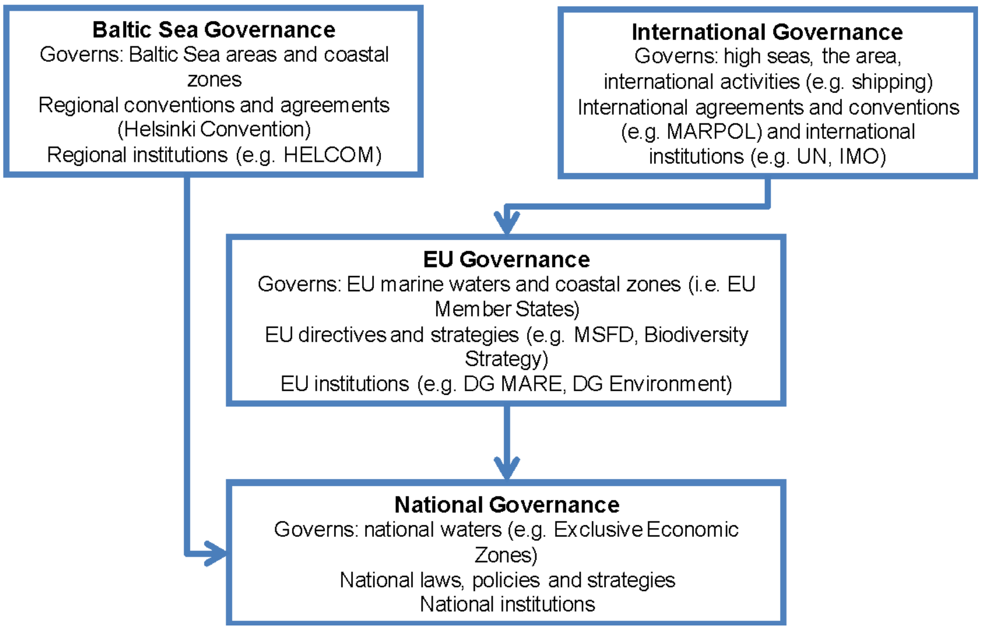


Figure 1 Overview of Marine Governance Levels

A model for emissions from leisure boats in the Baltic Sea has been developed further and a paper manuscript has been written. Figure 2 shows the calculated distribution of fuel consumption in leisure boats. The results show significant emissions to air, especially of carbon monoxide and hydrocarbons. This is mainly associated with poor performance of many old Otto engines and is concerning, especially since the emissions are close to the coast lines. Also leakage of Cu and Zn from antifouling paints applied on the boat hull is a concern.

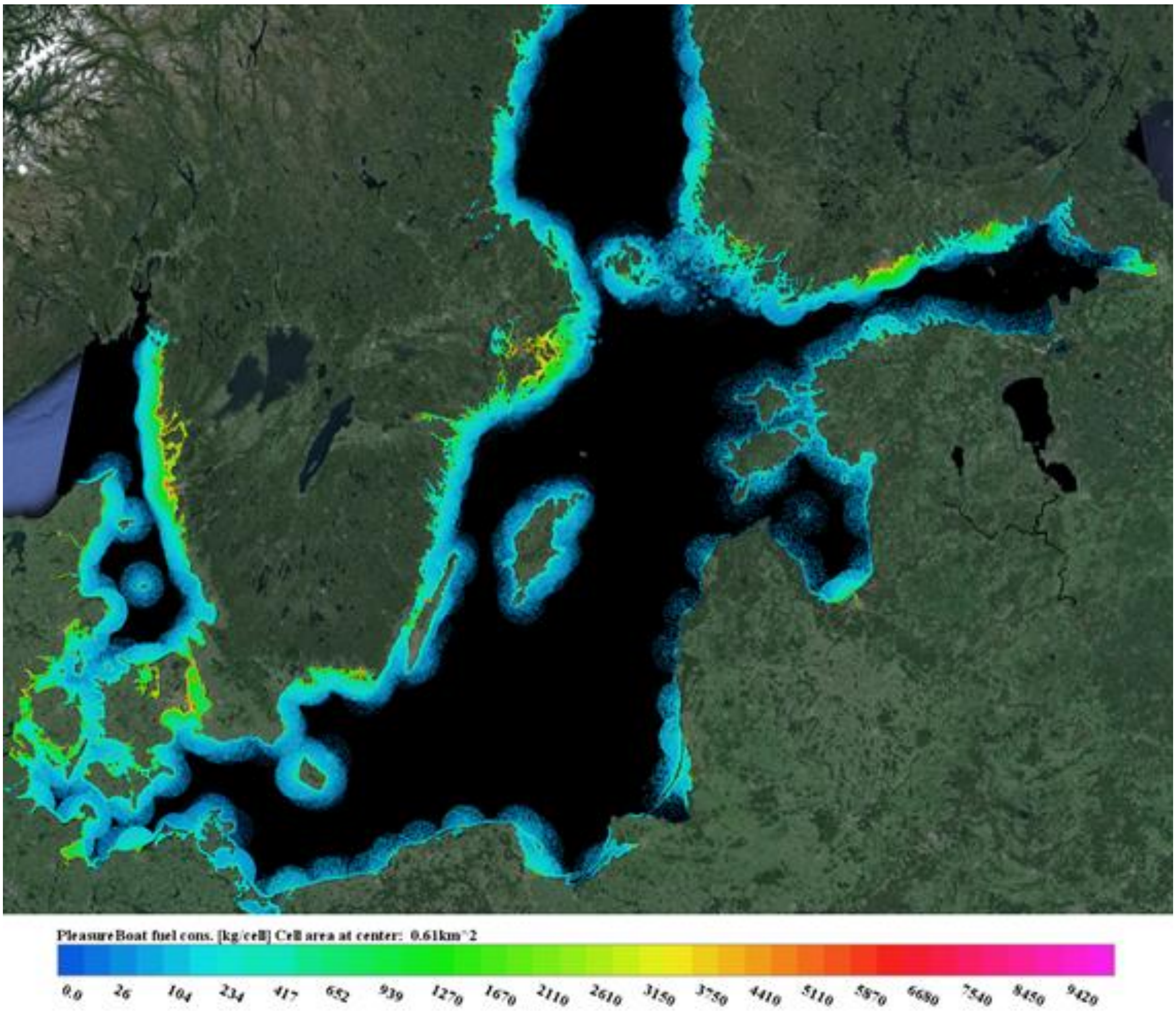


Figure 2 Estimated total fuel consumption of the Baltic Sea leisure boats.

The vessel activity of the Baltic Sea shipping has been produced in D1.2 described by the position reports sent by the Automatic Identification System (AIS). It is mandatory for all vessels and consists of position updates of every vessel with two second intervals. In SHEBA, AIS data is the raw material which will be used to generate datasets describing the contribution of ships to air pollution, water pollution and underwater noise. Previously, vessel activity has been one of the largest unknowns in environmental impact studies of shipping, but the use of navigation data such as AIS have significantly reduced the uncertainty commonly associated with the shipping sector. The D1.2 report described the AIS dataset and how it was used to generate various emission data required by consecutive work of WPs 2-4.

The background assumptions for the scenarios used in SHEBA were presented in D1.4. The business as usual scenario considered decided legislation and expected transport demand to construct a scenario that describes ship types and size, shipping routes, fuel mix in the sector and the use of technologies relevant for the environmental impact (scrubbers, NO_X-abatement, ballast water systems, underwater noise, etc.).

The work on scenarios has produced predictions of emissions to air and water as well as underwater noise for present times, 2030 and 2040 for shipping in the Baltic Sea. The results are displayed for a number of pollutants and disaggregated by ship type. Figure 3 shows an example with the emissions to air in the business-as-usual (BAU) scenario.

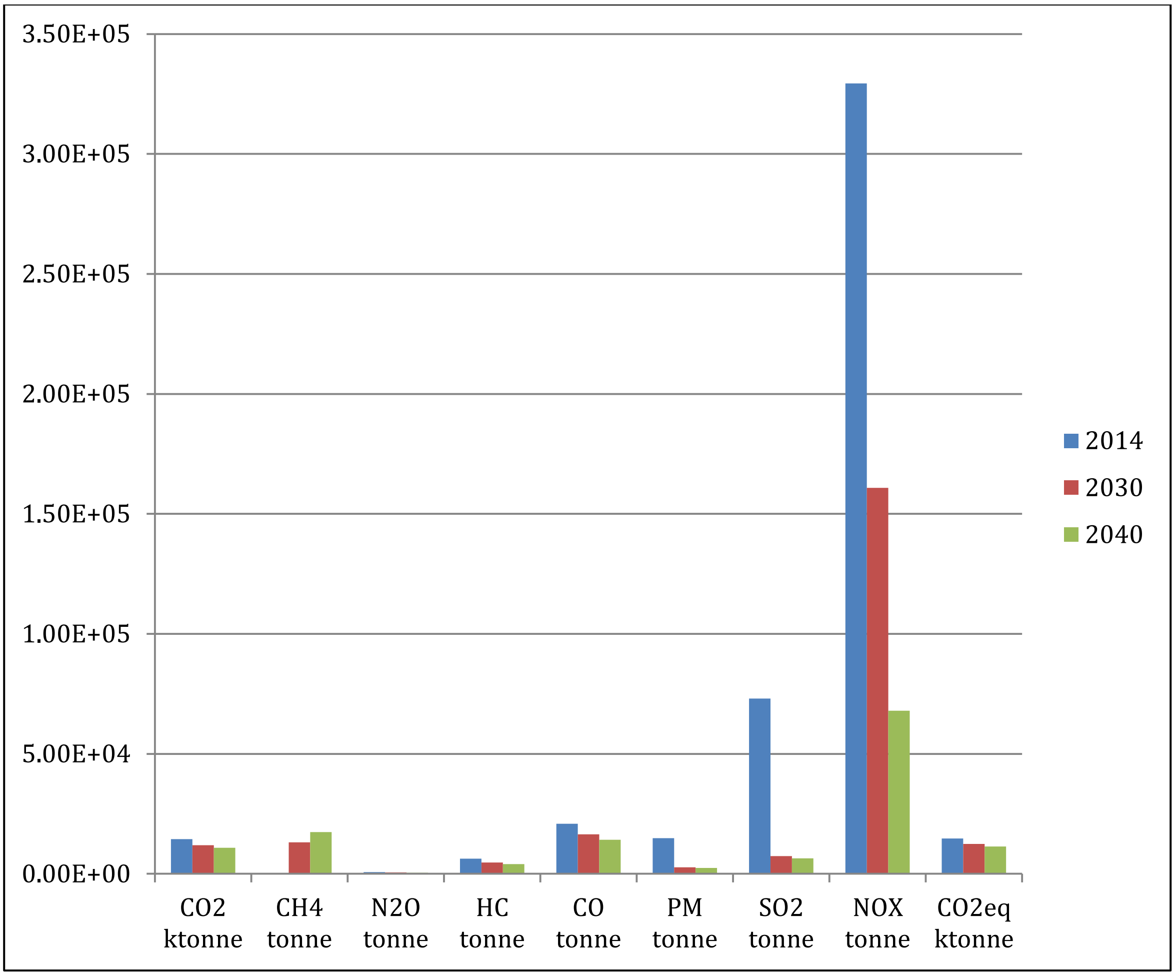


Figure 3 Emissions to air from all ships in the Baltic Sea in the BAU scenario.

Emissions have also been calculated for a number of the scenarios described in D1.4 and the data are being used in other WPs for further analysis on the impact on air and water and to calculate societal costs. The studies scenarios are summarised in Table 1 and some results regarding annual emissions and discharge volumes and amounts are given in Table S1 and S2 in the Supplement. The work on scenarios has been extensive through stakeholder consultations, literature reviews and project meetings. Scenarios are also being developed for the development of shipping within Shared Socio-Economic Pathways. This work has been done for the Baltic region by SHEBA in collaboration with other BONUS projects looking at other sectors.

In the deliverable “Sustainable Shipping Scenario” the emissions to air and water, as well as underwater noise are reported for 2030 and 2040. The scenarios include a business as usual scenario, a set of “single scenarios” aimed at investigating one specific topic, and “cumulative scenarios” describing different futures. A discussion was presented on what is needed to reach sustainable shipping. The latter was then identified either as SSP1 or as a set of policy objectives found for emissions of greenhouse gases and air pollutants, water quality and noise emissions.

Table 1. Summary of scenarios discussed in D1.5.

Scenario type	Name	Description
Cumulative	Business as usual (SSP2)	Includes current trends in the development of shipping and already decided regulations
Single	NoNECA	If a NECA in the Baltic Sea would not come in place
Single	No emissions to water	Most stringent possible regulations for emissions to water
Single	LNG	Significantly larger use of LNG
Single	Slow steaming	Further speed reductions
Single	EEDI	Energy efficiency follows the EEDI regulation
Single	Scrubber	Large use of scrubbers (open or closed loop)
Cumulative	SSP1 - Sustainability	A development with high concern for the environment and good technology development
Cumulative	SSP3 - Fragmentation	Development in some regions and poverty in others. Continued fossil fuel dependency and failure to meet environmental goals.

To reach the White Paper objective for greenhouse gases implies both efficiency gains and an increased use of renewable fuels. There is still a large potential for efficiency gains through better ship and engine design and through operational measures, mainly slower speeds and the objective is not unrealistic. State of the art ships can be almost 50 % more efficient than ships that are 10-20 years old. Biofuels, wind power and electrification could play a large part. The energy efficiency gains are to a large extent happening already while the introduction of renewable fuels may require policy measures such as a CO_2 tax and subsidiaries for electrification.

The policy objectives for reduced SO_2 within the SECA as well as reduced emissions of PM will mainly be reached by using low sulphur fuels, such as MGO and LNG, and by using scrubbers. New fuels such as LNG are only taken up slowly as investment costs are higher compared to standard systems. Furthermore, network of fuelling infrastructure still needs to be extended. The emissions reductions for NO_X within a NECA are reached by using established abatement methods such as SCR or EGR, or by switching fuel to LNG. There is also room for further reductions exceeding existing policy objectives – for NO_X SCR can be designed to reach much lower levels than Tier III of NECA, for PM (including black carbon) the application of filters and cleaner fuels can reduce the emissions further.

There are existing methods that can be employed to reduce emissions to water from ships, many simply involving leaving waste streams in ports. The direct nutrient load from scrubbers can also be reduced by using treatment plants on board. However, issues with toxic paints remain; here is a need for development of new products that will not leach contaminant into the sea. It might be necessary to combine new paints with mechanical cleaning systems to reach a sufficient effect. The transportation of invasive species with ballast water will be minimised in the future but the problems with the hull will remain.

The issue with underwater noise can be addressed through the development of engines and propellers and at the same time ship speed will have an influence.

1.2. WP2, Air pollution

Air emissions from ships and their influence on air quality and atmospheric deposition was in the focus of work package 2. Model simulations of atmospheric transport and chemical transformations have been performed on the regional scale as well as on the city scale. The contribution of shipping to air quality and atmospheric deposition has been determined for the year 2012. In addition, emission scenarios developed in WP1 were taken as a basis for future scenario runs for the year 2040. The exposure of the population and the effects of shipping emissions on health have been calculated subsequently.

Shipping emissions

Shipping emissions were calculated with the STEAM model based on AIS ship movement data for the year 2012. The emission data contains NO_x, SO_2, CO, CO_2 and PM, which was further subdivided into EC, OC, SO_4 and ash. The data was delivered as hourly values with a spatial resolution of 2x2 km². Figure 4 shows NO_x emissions from ships in the Baltic Sea as annual values per grid cell. One can clearly identify the main shipping lanes from the South West Baltic to Finland, Estonia and Russia. There is also intensive ship traffic in the most western part of the Baltic Sea.

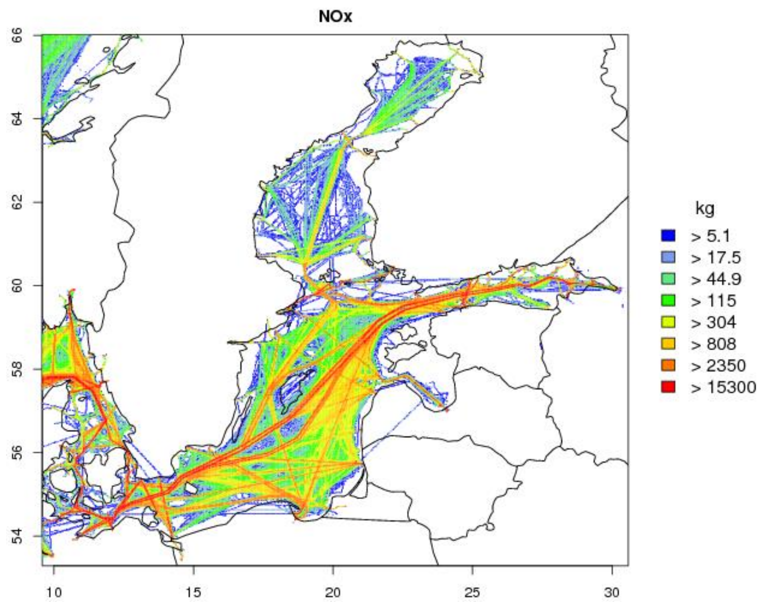


Figure 4: NOx emissions from ships travelling in the Baltic Sea in 2011 based on AIS data calculated with the STEAM model. Units are kg NOx (as NO2) per year and grid cell of 4 x 4 km².

Impacts of shipping on air quality in the Baltic Sea region in 2012

The CMAQ model was run for the entire year 2012 in order to quantify the impacts of shipping on the concentrations of numerous air pollutants. The most important ones are displayed in Figure 5 (for O_3), Figure 6 (for NO_2), and Figure 7 (for particle bound nitrate). Nitrate and NO_2 concentrations are higher in winter compared to summer while ozone is highest in summer because of its photochemical formation. It can be clearly seen that the impact of shipping on the concentrations of these pollutants is much lower in winter than in summer. In summer, shipping emissions may enhance ozone concentrations in coastal areas by on average 15 % and NO_2 concentrations by more than 50%. Over water, NO_2 concentrations are dominated by shipping emissions and they can be as high as in bigger cities. More detailed results for other months are given in BONUS-SHEBA Deliverable 2.3.

Nitrogen deposition (Figure 8) is also higher in summer than in winter, but this is mainly true over land where dry deposition of ammonia plays an important role. Although shipping affects mainly oxidized nitrogen, it may contribute more than 20% to the total nitrogen deposition in southern Sweden in summer.

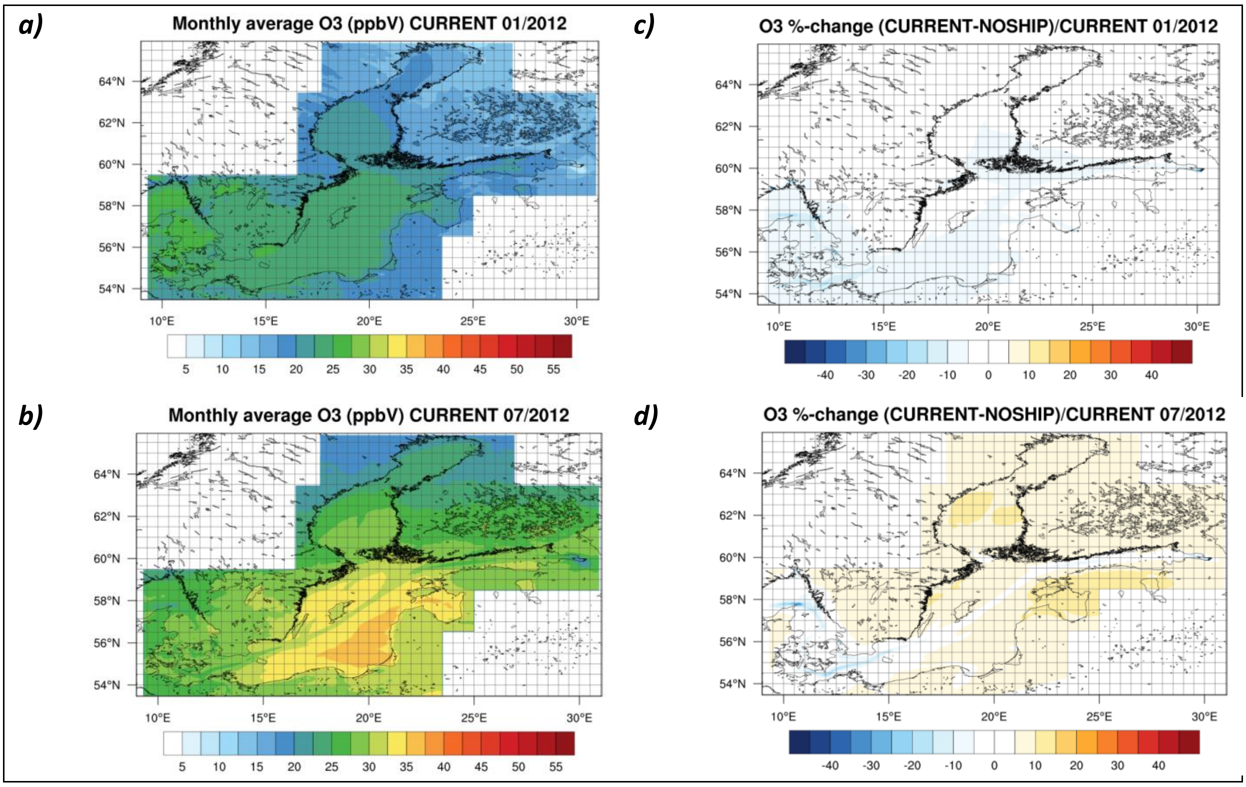


Figure 5: Monthly average ozone concentrations in January (a) and July (b) 2012 and the contribution of shipping emissions to them in January (c) and July (d) 2012.

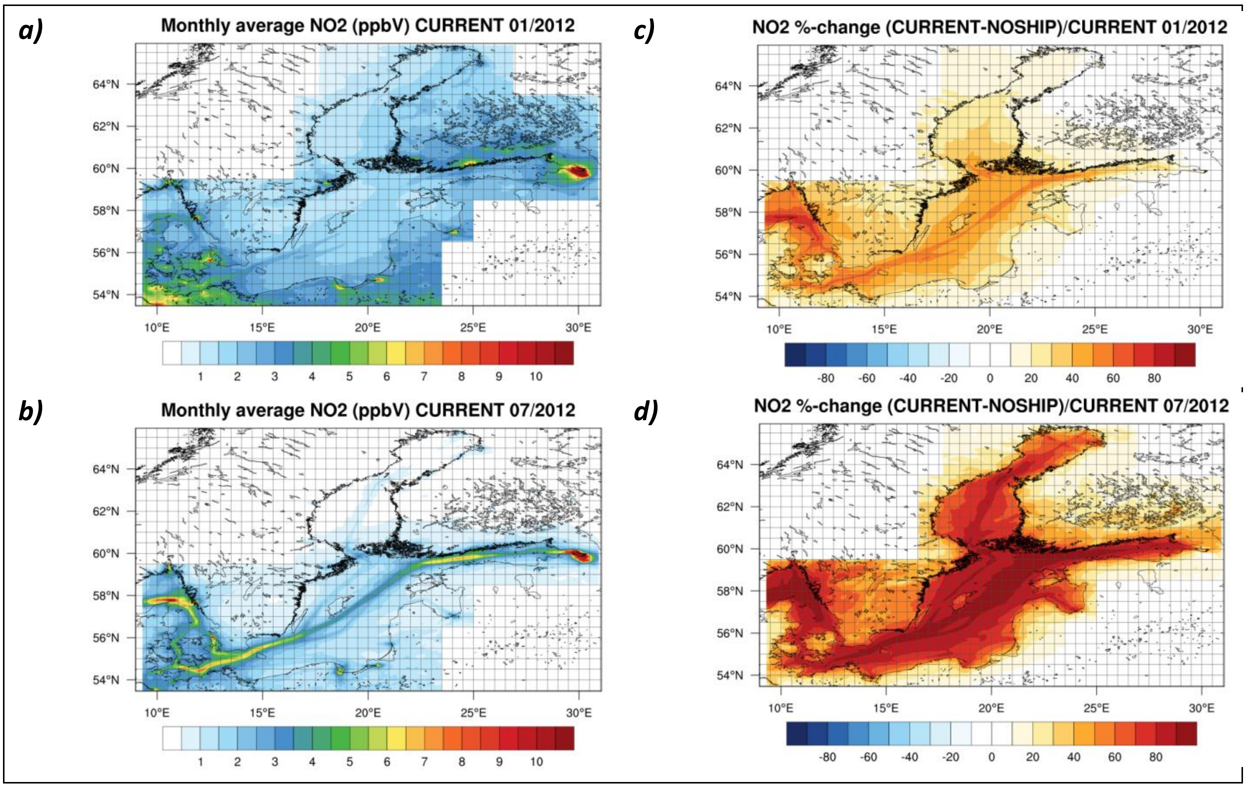


Figure 6: Monthly average NO2 concentrations in January (a) and July (b) 2012 and the contribution of shipping emissions to them in January (c) and July (d) 2012.

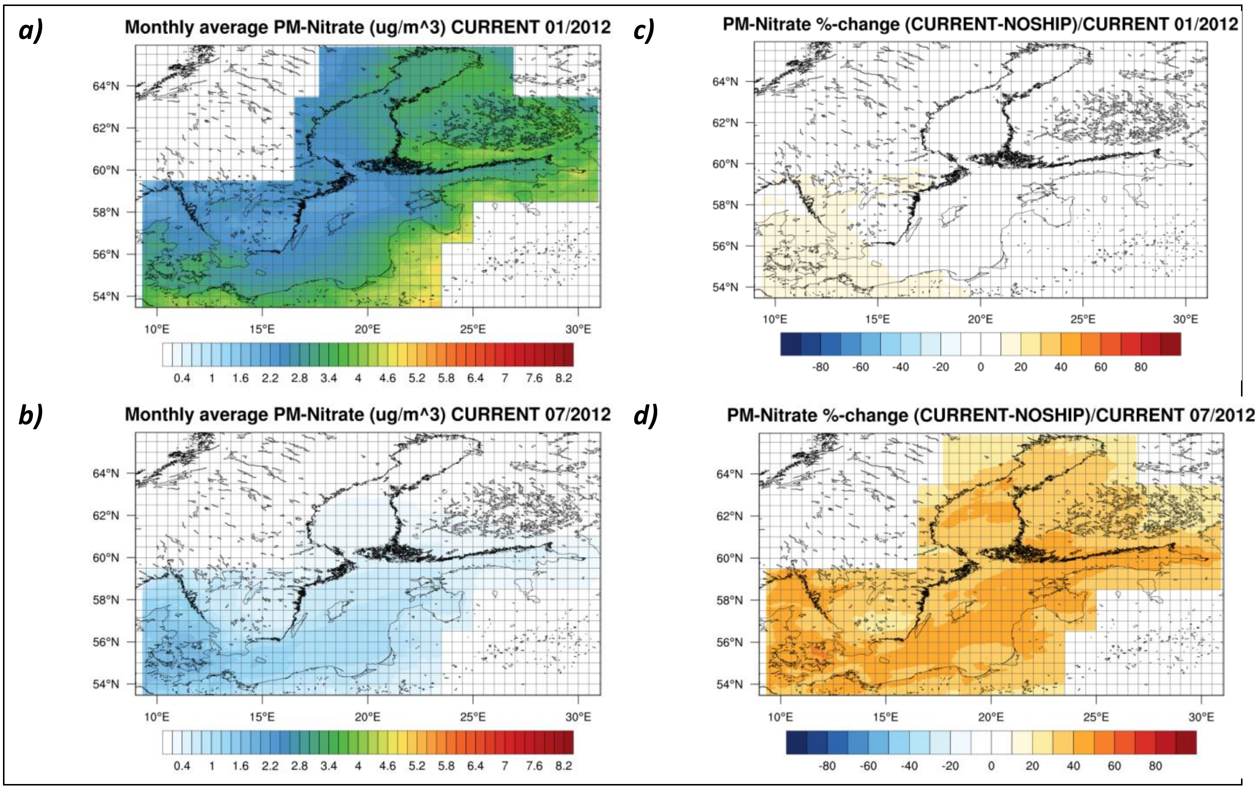


Figure 7: Monthly average particulate nitrate (NO_3^-) concentrations in January (a) and July (b) 2012 and the contribution of shipping emissions to them in January (c) and July (d) 2012.

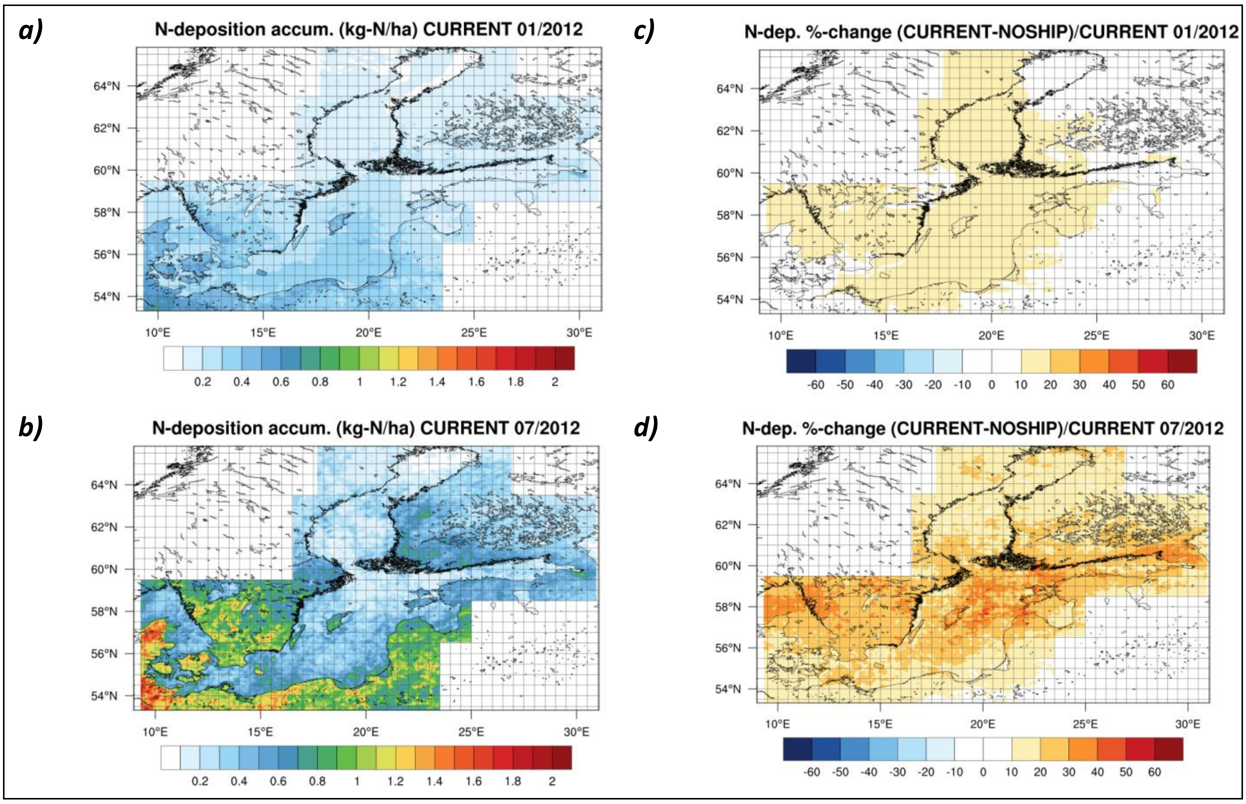


Figure 8: Monthly accumulated nitrogen deposition in January (a) and July (b) 2012 and the contribution of shipping emissions to it in January (c) and July (d) 2012.

Future scenarios 2040

Three of the future scenarios for shipping emissions in 2040 that were developed in WP1 were chosen for chemistry transport model calculations with the CMAQ model. Those were the BAU, the EEDI, and the NoNECA scenario (see Fig. 3 for the total emissions). Land based emissions were also scaled for the scenario runs, all following the current legislation scenario developed by IIASA in the ECLIPSE project. A detailed analysis of the results for NO_2 is shown for all scenarios in the summer months (June, July, August, JJA) in Figure 9. The results for ozone, particulate nitrate (NO_3^-), and atmospheric nitrogen deposition can be seen in the appendix (Figure S 1, Figure S 2, and Figure S 3).

In 2040, it can be expected that the NO_2 concentrations caused by shipping emissions will be significantly lower than today. Figure 9b shows that even in the shipping lanes over the Central Baltic Sea, NO_2 concentrations caused by ships will be between 0.5 and 1.5 ppb in summer, which is a reduction by 70 – 90 % compared to 2012 (Figure 9d). Even in the NoNECA scenario 50 – 60 % lower NO_2 concentrations from shipping can be expected over the Baltic Sea thanks to efficiency increases and a phase out of pre-Tier II ships.

While NO_x emissions from ships lead to ozone depletion over the Baltic Sea and higher ozone in coastal areas in 2012 (Figure S 1a), shipping lanes become almost invisible in the ozone maps for the BAU case in 2040 (Figure S 1b). Among the three scenarios, ozone concentrations are highest in the NoNECA case by approximately 2 ppb over land. In all three scenarios, ozone formation caused by shipping emissions is 15-20% lower than 2012, while some increase in the ozone concentrations can be seen where the most significant ozone titration was present in the south west Baltic Sea.

This will also affect the formation of particulate nitrate (Figure S 2). In the south west and the central Baltic Sea nitrate aerosol concentrations caused by shipping can be expected to be between 0.1 and 0.2 µg/m³ in the BAU scenario. This is a reduction by 50 – 70 % compared to 2012. In the NoNECA case, the reduction is weaker and lies between 30 and 40 % in the northern part of the Baltic Sea and between 40 and 50 % in the southern part.

Nitrogen deposition from shipping emissions (Figure S 3) will be below 0.15 kg N /ha in the BAU scenario in the three summer months. In many regions of the Baltic Sea it will even be below 0.05 kg/ha. This is 40-60 % lower than in 2012. In particular in southern Sweden deposition over land will be much lower than in 2012. In the NoNECA scenario, N deposition from shipping is reduced by 40-50 %, while the values for the EEDI case are between those for the other two.

Full information on the results for the future scenarios is given in BONUS-SHEBA Deliverable 2.5.

Model validation

For the year 2012, the concentrations of air pollutants in the Baltic Sea region and the impact of shipping on them was calculated with three model systems, CMAQ (HZG), SILAM (FMI) and EMEP (Met Norway). Met Norway investigated the Baltic Sea region in the framework of the ENVISUM project. They participated in the intercomparison because of a cooperation between ENVISUM and BONUS-SHEBA.

The results were compared to observations of NO_2 and $PM_{2.5}$ concentrations at a number of EMEP measurement stations (see examples in Figure S 4 and Figure S 5) and against each other on maps of annual average NO_2 concentrations (Figure 10). On average, SILAM showed the highest NO_2 concentrations at coastal stations, EMEP the lowest and CMAQ was in between the two. For $PM_{2.5}$, CMAQ showed the lowest values, in particular in summer. For NO_2, all models captured the concentrations quite well at Bornhöved in North Germany but they revealed too high values at the east coast of Sweden at Norr Malma. $PM_{2.5}$ was in good agreement between models and observations in winter, while in summer CMAQ and EMEP showed too low concentrations. The SILAM $PM_{2.5}$ concentrations were much higher but they typically overestimated the observations.

The spatial distributions of the annual average NO_2 concentrations (Figure 10) are quite different among the models. While the EMEP model shows quite distinct hot spots in cities and also along the main shipping lanes in the central Baltic, NO_2 concentrations from CMAQ and SILAM are much more dispersed. SILAM shows the highest dispersion and most likely also the longest atmospheric lifetime of all three models.

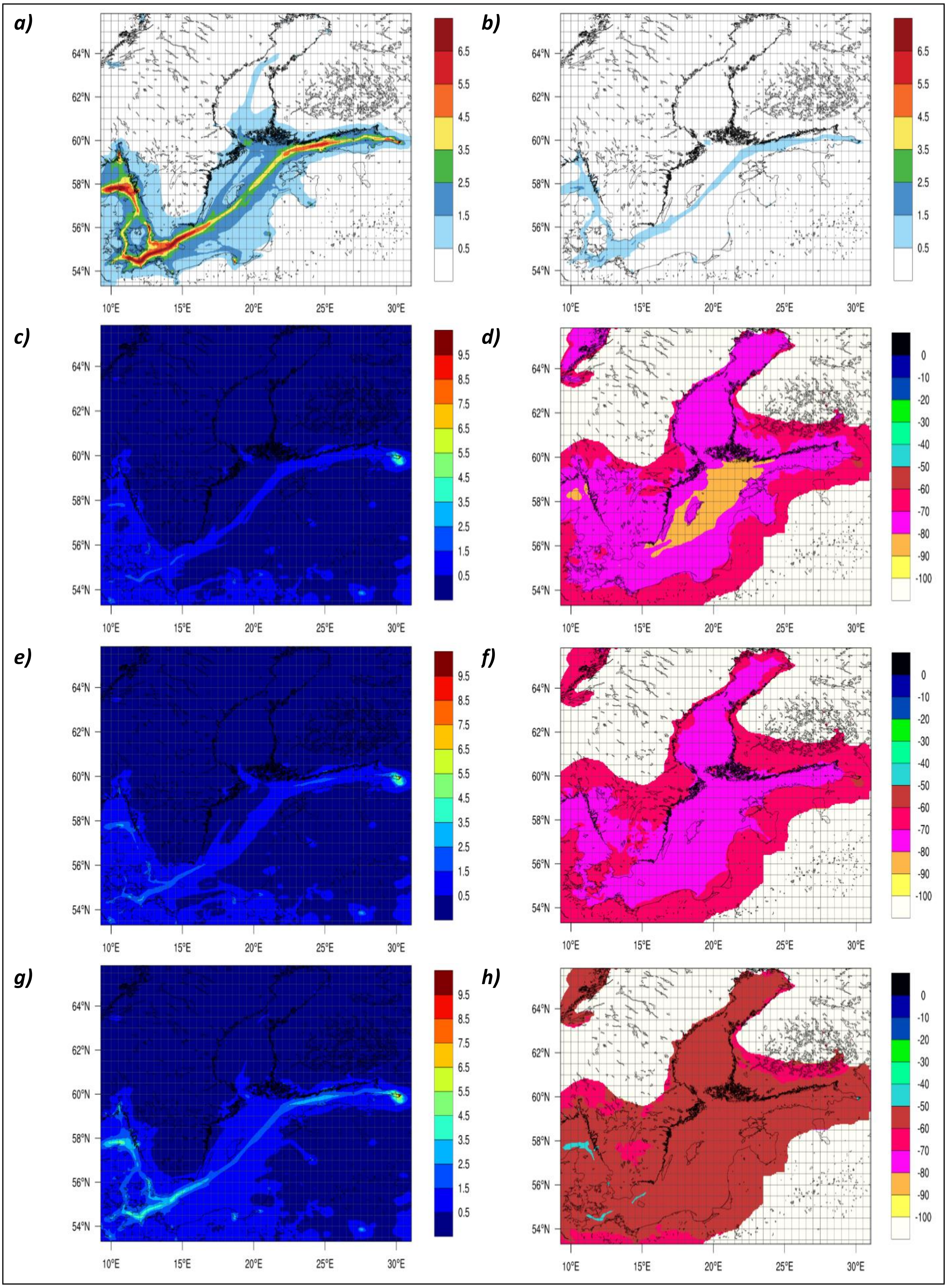


Figure 9: Air concentration of NO_2 as mean of summer months, JJA (unit: ppbV): future changes in the Baltic Sea region compared to present-day (2012) for three future scenarios. (a) Present-day ship contribution, (b) BAU scenario (2040) future ship contribution, (c) BAU scenario (2040) future situation, (d) relative change (%) of BAU scenario (2040) compared to present-day, (e) EEDI scenario (2040) future situation, (f) relative change (%) of EEDI scenario (2040) compared to present-day, (g) NoNECA scenario (2040) future situation, (h) relative change (%) of NoNECA scenario (2040) compared to present-day.

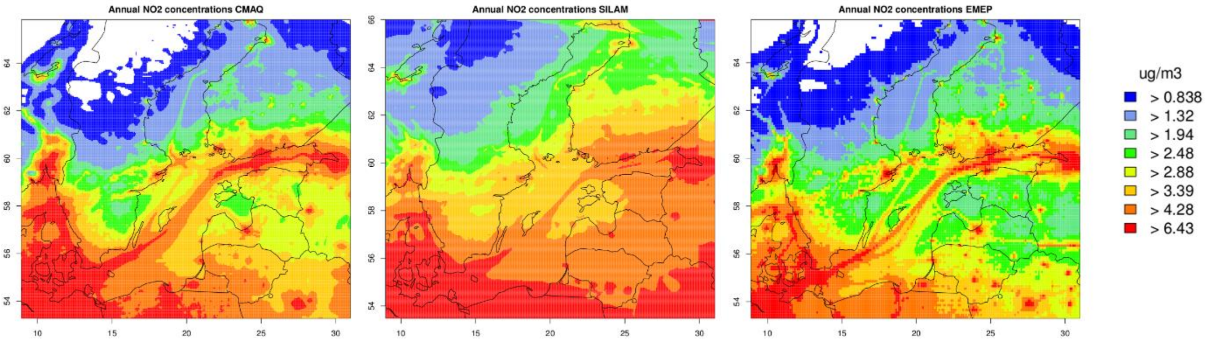


Figure 10: Intercomparison of the model results from CMAQ (left), SILAM (middle) and EMEP (right) for annual average NO2 concentrations in the Baltic Sea area.

City Scale results

In addition to the computation of the shipping impact on air quality in the entire Baltic Sea region, selected port cities were investigated with the city scale air quality models EPISODE-CityChem and TAPM. EPISODE-CityChem is developed at HZG by Matthias Karl. It has been applied to the cities of Rostock, Gdansk and Riga. Time series of NO_2 concentrations close to the main port areas can be seen in Figure S 6. For Rostock Warnemünde and Gdansk Noviport observations are given as well. The shipping impact on the NO_2 concentrations is clearly visible at all stations.

Concentrations of several air pollutants (NO_2, NO_x, O_3, PM_{10}, $PM_{2.5}$ and SO_2) together with the contribution of shipping to them in the city of Gothenburg are displayed in Figure 11. The model runs have been performed by the groups at IVL and at HZG with the TAPM model. This allowed for an additional intercomparison of the operational part of the model application. For Gothenburg, also 2 future scenarios were investigated, BAU and scenario with maximum uptake of shore electricity in ports. In Gothenburg, the main port area is west of the densely populated regions of the city. Because the wind is most frequently coming from the west and southwest, some of the main living areas suffer from air pollution caused by shipping emissions. Figure 12 shows a modelled time series of the NO_2 concentrations at Eriksberg, a recently developed living area in Gothenburg. It can be seen that on average more than one third of the NO_2 concentrations is caused by shipping emissions. Further information is given in BONUS-SHEBA Deliverable 2.4.

The modelled concentrations of the main air pollutants NO_2, O_3 and $PM_{2.5}$ can be used for calculating the exposure of the population to air pollutants from different sources. Figure 13 shows the modelled annual population exposure to NO_2 in Gothenburg in 2012 and 2040 and the relative contribution of shipping in 2012 and in 2040 BAU scenario. Figure S7 shows the corresponding results for $PM_{2.5}$.

To assess the extent of environmental damage due to ship emissions of N and S for the land area surrounding the Baltic Sea, the exceedance of critical loads for nutrient N and acidity has been calculated. The critical load (CL) is a threshold of the amount of pollutants that an ecosystem can tolerate before suffering unacceptable damage (Nilsson & Grennfelt, 1988) either through acidification of soils and waters or because of eutrophication. Exceedance of the critical load is the amount of deposition above the critical load, i.e. the measure of how much the deposition must decrease to prevent ecosystem damage. This concept is used within the convention for long-range transboundary air pollution (CLRTAP).

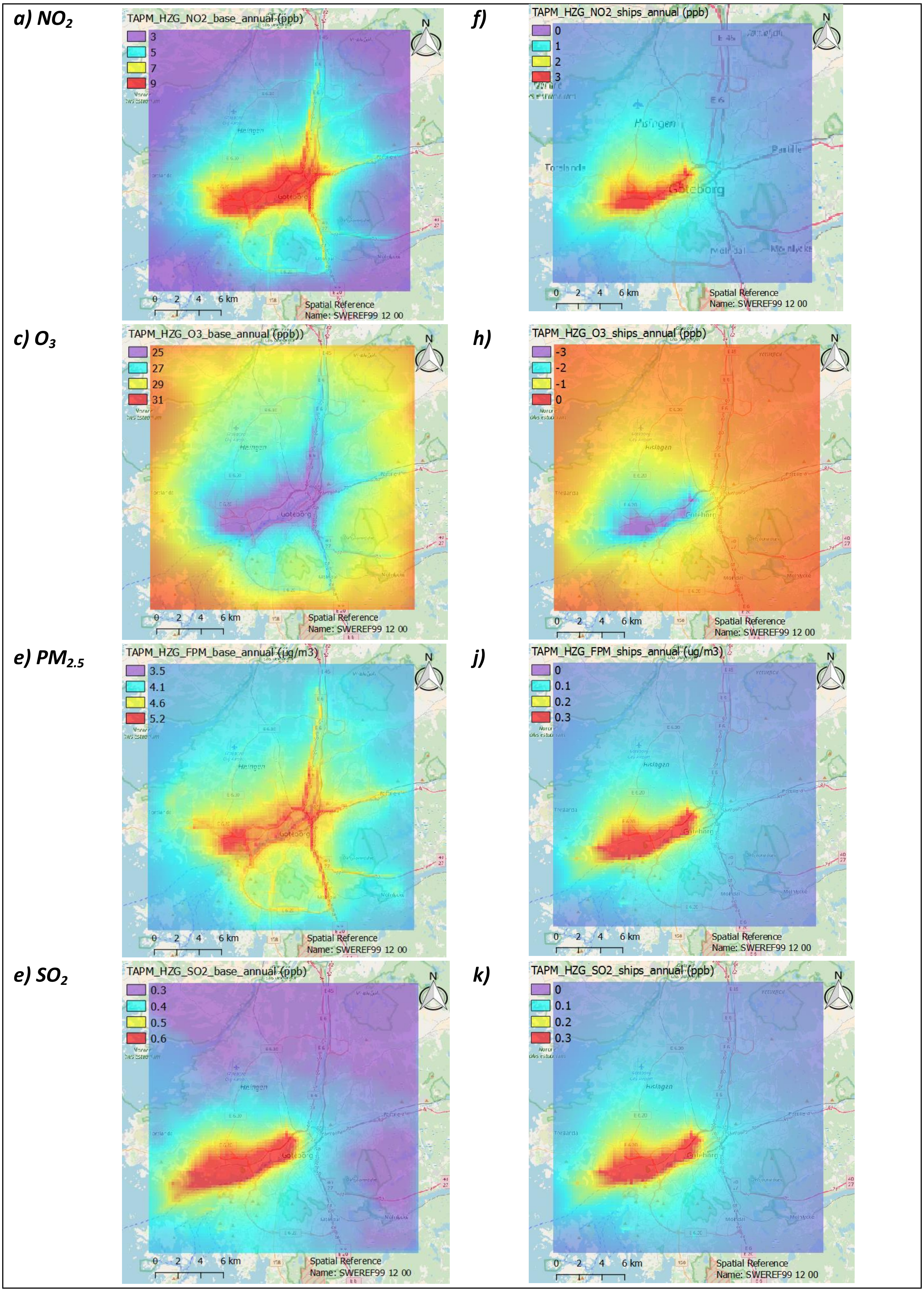


Figure 11: Annual mean values of NO_2, O_3, $PM_{2.5}$ and SO_2 in the city of Gothenburg from TAPM by HZG. Total concentrations including all sources are displayed on the left side, the contribution from shipping is given on the right side.

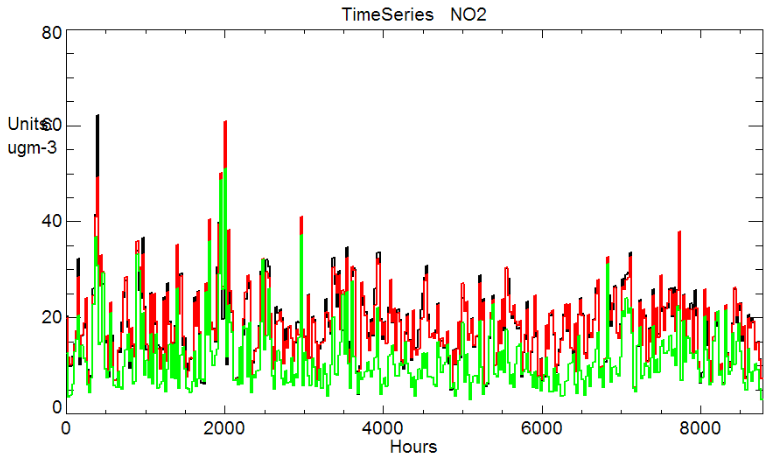


Figure 12: Annual time series of NO_2 based on daily average concentrations at Eriksberg, located at the north of the river Göta Älv in Gothenburg for the year 2012. Model results from the "Base" run (red line from HZG and black line from IVL) compared to the "No local shipping" run (green line). Modelled average NO_2 concentrations including ships are 18.3 µg/m^3 (HZG) and 18.4 µg/m^3 (IVL). Modelled concentrations without ships are 11.6 µg/m^3 (HZG) and 11.4 µg/m^3 (IVL).

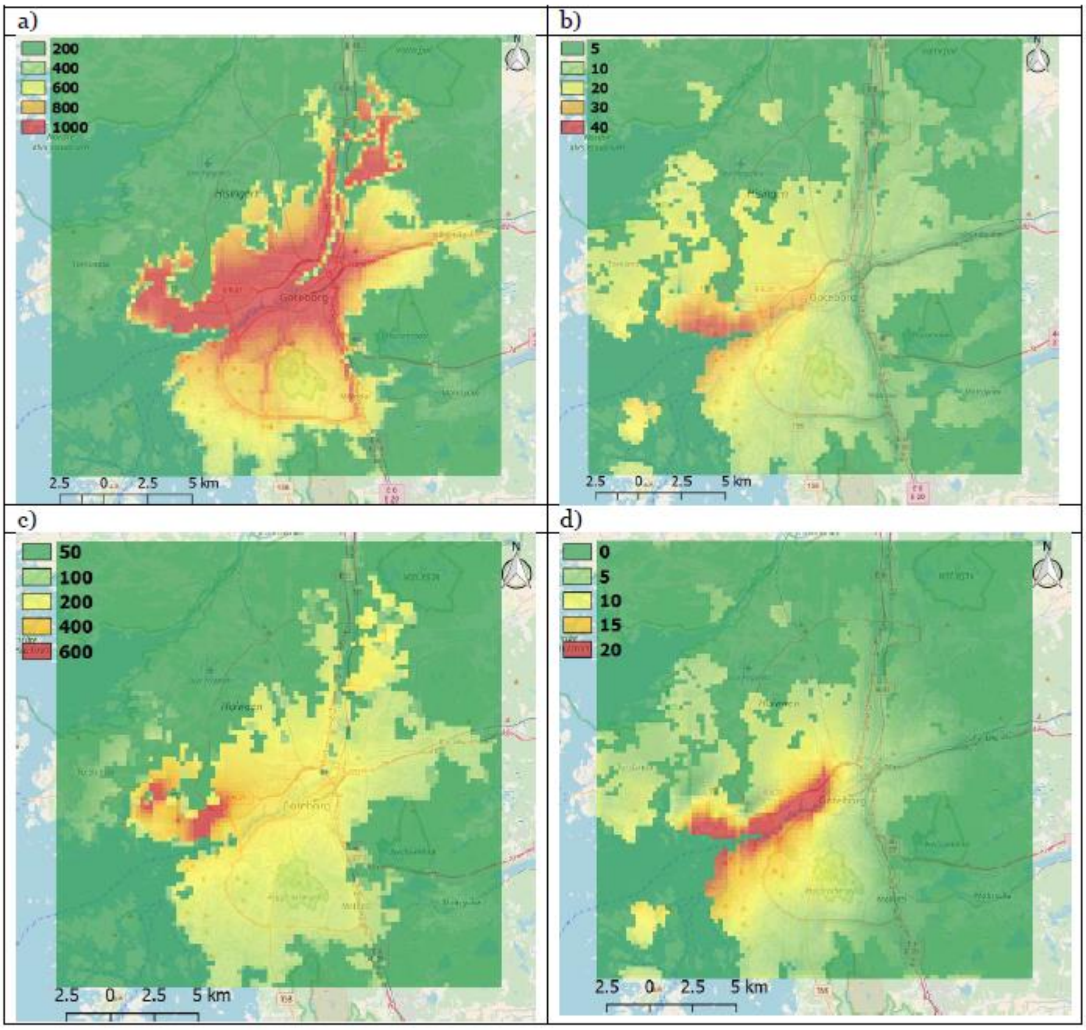


Figure 13: Exposure to NO_2 concentrations of the population in Gothenburg in 2012 (a,b) and in 2040, BAU scenario (c,d). The total exposure in ppb*capita/grid square is shown on the left (a and c), relative contribution of the local shipping to the total exposure (in %) on the right (b and d).

Exceedance maps for eutrophication and acidification have been created using the latest version of the reported CLs for the Baltic countries together with deposition based on the emissions for 2012 and 3 future emission scenarios for year 2040 (BAU2040, NoNECA2040 and EEDI2040). The results show a significant reduction of the impact of shipping on the critical load exceedances in 2040 compared to 2012.

For the exceedance of critical loads for acidity, the contribution from shipping decreases from over 20% of the exceeded area to only 2% in the BAU2040 scenario. This decrease can be mainly attributed to the introduction of the SECA (cap of 0.1% S in ship fuels) in 2015 and of the global fuel sulphur content cap of 0.5% S in 2020. Comparing the other two scenarios for the year 2040 to the BAU2040 scenario, the impact of the NECA and lower fuel efficiency does not have a great impact on the critical load exceedances for acidity, with the shipping contribution to the exceeded area for both of these lying at ~ 3%.

The area with exceedance of critical loads for nutrient N also decreases between 2012 and 2040, Figure 14 shows exceedances of critical loads for both years when all emissions (land sources and shipping) are considered and when the shipping emissions are excluded. For the BAU2040 scenario the exceeded area attributed to shipping has decreased from about 20% in 2012 to 5 % in 2040. In contrast to the results for acidification there is a larger difference between the 2040 scenarios. For the scenario where the NECA has not been implemented the difference in the exceeded area between 2012 and 2040 is smaller. For the NoNECA2040 scenario the exceeded area for nutrient N from shipping is about 14%. The result for the scenario with lower energy efficiency increase (EEDI2040) is closer to the BAU2040 scenario: 7% exceeded area from shipping.

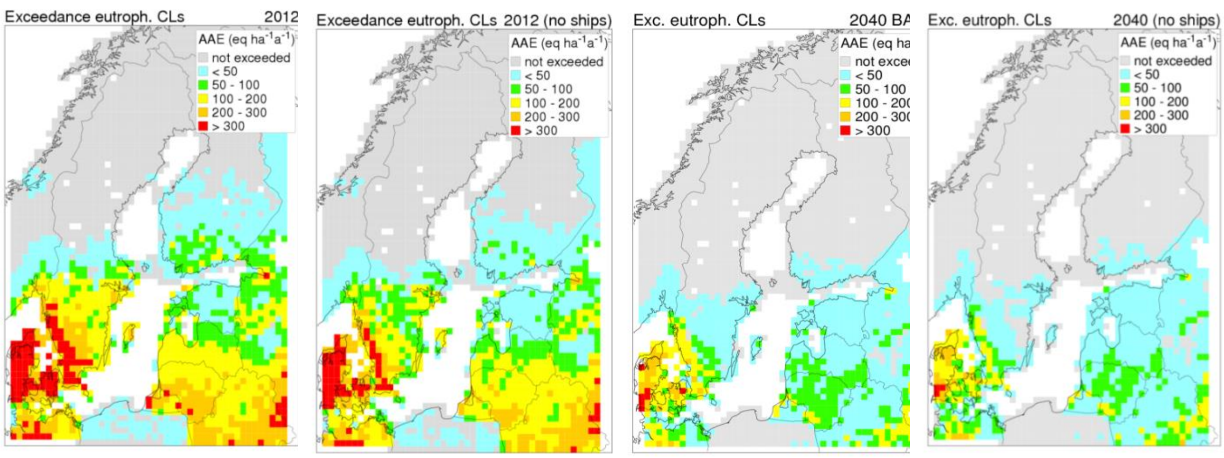


Figure 14. Exceedances of the critical loads for nutrient nitrogen in eq * ha-1 * year-1. From the left: 1. in 2012 Base case, 2. 2012 – No shipping emissions, 3. 2040 BAU, 4. 2040, no shipping emissions

1.3. WP3, Water pollution

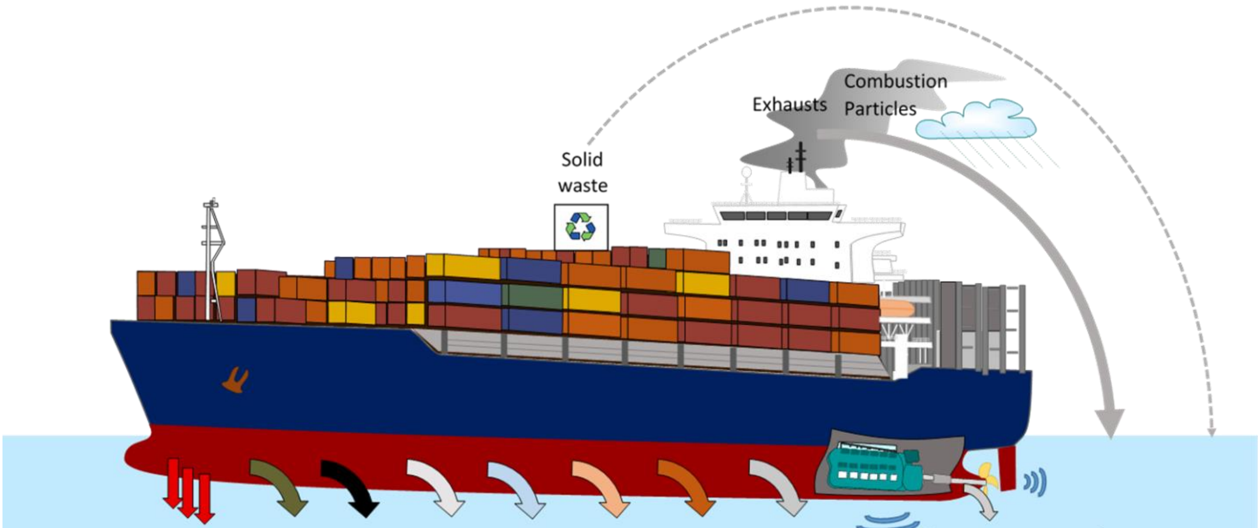
The overall objective of WP3 was to determine the fate and effect of different types of water pollution from shipping; from present situation and predicted according to the scenarios developed in WP1. Specific aims were to:

- Create an inventory of contribution of shipping and recreational boating to different categories of stressors in the marine aquatic environment according to the MSFD and WFD
- Use a combination of physical-biogeochemical and ecotoxicological modelling to assess the spatio-temporal distribution, fate and effect of different pollutants in Baltic Sea and on small scale in ship lanes and harbours on the marine environment.
- Quantify impact of different pollutants in relation to water quality indicators in MSFD and WFD.

It should be noted that in the following chapter, the term "pollutant" is used as collection concept for nutrients, contaminants, acidifying substances, particulate matter and invasive species. In 2016 a field campaign was carried out with the sailing R/V Hrimfare af Ranrike. The results from the campaign is described in detail in D3.9, but as the main focus of WP3 in SHEBA concerned modelling of existing data the pilot data from the campaign is not elaborated further on in this report.

Generation of pollutants onboard ships

Pollution from shipping is primarily regulated on individual ship-basis; most often as maximum allowed concentration of different substances arising from different subsystems that generate different emissions or waste streams (Figure 15).



	Biofouling & Antifouling	Ballast water	Black water	Grey water	Tank cleaning	Cooling water	Scrubber water	Bilge water	Noise	Prop. shaft lubricants	Atmos. deposition	Solid waste
D2. Invasive species	x	x	x	x								
D5. Nutrients, N, P		x	x	x	x		x	x				x
D8. Org. subst. HC, PAH					x		x	x		x	x	
D8. Metals, e.g. Cu, Zn	x					x	x	x		x		
Acid. subst. SO_X, NO_X, CO_2							x				x	
D10. Litter, PM					x						x	x
D.11 Energy/noise									x			
Shipping regulations	AFS	BWMC	MARPOL Annex IV	MARPOL Annex IV	MARPOL Annex I		MARPOL Annex VI	MARPOL Annex I		MARPOL Annex I	MARPOL Annex VI	MARPOL Annex V

Figure 15. Different subsystems onboard ships, e.g. Antifouling, Ballast water or Bilge water give rise to waste streams from ships, regulated on individual ship's basis. The different waste streams may contain several pollutants, here categorized according to the descriptors in the MSFD, e.g. D2 Invasive species.

Different waste streams may contain the very same pollutant, e.g. NO_X may originate from exhausts or scrubber water as well as grey and black water, but until the SHEBA project there were no comprehensive analyses made of the total pollution pressure from shipping. Since no two ships, not even sister vessels, are identical with respect to generation of pollutants, it is imperative to gather as much data on emissions and waste streams characterization, to build a statistically robust database. The first deliverable in WP3, D3.1, was therefore the result of a comprehensive literature search, where scientific articles and databases, along with grey literature and reports, were assessed and over 600 pollutants discharged by ships were identified. The onboard subsystems included were stern tube oil, ballast water, bilge water, scrubber water, grey water, black water, scrubber water food waste and antifouling paints. Atmospheric deposition was included as output from WP2.

Calculation of emission and load factors of pollutants from ships

As it was beyond feasibility within the project time- and budget frames to assess all identified pollutants, it was decided to include nutrients, copper, zinc, dibromochloromethane, naphthalene and pyrene as model substances along with pH and invasive species. In D3.3 emission or load factors for these variables. As far as possible, with reference to data availability, the factors were calculated separately for the different ship types used in the AIS data system and the STEAM model (Figure 16).

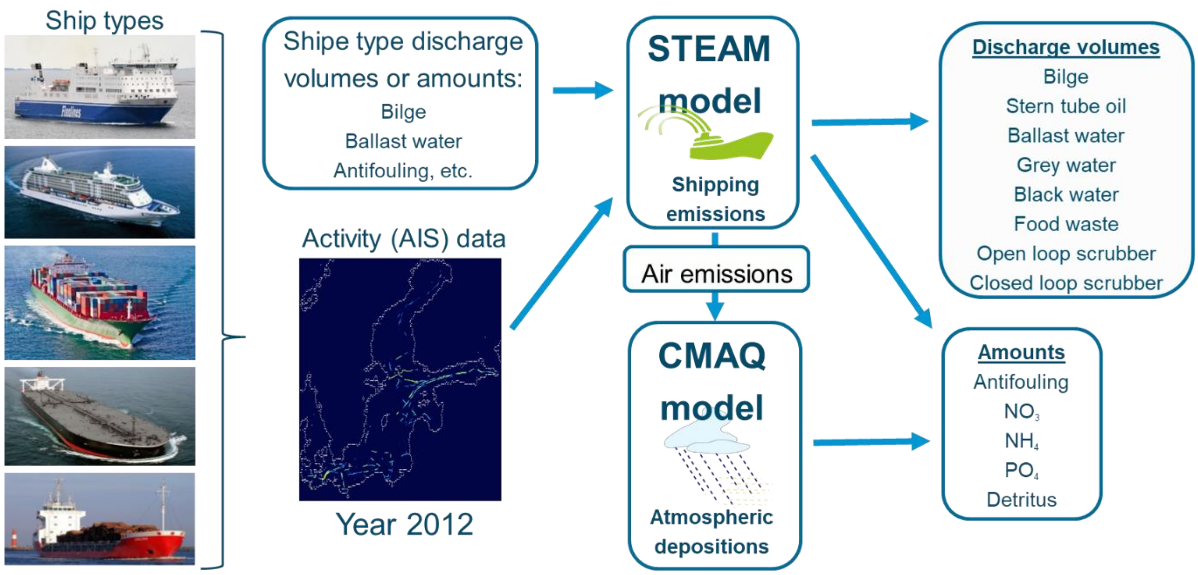


Figure 16. Approach to assess shipping emissions and discharges to water.

Discharge operational patterns were modelled considering both speed and geographical aspects. For example, in the model, nutrients accumulate to a tank at a constant rate which is a function of people on board. When the IMO requirements for release are met, tank is drained to the sea at a constant rate. The discharge rate depends on size of the ships and draft as outlined in MEPC.157(55) (IMO 2006). Since there is no regulation on the discharge rate for greywater and food waste, the rate of discharge of sewage can be applied for all waste streams to simplify modelling. When a vessel travels at slow speed or travels near the coastline, no release of black water and food waste is allowed but the nutrients go to a modelled tank instead. This results in a discharge pattern like illustrated in Figure 17.

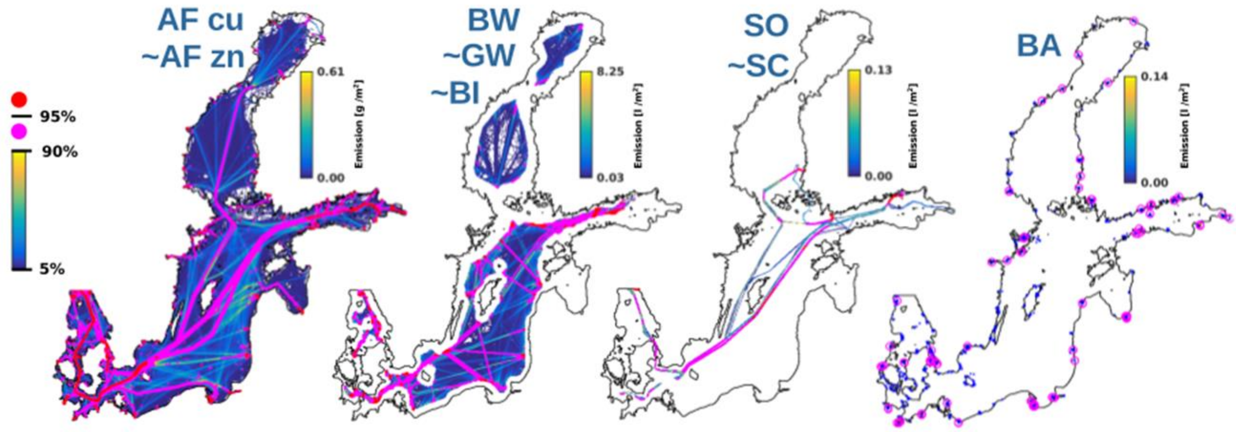


Figure 17 Illustration of different types of emissions/discharge patterns in the Baltic Sea. From left to right, the first map shows leakage from antifouling (AF) shown as a continuous process, while the second map show areas where black water from ships can be discharged (coloured areas) and cannot be discharged (white areas) to the sea according to the IMO regulations. The BW pattern is approximated to be valid also for grey water, bilge water and food waste. The third map shows estimated discharge patterns for Open loop scrubbers (SO), which are also approximated to be valid for closed loop scrubbers. Northward from the Bothnian Sea, the low alkalinity is assumed to limit functionality of open loop scrubbers. The fourth map show main discharge areas for Ballast water, which is mainly in ports. The load and emission factors calculated in D3.3 was then applied in the STEAM model together with shipping activities from AIS data in 2012, as well as modelled activities according to the scenarios outlined in WP1.

Modelling the fate and effect of shipping related pollutants in the Baltic Sea

The output from STEAM, both in terms of direct discharge to water and indirect deposition of emissions to air (via CIMAQ model in WP2), were used as input in a coupled oceanographic and biogeochemical model (GETM-ERGOM; General Estuarine Transport Model-Ecological Regional Ocean Model) to assess the fate and effect of shipping related pollutants in the marine environment (Figure 18). Coupling was enabled through the Framework for Aquatic Biogeochemical Models (FABM) and the horizontal resolution was 1NM (~2km) and vertical resolution 40 layers. Regarding nutrients and acidification, the modelling also included biogeochemical reactions, while contaminants and invasive species were modelled as passive tracers. Due to too scarce data availability, particulate matter and litter was not included in the modelling effort, but instead qualitatively described in a report (D3.7).

The fate and effect of shipping related pollutants in the Baltic Sea were analysed with the year 2012 as baseline, as two runs; SHIPS and NOSHIPS. According to scenario design in WP1, the following scenarios were analysed for pollutants entering the marine environment: *Business As Usual* (*BAU*), *No Nitrogen Emission Control Area* (*NoNECA*), *Zero emission to water* and two scrubbers scenarios (*All open loop* and *All closed loop*). These scenarios have been analysed for the years 2030 and 2040.

High resolution modelling of contaminants in selected harbours and shipping lanes

In addition to the basin-wide modelling, a handful of case studies were modelled in the antifouling model MAMPEC. Based on shipping intensity and the harbour geography, three harbours were selected for calculation of PEC of the contaminants. These are Muuga (Estonia), Primorsk (Russia) and Gdynia (Poland). Initially, some more harbours were considered for PEC calculations but the complex geography and shipping patterns in these harbours prohibited modelling. In addition, two high intensity shipping lanes were selected for calculation of PEC for the contaminants. These shipping lanes were the same as the ones sampled in the field sampling campaign (described in D3.3), i.e. one north of Bornholm in Baltic proper, one northeast of Anholt in Kattegat. The specific areas in the harbours and shipping lanes were selected based on the results of the copper antifouling emission from the General Estuarine Transport Model (GETM). More specifically, the shipping intensity, as modelled in STEAM, was used in GETM. In GETM, the emission of copper from antifouling is assessed on a grid of 1 × 1 nautical miles, and the areas with high copper emission in the harbours and the shipping lanes were selected for calculations of all shipping emissions to water.

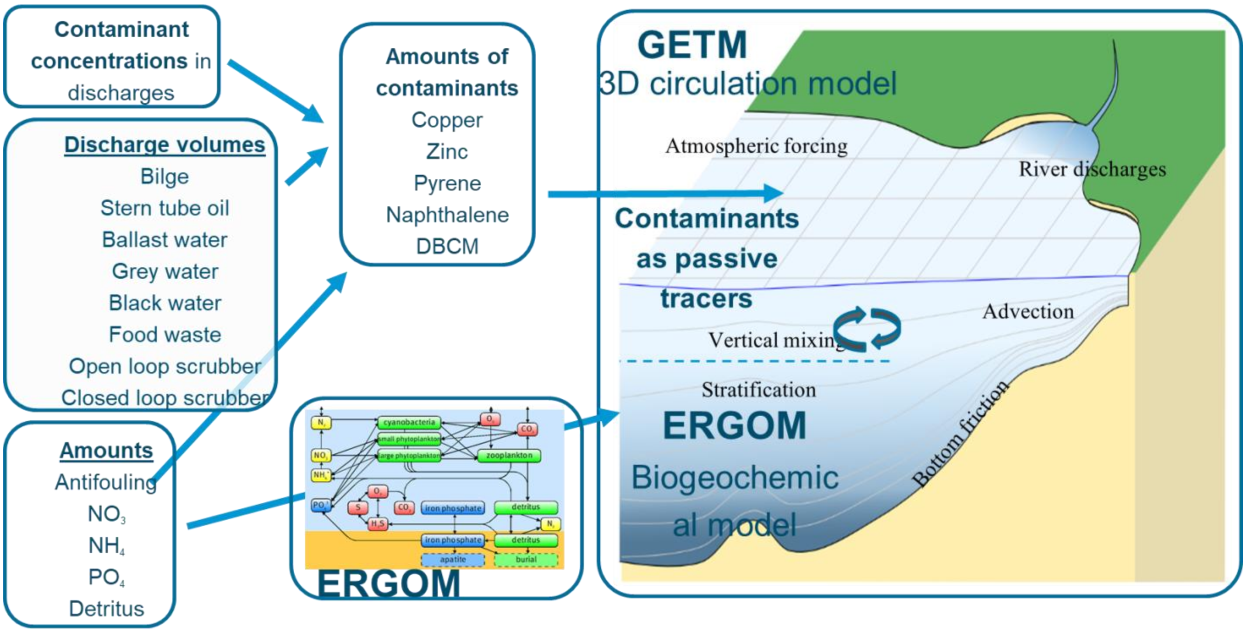


Figure 18 Approach to assess fate and effect of shipping related pollution. Output from the STEAM model (Figure 16) is used as input in the 3D circulation model GETM and the effect from added nutrients are calculated in the coupled biogeochemical model ERGOM. Contaminants and invasive species are modelled as passive tracers.

Input of nutrients from shipping in the Baltic Sea

Nutrient input from shipping was calculated as the difference between two simulations: 2012 SHIP, which included shipping as well as other sources of nutrient input, and 2012 NOSHIP where the input from shipping were excluded. The major contribution of nutrients from shipping in the Baltic Sea is atmospheric deposition of NO_X, which in line with previous publications are estimated to be approximately 6% (20kt) of the total annual N-input from all sources in the Baltic Sea[1]. The other waste streams contribute together with approximate 1kt N, (Figure 19) where ammonium from blackwater is negative due to atmospheric processes. The shipping contribution to nutrient input in the Baltic Sea is small, but cannot be ruled out as negligible in a longer perspective; in longer runs the primary production shows nonlinear increase (as does the growth of the shipping activity) and

[1] http://www.helcom.fi/Documents/Baltic%20sea%20trends/Eutrophication/CORE_indicator_nutrient_inputs_1995-2012.pdf

there may also be locally more pronounced effects as the input is not evenly distributed in the basins. Regarding phosphorus the shipping related input is roughly 60t (or about 2 per mille) of the total input from other sources, which exceeds 31kt.

The analysed different scenarios, in general, produce a complex trend pattern for nutrient concentrations and their effects on descriptors of the MSFD and the quality elements of the WFD. For the BAU scenarios, the concentrations of NO_3 increase while those for PO_4 and cyanobacteria decrease. Eventually reduced remineralization of decreased organic matter due to lower N-fixation can alter the effects of shipping nutrients loads. One scenario is sticking out, the *All closed loop scrubber,* which resulted in immense 7.5 fold increase in nitrate loads, due to the very high NO_3 concentrations in closed loop scrubber water emissions (SHEBA deliverable D3.3, Table 7). Resulting load (1.08 ktons of NO3) is still only ~ 10% of total shipping (10 kton BAU 2040). However it should be noted that the extrapolation is based on a small data set, and it is important to stress the necessity of more data on both open and closed loop scrubber concentrations and volumes to enable correct assessments, which eventually may motivate adoption of stricter regulations.

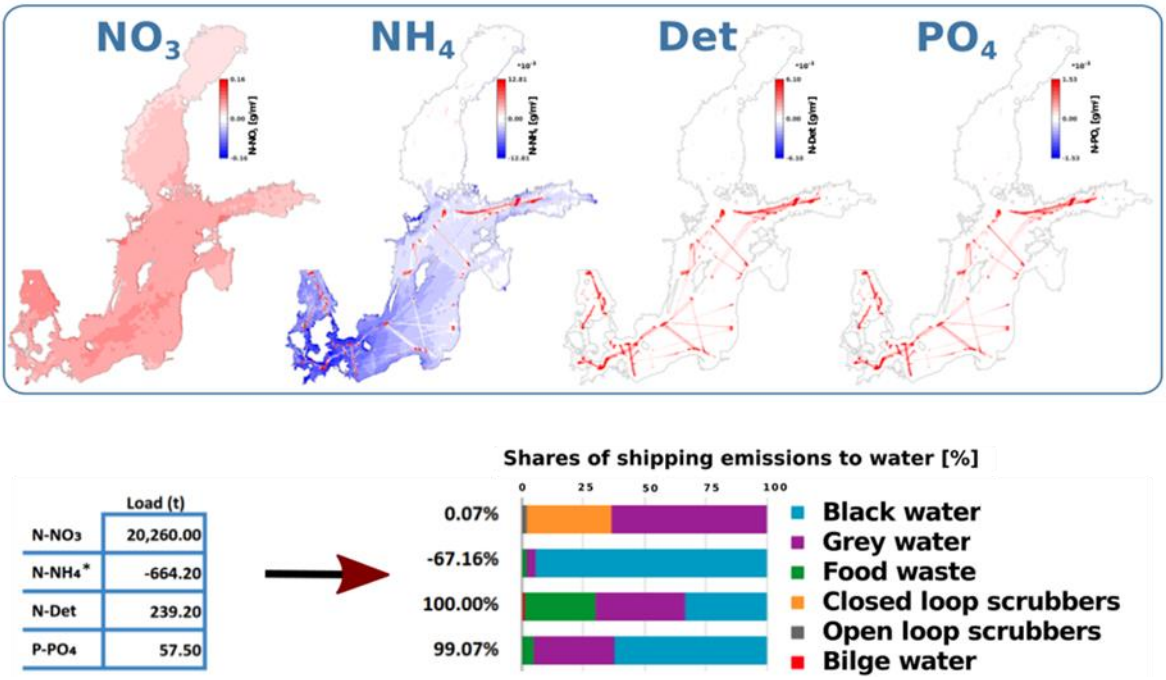


Figure 19 Nutrient input from shipping, as three different N-species, as well as phosphate, in the Baltic Sea. Left bottom corner shows the total input. Ammonium load is negative, due to atmospheric processes. Right bottom shows the share of shipping discharges to water in relation to total ship related load of the respective species (bottom left). It may be worth to note that 0.07% of the N-NO3 corresponds to a load of roughly 1400 t, i.e. almost six times the load of N in N-Det.

Input of contaminants from shipping in the Baltic Sea

For the *reference year of 2012*, the load factors of the contaminants were reported in the Deliverable 3.3. These load factors were used in GETM modelling, producing the concentrations of the contaminants in the Baltic Sea. Clearly, the compounds with the highest emissions are copper and zinc. It can be noted that the copper emissions for the reference year 2012 (302 tons) are larger than the copper emissions from Sweden in 2006 (239 tons), and is approximately one third of the total copper emissions to the Baltic Sea (886 tons), as assessed by HELCOM[2] (2011). According to the BAU scenarios used here, the copper and zinc emissions from shipping will increase.

The total emissions of copper, zinc, dibromochloromethane and pyrene (Table S2), increase over time from 2012 to the year 2030 and 2040. The exception is naphthalene that continuously decreased over time. This decrease was caused by the smaller volumes of discharged bilge water in *BAU 2030* and *BAU 2040*.

The contaminant loads for different scenarios, modelled in the GETM, were used to visualize the concentrations in surface waters in different parts of the Baltic Sea (Figure 20). To get an improved visualization of the data, three standard deviations of the concentrations have been plotted in (Figure 21). These maps show that there are areas of substance-specific high concentrations of the contaminants. For the antifoulants copper and zinc, the concentrations are high in the Eastern Gulf of Finland, Gulf of Riga, Gulf of Gdansk and some specific areas in Germany, Denmark and Sweden. For the other contaminants, high concentrations can be found in other parts of the Baltic Sea. These patterns are to a large extent dependent of the emission source of the contaminants. For example, the concentration of pyrene is high is shipping lane areas, which is a result from the high pyrene concentrations in bilge water and open loop scrubber water emitted during transport in shipping lanes.

Concentrations and Environmental Quality Standards (EQS)

To assess the environmental impact of shipping in the Baltic Sea Area, the shipping generated concentrations of contaminants were compared to Environmental Quality standards according to the Water Framework Directive. As the areas where the concentrations are above the EQS are difficult to spot in (Figure 20 and Figure 21), we provide maps pinpointing these areas in (Figure 22).

The size of the areas for which the copper and zinc emissions from shipping leads to concentrations above the EQS values are listed in (Table 2). It is clear that the area where the EQS values for zinc are exceeded are small, only a few square kilometres. The area where the EQS values for copper are exceeded increase from 431 km^2 in 2012 to 526 km^2 in 2040. The *Zero emissions to water* scenario decrease the area to 379 km^2, but the two scrubber scenarios do not affect the size of the area compared to *BAU 2040*. It is difficult to assess whether a linear relationship exists between time and the size of the areas for which the EQS values are exceeded. Hence, any interpolation between 2012 and 2040, to estimate the area for 2030, would contain large uncertainties and are not included in (Table 2).

[2] HELCOM, 2011. Fifth Baltic Sea Pollution Load Compilation (PLC-5). Baltic Sea

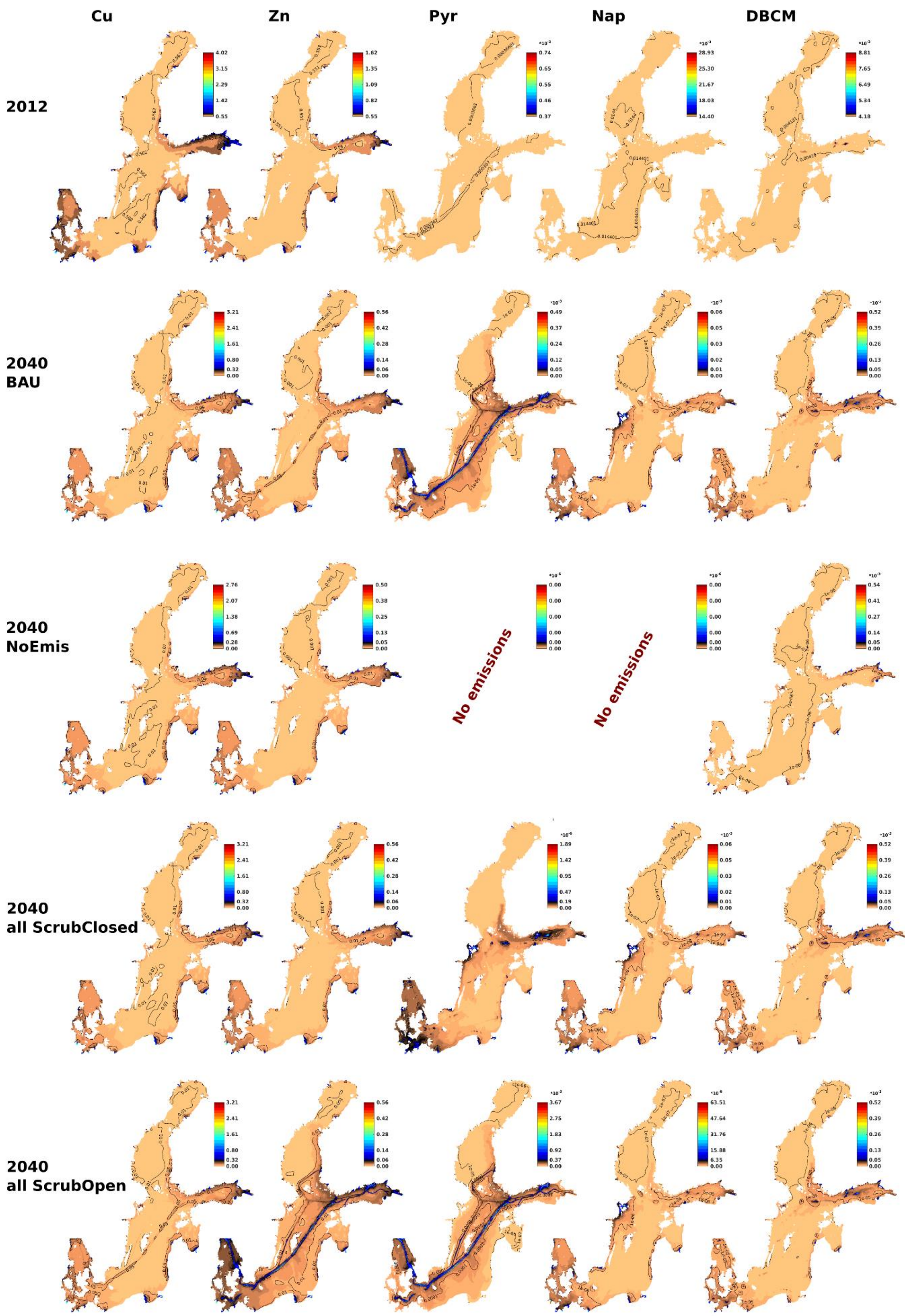


Figure 20 Maps of the Baltic Sea showing the concentrations of copper (Cu), zinc (Zn), pyrene (Pyr), naphthalene (Nap) and dibromochloromethane (DBCM), resulting from the emissions in the reference year 2012 (2012), and the scenarios Business as usual 2040 (2040 BAU), Zero emissions to water 2040 (2040 NoEmis) and Scrubber 2040 all closed (2040 all ScrubClosed). The colour bars represents concentration in µg/L, and the lines with numbers in the sea areas depicts areas with the concentration given by the corresponding number. The missing maps for pyrene and naphthalene indicates that these compounds would have no emissions under these scenarios.

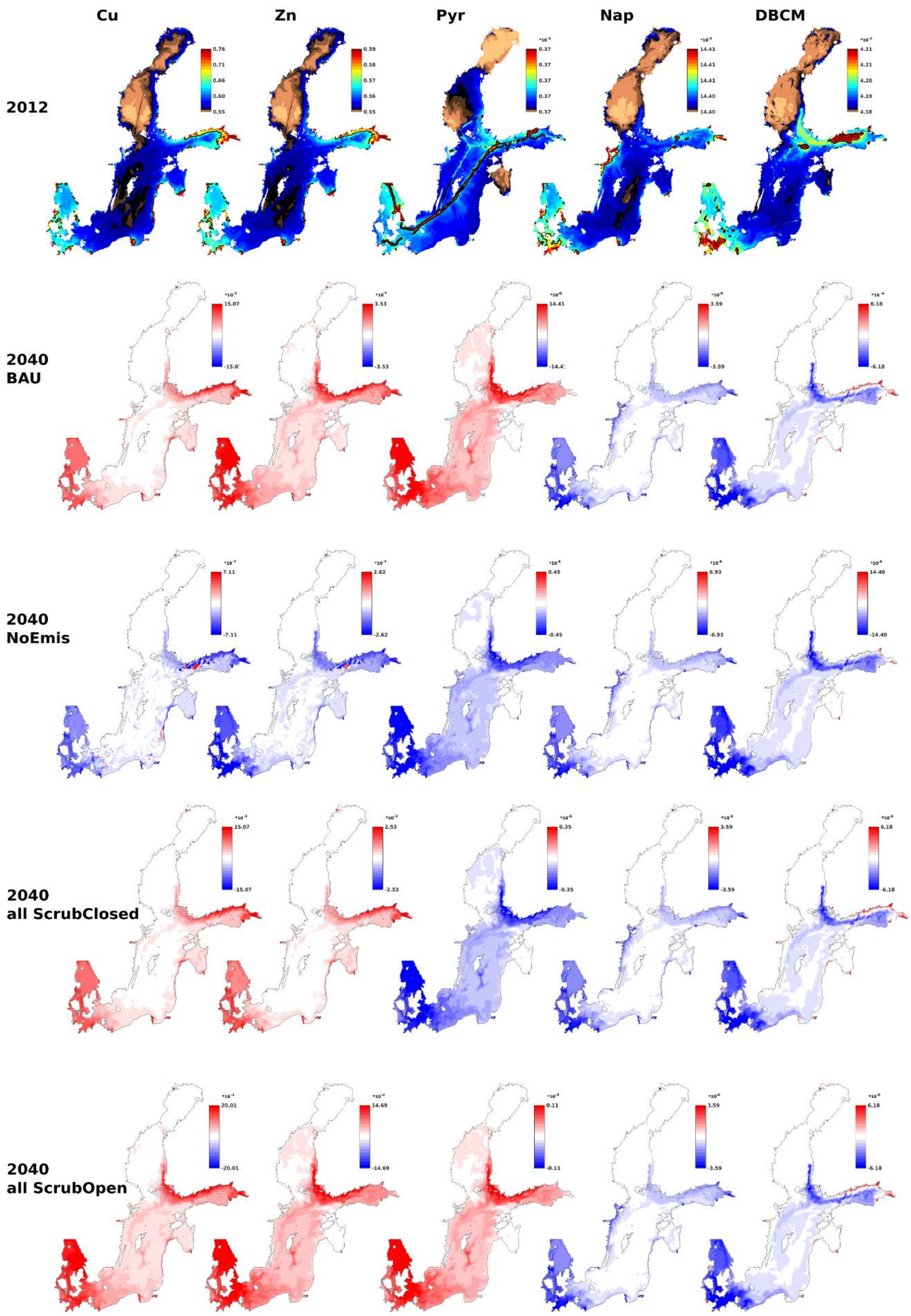


Figure 21 Maps of the Baltic Sea showing the maximum (daily) concentrations of copper (Cu), zinc (Zn), pyrene (Pyr), naphthalene (Nap) and dibromochloromethane (DBCM), and the relative change compared to the reference year 2012 for the scenarios Business as usual 2040 (2040 BAU), Zero emissions to water 2040 (2040 NoEmis) and Scrubber 2040 all closed (2040 all ScrubClosed). The top panels shows the concentrations of the contaminants where the colour bar is limited to 3 times the standard deviation of the maximum values for the reference year 2012 (2012). This scaling enables a good visualization of areas with high and low concentrations. The lower panels shows the relative change compared to the reference year 2012 for the scenarios Business as usual 2040 (2040 BAU), Zero emissions to water 2040 (2040 NoEmis) and Scrubber 2040 all closed (2040 all ScrubClosed). The coloured bars represent the maximum values of 3 standard deviations.

Table 2 Size of areas for which the copper and zinc emissions from shipping leads to water concentrations above the EQS values, for the reference year 2012 and the different scenarios for 2040.

Scenario	Area where copper concentration exceeds EQS (km^2)	Area where zinc concentration exceeds EQS (km^2)
Reference year 2012	431	0
BAU 2040	526	3.47
Zero emissions to water 2040	379	0
Scrubber scenario 2040 All open loop [l]	526	3.47
Scrubber scenario 2040 All closed loop [l]	526	3.47

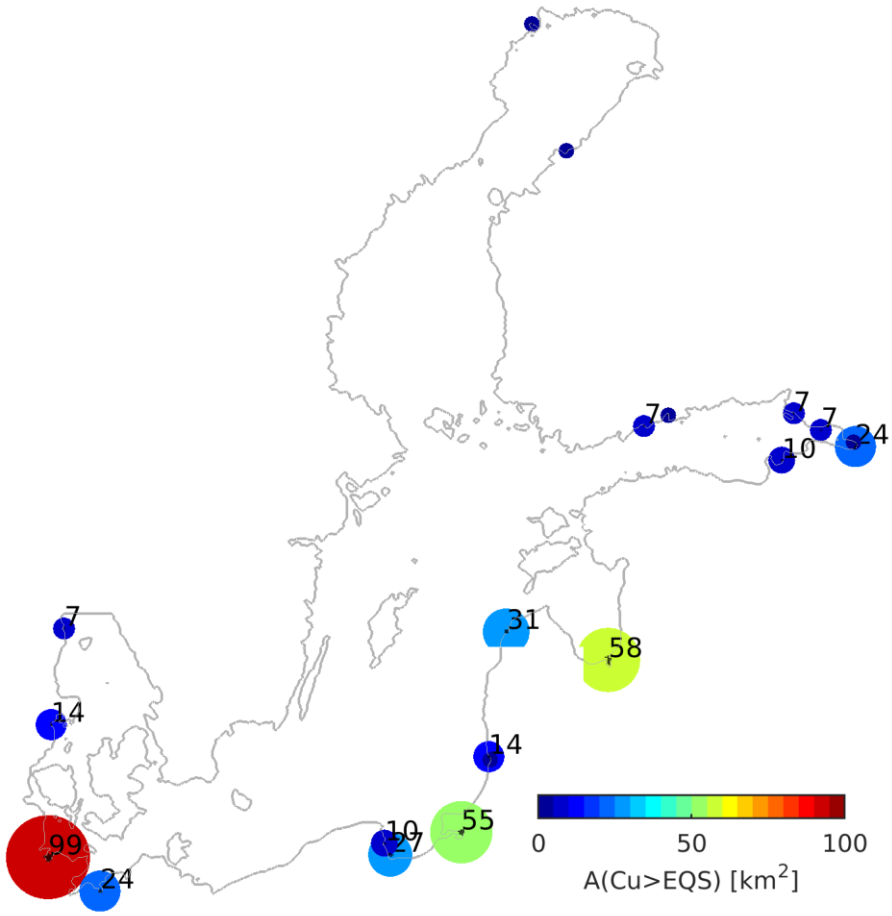


Figure 22. Map of the Baltic Sea showing the areas where the copper (Cu) concentration is modelled to be above the EQS, for the reference year 2012. The centre of the coloured circles, marked with a dot, corresponds to the areas where the concentration is modelled to be above the EQS. The size of the coloured circles and the numbers in or next to the circles, correspond to the size of the area where the concentration is modelled to be above the EQS. The colour of the circles corresponds to the concentration according to the colour bar.

Effects on MSFD descriptors

As previously mentioned, the assessment of contaminants in SHEBA has been focused on a handful of model substances, thereby per se an underestimation of the more than 600 substances that have been identified in shipping waste streams. Nevertheless, regarding five of the MSFD descriptors (D1 Biodiversity is maintained, D3 The population of commercial fish species is healthy, D4 Elements of food webs ensure long-term abundance and reproduction, D6 The sea floor integrity ensures functioning of the ecosystem, D8 Concentrations of contaminants give no effects), a negative effect from shipping is observed or cannot be ruled out. For D9 Contaminants in seafood are below safe levels, emissions from shipping are assessed as low to moderate impact.

Effects on WFD status

The quality elements of the WFD of relevance for contaminants in this deliverable are

- Specific pollutants
  As the emissions of copper and zinc resulted in concentrations that exceeded the EQS in some areas, the shipping emissions may to compromise this quality element. Furthermore, in all scenarios except *Zero emissions to water*, the copper and zinc emissions and environmental concentrations increase, resulting in increased areas where the EQS are exceeded. Hence, the trend in ecological status is negative for this quality element.

- Pollution by all priority substances identified as being discharged into the body of water
  Of the compounds modelled in the GETM model, only naphthalene is a priority substance in Annex II of the WFD. Shipping emits naphthalene primarily via bilge water. However, there is a lack of emission data for naphthalene, e.g. in open and closed loop scrubber water, which may result in an underestimation of the naphthalene emissions and environmental concentrations. Still, there are reductions in naphthalene emissions and environmental concentrations in the scenarios *BAU 2030* and *BAU 2040*, as well as in *Zero emissions to water*. Hence, there is a positive trend for this quality element. The metal loads from scrubber water are based on data from only three studies. Hence, the uncertainties in the *Scrubber scenarios* is high and more research is needed to fully assess what impact scrubber water discharge has on the marine environment

- Pollution by other substances identified as being discharged in significant quantities into the body of water.
  Since large amounts of copper and zinc are emitted from shipping, these substances must be regarded as falling under this quality element. These metals are primarily emitted from antifouling paints. As the emissions of copper and zinc resulted in concentrations that exceeded the EQS in some areas, the shipping emissions must be said to compromise this quality element. Furthermore, in all scenarios except Zero emissions to water, the copper and zinc emissions and environmental concentrations increase, resulting in increased areas where the EQS are exceeded. Hence, the trend in ecological status is negative for this quality element.

Ocean acidification

Ocean acidification is a threat to marine species worldwide and predicting its impact on the marine environment is of high priority for science, management and policy. Nonetheless, neither the MSFD nor the WFD requires EU member states to monitor the pH in marine surface water. In addition, ocean acidification is not included in the directives requiring environmental status assessment (see MSFD descriptors in Table 1). Thus, this task will not be able to address how shipping-induced ocean acidification affects the environmental status according to the MSFD and WFD. However, ocean acidification may have an indirect effect on other MSFD descriptors including Descriptor 1. Biodiversity is maintained, Descriptor 4. Elements of food webs ensure long-term abundance and reproduction, and Descriptor 6. The sea floor integrity ensures functioning of the ecosystem.

Shipping may contribute to ocean acidification via CO_2 as well as via SO_X and NO_X, where the latter also decrease the alkalinity[3]. SO_X emissions from a specific ship depend on the sulphur content in the fuel used, while NO_X emissions primarily depends on the engine type used and operation mode. The SECA regulations on SO_X emissions have reduced the emissions of acidifying SO_X to the atmosphere in the Baltic Sea area. However, if open loop seawater scrubbers are used the net input of SO_X to the Baltic Sea environment may actually increase significantly as it allows for combustion of HFO with a sulphur content of up to 3.5% where the acidified effluent is discharged directly to the surface water (typically at a discharge rate of 45 m3/MWh[4].

Apart from the *BAU scenarios* we have also, in SHEBA, developed *scrubber scenarios* where much larger use of scrubbers are assumed. This will influence the emissions of scrubber discharge water. The assumption made is that the fraction of fuel being HFO in 2014, per ship type, is kept constant until 2040 and that the use of HFO is combined with the use of scrubber to meet the Sulphur regulations. Two cases are considered: either all scrubbers are of the open loop type (*Scrubber All open loop)* or all scrubbers are of the closed loop type (*Scrubber All closed loop*), which also implies that when open loop scrubbers are assumed the discharge of closed-loop scrubber water is zero and vice versa.

Two of the SHEBA scientists have recently assessed the effect of shipping on pH and alkalinity in the Baltic Sea in the Swedish research project SHIpH[5], why that analysis was not redone in SHEBA. In SHIpH the effect on pH was assessed using an extreme future scenario, where 100% of the shipping fleet was assumed to use open loop scrubbers and operate on a fuel containing 2.7 % sulphur content. The results showed a reduction between 0.001 and 0.003 pH units over a period of 30 years, with a maximum yearly reduction of 0.0001 pH unit. The modelling work was performed using low spatial resolution resulting in average effects on water basin scale. Thus, it cannot be ruled out that extensive use of open loop scrubber water may give rise to larger impacts in semi-enclosed areas such as harbours and coastal areas. However, considering the uncertainty of the impact of open loop scrubber water discharge on pH as well as how this impact may affect the MSFD descriptors 1, 4 and 6 it is beyond the scope of this project to quantitatively determine the impact of shipping-derived ocean acidification on MSFD descriptors. One can only speculate that the impact

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[3] Turner, D., *et al.*, 2017. Elementa Science of the Anthropocene. 5 45

[4] IMO, 2008. Resolution MEPC.170(57) Guidelines for Exhaust Gas Cleaning Systems.

[5] Turner, D.R., *et al.*, 2017. AMBIO. https://doi.org/10.1007/s13280-017-0950-6

will be larger in the Scrubber scenario as compared to the *BAU* and *Zero emission to water scenarios*.

Nano- and micro-particles and macro litter

Two categories of ship derived particles have been considered in this task, combustion and anti-fouling paint particles. Both categories are partly composed of contaminants that could be harmful to marine biota, combustion particles contain high concentrations of PAHs, and particles of antifouling paint contain high concentrations of biocidal compounds e.g. Cu and Zn. Depending on how the exhaust gases from ships are treated, combustion particles may reach the seawater either through air deposition or through direct discharge to the water column. Some field data on the concentrations of these particles in areas with intense shipping have been gathered within SHEBA during the Hrimfare campaign (D3.9) but data in the scientific literature is still very limited. It was therefore not possible to make any well-founded predictions of what impact the different emission scenarios would be expected to have on their concentrations in the marine environment.

No data is available on neither the concentrations nor the discharge rates of combustion particles to the water in 2012. It is therefore not possible to predict what the situation will be like in the *BAU scenarios* for 2030 or 2040. Also for antifouling paint particles data is lacking. However, as long as the formula for antifouling paint is not dramatically changed the shedding of particles to the water is likely to be linked to the number of ships and maybe also to ship speed.

The *BAU scenario,* in which it is assumed that a NECA will enter into force, will reduce the formation of nitrate from NOx in ship exhaust and thereby also the formation of particulate matter will be reduced. This will in turn reduce the amount of particulate matter deposited on the surface of the sea. In the *Zero emission to water scenario* emissions of black, grey, bilge water and open loop scrubbers are prohibited. The use of antifouling paints is only prohibited on ships exclusively on routes in the Baltic Sea. Hence, particle emissions to water are actually not zero in this scenario. Since the release of black, grey, bilge water and open loop scrubber wash water emissions are prohibited, the amount of particles emitted to the Baltic Sea will decrease. In the *Zero emission to water scenario*, the emissions of biocides from self-polishing antifouling paint is expected to decrease to 84 % of the emissions in the BAU scenario for both 2030 and 2040. The factor behind this change is a reduced use of anti-fouling paint on ships exclusively on routes in the Baltic Sea. Hence, a similar reduction could be expected in the shedding of antifouling paint particles from ship hulls in the *Zero emission to water scenario*.

A substantial proportion of emitted combustion particles are under 20 µm[6] , which is the same size as the food particles consumed by many marine invertebrate species. Combustion particles have also been detected in the digestive tract of e.g. marine blue mussels (IVL data, report from Hanöbukten in the Baltic Sea, *in press*,). Particles of antifouling paint are released from ship hulls both during maintenance of the ship but also when the ship is en route and at least part of them are also likely to be in the same size range as food particles. Consumption of these particles by

[6] Moldanova, J., *et al.*, 2009. Atmospheric Environment. 43 (16) 2632-2641

invertebrates may be an important entrance route for the associated contaminants to marine food webs[7].

Since the adverse effects caused by combustion particles and antifouling paint particles are directly linked to the contaminants associated to them, the effects of these particles on the MSFD descriptors will be the same as for contaminants. It could thus be presumed they have an effect on descriptors 1, 3, 4, 6, 8, and 9. In addition the ship derived particles have an impact on descriptor 10, concerning marine litter, including micro-litter.

As for the effects of shipping derived particles on the MSFD descriptors the adverse effects on the WFD quality elements are the same as for shipping derived contaminants (described above). EQS for both ecological and the chemical status could be expected to be affected. The EQS for the chemical status of coastal water sets the annual average concentration and/or the maximum acceptable concentration for the priority pollutants defined in the WFD, and among these there are several PAHs that are found in combustion particles.

Invasive species

Shipping is the largest vector for transfer of invasive species in the marine environment, and they are transferred both via ships ballast water and as marine growth (biofouling) on ship hulls[8]. In SHEBA invasive species have only been modelled for the ballast water (Figure 23). For the scenario analyses, the *NECA* and the *Scrubber scenario* do not influence the carriage of invasive species and were not included. Likewise, since the BWMC is included in *BAU*, the *Zero emissions to water scenario* does not influence the carriage of invasive species and was also omitted.

Ballast water typically contains a diverse assemblage of phytoplankton, zooplankton, invertebrates, fish and bacteria[9]. Transfer of invasive species with ships ballast water is controlled under International Maritime Organization by the Ballast Water Management Convention, which entered into force on the 8th of September 2017[10]. From the Baltic Sea perspective this means that traffic coming to the Baltic Sea need to treat the ballast water before discharge and the most likely option is to have a ballast water treatment system installed. It should be noted though, that BWMC applies immediately to new built ships, while start-date for when older ships need to follow the convention is dependent on the planned intermediate service of each ship. For international Intra-Baltic traffic some ships, mainly passenger-ferries in traffic between two ports, may seek for an exemption not to treat the BW. This exemption can be granted after port-surveys in the two ports of interest confirming that there is low risk in spread of invasive species[11].Invasive species introductions are expected to flatten out when the Ballast Water Management Convention (BWMC) is in force.

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[7] Turner, A., 2010. Marine Pollution Bulletin. 60 (2) 159-171

[8] Williams, S.L., *et al.*, 2013. Bioscience. 63 (12) 952-966

[9] Carlton, J.T., *et al.*, 1993. Science. 261 (5117) 78-82

[10] IMO. 2016 Ballast water management. http://www.imo.org/en/OurWork/Environment/BallastWaterManagement/Pages/Default.aspx.

[11] HELCOM, 2014. HELCOM ALIENS 3 – Tests of the Harmonized Approach to Ballast Water Management Exemptions in the Baltic Sea. http://helcom.fi/Lists/Publications/HELCOM%20ALIENS%203%20%E2%80%93%20Tests%20of%20the%20Harmonized%20Approach%20to%20Ballast%20Water%20Management%20Exemptions%20in%20the%20Baltic%20Sea.pdf

However, ship hull fouling is also a vector known to be responsible for about the same proportion of introductions of invasive species as ballast water[1] and ship hull fouling will not be regulated.

Published data of phytoplankton, zooplankton and bacteria concentration in ballast water were compiled in D3.8. The data of expected invasive species introductions achieved in SHEBA is limited both as only including BW-introduced species, and not ship hull introductions. In addition, the invasive species are modelled as passive particles, which might be representative for some but not for all the invasive species. Average concentrations of the collected data were used for zooplankton, phytoplankton and bacteria as organisms per litre. However, as this is the total concentration of organisms and all will not be invasive, a factor of 0.4 will be used through multiplication to assume the concentration of invasive species to Europe of total concentration. This factor is based on data from Gollasch, S. (2002)[12] , which is directly applicable to zooplankton and phytoplankton, but assumed to be applicable for bacteria as well.

Considering the limitations (already outlined in the proposal) of the analysis of invasive species in SHEBA, it is not possible to draw any quantitative conclusions about the impact from shipping on the impact on related MSFD descriptors and WFD status. However the results from SHEBA provide a very good platform for future analysis, where more adequate behaviour of the organisms released in ballast water could be included.

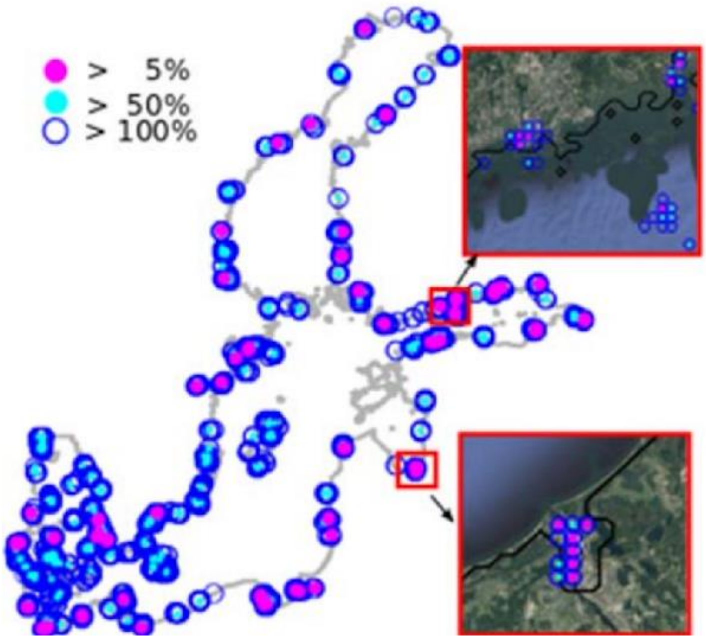


Figure 23 Distribution of ballast water discharges for the year 2012 from STEAM simulations Percentiles of highest discharges marked with different colours. Model coastline and locations of discharges shown in detail for Helsinki and Riga harbour areas on subplots.

[12] Gollasch, S., 2002. The Journal of Bioadhesion and Biofilm Research. 18 (2) 105-121

1.4. WP4, underwater noise

The aim of WP4 was to:

- Establish an improved noise source model optimized for the Baltic Sea and to use it to make a source map. The map can further be used to establish source density per block area.
- Develop an efficient proxy for the shipping induced noise in the Baltic Sea area
- Conduct an impact assessment of ship generated noise. The source density will be compared year by year and trends can be recognized and dealt with accordingly.
- Collect experimental data on underwater noise exposure of fish in controlled environment

Work Package 4 consisted of eight deliverables, of which D4.3 was the mid-term report. The work of WP4 was started from a review of existing noise source models which could be suitable for the project, considering the available activity and technical data for the Baltic Sea fleet. The approach taken was a simplified one, because the selected model would have to be applicable to the whole fleet of ships; tens of thousands of vessels, instead of accurate description of a single vessel or small number of ships. Five different models were tested and a recent noise source description proposed by Wittekind (Wittekind, 2014) was selected. This approach describes three contributions to shipping noise, arising from 1) low and 2) high frequency cavitation and 3) machinery components. Further, Wittekind noise model contains speed dependency, which increases generated noise when vessels travel at high speeds. It is the only one of the considered models which specifically has description of cavitation as a function of vessel parameters.

In D4.2, Wittekind noise source model was tested against the results of hydrophone measurements, which were made during the LIFE+ BIAS project (Baltic Sea Information on the Acoustic Soundscape). Some of the partners in SHEBA were also involved in the BIAS project. Although, BIAS measurements were conducted in 37 locations in the Baltic Sea, data from a hydrophone located south of island of Öland where ships passed within a kilometre distance from the measurement location were selected for analysis. Observed noise recordings were modelled backwards to the standard distance, considering transmission loss of different frequencies. This yielded noise source fingerprints at 1 meter distance from the noise source, which were compared with Wittekind model source predictions. In total, 2088 vessel crossings were used for comparison and it was observed that for cargo ships, Wittekind noise model was performing well, but was not producing as large differences in emitted noise as the experiments showed when vessel speeds were varied. The performance of the noise model was not as good for passenger vessels as with cargo ships, which was probably because the Wittekind model was originally developed for cargo ships with four stroke engines and fixed pitch propeller. Further work is required to improve the noise model for vessels typically found in the Baltic Sea fleet.

The mid-term report, D4.3, contained a description of the progress made during the first 1.5 years of the project.

The Wittekind noise source model was implemented in the STEAM emission model of the FMI (D4.4). This enabled dual outputs from the emission model, which uses individual vessel location and technical description as a basis for fuel consumption and emission predictions. Two outputs were required from the model; first was the point source data describing the noise emissions of a specific ship at a given time and location. Point source data was used as input to noise propagation model, which described the noise dispersion below the sea surface. Second output generated by STEAM were the noise source maps (D4.5), which were needed to visualise the noise emissions to facilitate annual reporting of shipping noise for the HELCOM Maritime group. These were presented at the 18th meeting of the HELCOM Maritime group in Hamburg (Sep 2018, see document Maritime18/12-4.INF and 12-5.INF). Inclusion of noise emissions in STEAM required overcoming several problems concerning the data required to run the Wittekind noise model. There were five key parameters needed by the noise model, which could not be obtained from commercially available ship databases. Two of the five parameters, Block coefficient (hull form factor) and number of operating engines, were already estimated by STEAM during a regular emission model run, but an alternative approach was required for three remaining parameters. First of these was the engine mass, which was collected from marine engine manufacturers' data for 95 000 ships, but two others (cavitation inception speed and engine mounting parameter) were estimated based on general construction principles of naval architecture and propeller design.

In D4.5, a methodology was described for the generation of noise source maps. This included depicting noise as a map of energy emitted to water. It includes the sum of annual energy emitted to water at different frequencies. For this purpose, a time integration step was needed and alternative representation to the decibel scale was required to enable summation of various noise sources. Noise source maps are visual outputs of the noise emission modelling and facilitate annual reporting of noise in the Baltic Sea. This output will be included in HELCOM reporting of ship emissions in 2018 for the first time, an example of these maps is given in Figure 24.

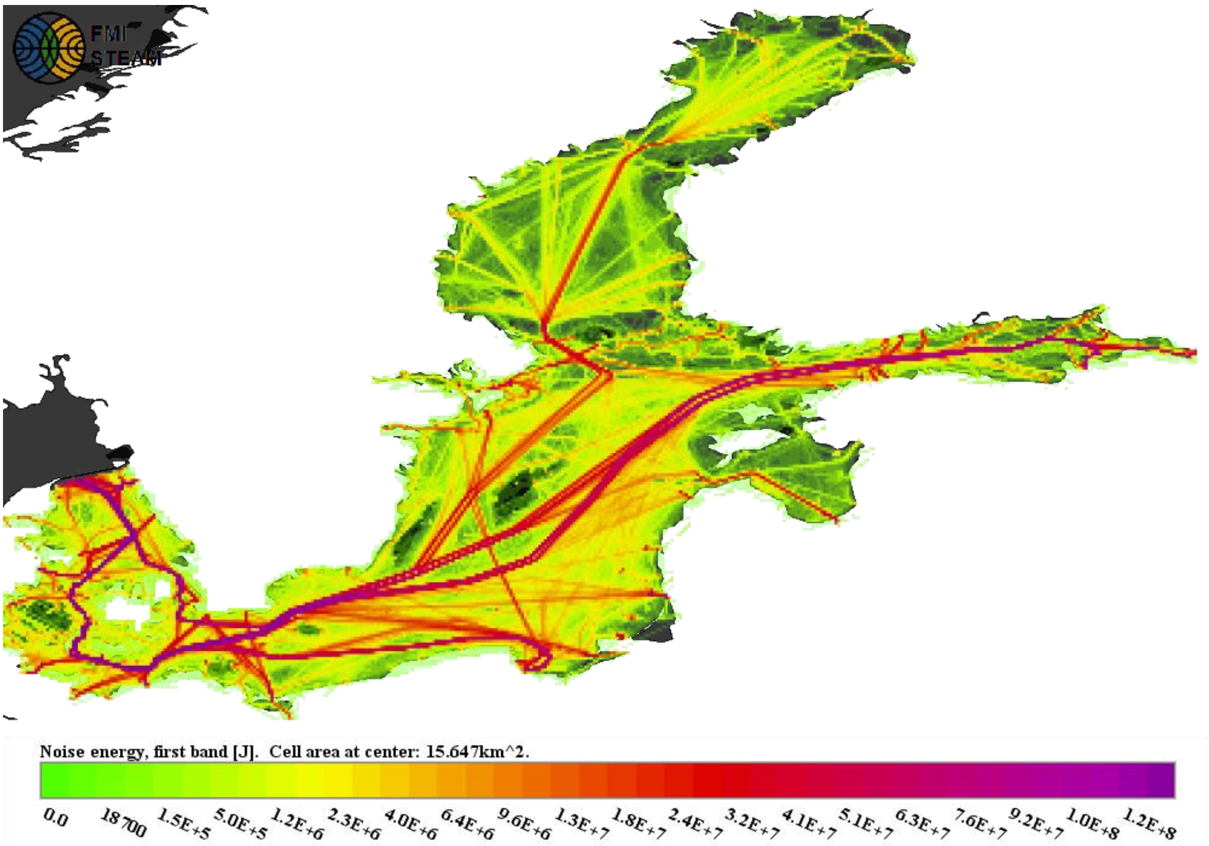


Figure 24 Noise from Baltic Sea ship at 63 Hz frequency band during 2017. The unit is total noise energy emitted in Joules emitted during one calendar year.

The noise propagation modelling results (D4.6) were reported for two pilot locations, one in a location south of Gotland island and the second in the western part of the Gulf of Finland. Calculations were computed for February and August for year 2014, because of limitations of available computing resources. Three dimensional structure of the sea floor, bottom sediment type, water temperature and salinity profiles were taken from Baltic Sea bathymetric database and HIROMB model data (High Resolution Operational Model for the Baltic Sea, provided by SMHI). This modelling resulted to noise dispersion maps, which describe the noise experienced by fauna living at pilot areas. Analogous to atmospheric chemical transport modelling outputs, emissions only describe the source of pollution, whereas the dispersion maps report the actual concentrations of pollution experienced by living creatures at a specific location. Conclusions of exposure to noise should be based on noise propagation modelling maps, not emissions alone.

The D4.7, reported the results of an experimental campaign, which was conducted at Tvärminne zoological station during Spring-Summer 2016. A collection of local fish was captured in a net cage and underwater loudspeakers were used to play back noise to fish. The behaviour of fish was observed with sonar equipment, which enabled observations of fish movements as a function of time. It was found that a playback of low frequency noise triggered a reaction in the fish, where a loose school of fish were tightly packed to a dense school once the noise was started. This experiment was repeated at various frequencies to determine the relevant range of frequencies where a visible reaction in fish was observed. Most visible were the behavioural changes with frequencies less than 1 kilohertz, which also represents the frequency range emitted by ships. The existing literature and experimental observations are fish species dependent (different species of fish hear differently) and six different species were tested during the campaign. In addition, habitat maps for different fish species were collected and overlaid with shipping noise maps to find hot-spots with fish habitats affected by high shipping noise levels (Figure 25).

Unfortunately, a more detailed impact assessment of underwater noise on fish was not possible because noise exposure functions for marine life are not available. This is clearly an area for future research, because pollution response functions exist for human exposure to atmospheric pollution, but similar developments for underwater noise and fish are missing.

In D4.8, an overview was provided for future developments of shipping noise in the Baltic Sea area. There are no compulsory regulations to design silent vessels with low noise emission levels, but there are mandatory rules for energy efficient ships. These two requirements (energy efficiency and noise emissions) are somewhat contradictory because efficient propeller designs may not be the most silent ones. It is easy to see that optimisation of performance may lead to larger noise emissions, if noise is not regulated. This development was also considered in the future projections of Baltic Sea shipping. Annual growth rate was applied to noise emissions until year 2040, which steadily increased shipping noise.

Operational changes, like slow steaming and route changes, may reduce shipping noise at some areas, but limitations of the Wittekind noise source model, safety requirements of rerouting and lack of knowledge of other noise sources (anthropogenic and natural), these approaches were not considered in the project, but would require an additional project dedicated to this topic.

The work on WP4 underwater noise was successfully completed and new capabilities to existing models were added. Future emission reporting for the HELCOM member states has greatly benefitted from the work carried out in SHEBA.

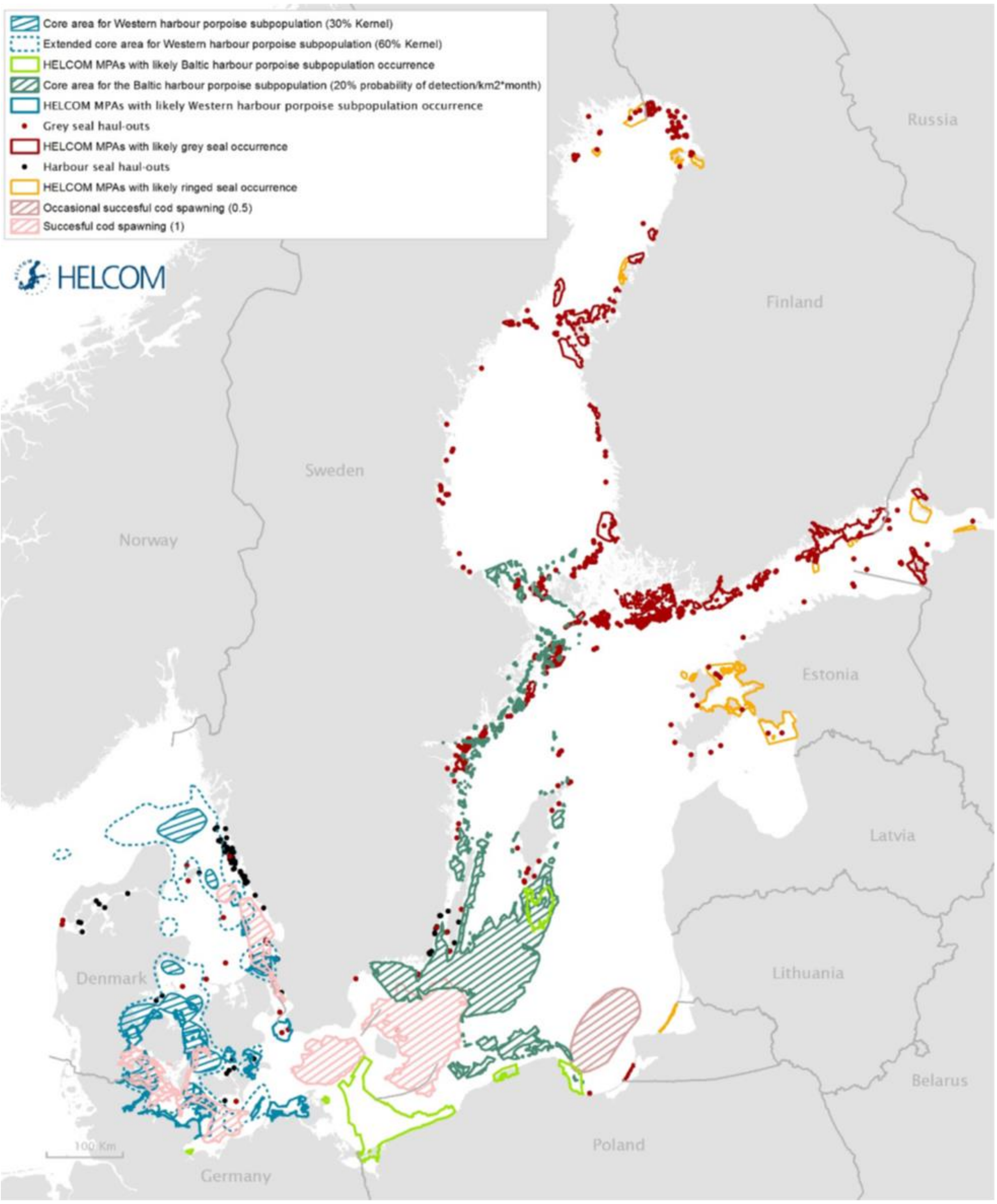


Figure 25 Noise sensitive areas derived from biological data on so far identified noise sensitive species. (Source: HELCOM 2017).

1.5. WP5, Assessments and policy

The aim of WP5 was to:

- Develop an analytical framework for the integrated assessment of shipping in the Baltic Sea.
- Assess changes to ecosystem services compared to Business As Usual based on different scenarios.
- Evaluate technology and policy options to reduce pressures and impacts from shipping and harbours in the Baltic Sea and identify and analyse synergies and trade-offs between these options as well as marginal changes in costs and benefits through the cost-benefit analysis (CBA).

WP5 was structured in three tasks. The aim of Task 5.1 was to create a framework to understand and ultimately assess the linkages from the drivers of shipping in the Baltic Sea to its effects on ecosystem services and human wellbeing. WP partners have conducted a review of literature on developed DPSIR frameworks in order to build on scientific understanding and adapt existing frameworks for use in SHEBA, and therefore shipping in the Baltic. There are at least a handful of European research consortia that have conducted ecosystem services assessment that includes shipping, e.g. ODEMM, KNOWSEAS, UKNEA, ELME, and VALMER. However, none of them have resolved the onboard subsystems and different pressures from shipping, why their outcome is of limited value when aiming at closing the DPSIR-circle and aiming at reduced environmental input from shipping e.g. through regulations of individual onboard activities. The analytical framework developed in SHEBA is unique as it enables semi-quantitative analyses along the DPSIR approach (Figure 26) and will allow for additional extensive analyses in the future; the SHEBA project budget only allowed for completion of a couple of examples, e.g. how shipping emissions of nutrients may lead to reduced volumes of landed cod in the Baltic Sea (described in D5.2). The work on D5.1 required a truly interdisciplinary approach and an internal workshop was held in February 2016 in Berlin in order fine-tune the framework and ensure a common understanding across the different disciplines and scientists within BONUS SHEBA. The consortium members contributed to a survey to be filled out by the BONUS SHEBA team to understand the main pressures resulting from shipping activity and how the main ecosystem services to be affected.

To structure the analyses in the framework, all onboard subsystems were mapped (Figure 15), and their relation to different levels of drivers was assessed. The next step was to identify all different types of environmental pressures arising from the different onboard subsystems, e.g. copper may leak both from antifouling paints and scrubber water (Pressure Level 1). To allow for a holistic assessment a second Pressure Level was introduced; the cumulative pressures. Analogously parallel Levels in State, Impact and Response, respectively, were created. The approach to include assessment of the cumulative pressure from shipping makes it possible to compare the emissions from shipping with the environmental quality elements in the WFD, and the Good Environmental Status Descriptors in the MSFD. This is a novel approach bridging the gap between environmental regulations applied on onboard subsystems, e.g. how much NO_X that is allowed to be discharged from a scrubber (*pressure*) in relation to the nutrient concentration in the marine environment (*state*) and what potential *impact* that may result in and finally if there are any measures (*response*) that is required to reduce the pressure.

In Month 15 (June 2016) of the project WP5 partners submitted D5.1 ‘Report on analytical framework for assessment of shipping and harbours in the Baltic Sea’. The adapted DPSIR framework was used in Task 5.2 and 5.3 to assess potential changes to ecosystem services compared to Business As Usual (BAU) and an integrated assessment and policy analysis to reduce pressures from shipping in the Baltic Sea (Figure 26).

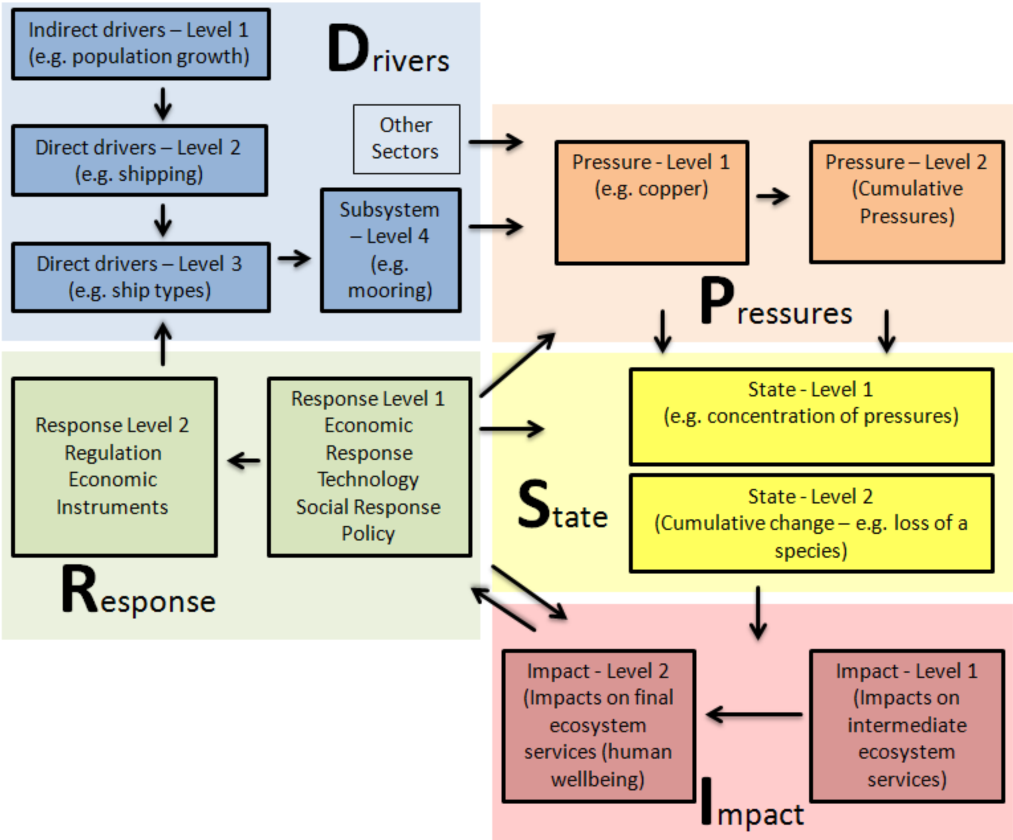


Figure 26 The DPSIR framework for shipping in the Baltic Sea region

Main output of Task 5.2 is 'Report on ecosystem services linked to shipping in the Baltic' (D5.2), where two main assessment approaches for costs of degradation has been used: an analysis of ecosystem services and an estimation of abatement costs. A semi-quantitative assessment of ecosystem services was developed as well as three case studies, two of the case studies estimated quantitatively changes by shipping on ecosystem services in the Baltic. A coordination meeting between WP5 and WP2/3/4 was held in Berlin in January 2017. A background document was provided for the meeting. The workshop was used to discuss an overall approach, methods, data sources and links to other WPs. The Deliverable 5.2 has been finalized in October 2017.

As input for Task 5.2 and 5.3, a stakeholder session was held as part of the project's general assembly in Tallinn in October 2016. The stakeholder session was used to gain a stakeholder's perspective on the pressures on marine environment, state of the environment as well as economic and social benefits impacted by shipping in the Baltic.

As basis for the main output of Task 5.3 'Report on policy evaluation and trade-offs to reduce environmental pressures of shipping in the Baltic Sea' (D5.3) the WP5 partners prepared an overview of integrated assessment frameworks for policy options based on a literature review. The results were summarized in a background paper. The assessment criteria were discussed and agreed with the WP5 partners during a project workshop in March 2018 in Gothenburg. Additionally, a web and literature research has been implemented on existing and possible policy instruments and technological solutions to reduce environmental pressures from shipping in the Baltic. Based on defined selection criteria 20 policy options have been prioritized by the consortium out of a long list of 85 options. The team discussed the options' selection during the project workshop in Gothenburg. With the support of all WP5 partners and especially partners contributing with results from the assessments in WP2, 3 and 4 the multidimensional assessment framework has been implemented for the 20 selected policy options. The results of the assessment by stakeholders (web-survey), experts and literature were used to implement a multi-criteria analysis (MCA) of the policy options. The deliverable 5.3 was finalized by the end of the project.

During the stakeholder workshops in Hamburg (2016) and Tallinn (2017) suitable and possible policy options and pressures from shipping have been discussed. Additional to these workshops, a web-survey was implemented targeted on stakeholders from different institutions. The stakeholders had the possibility: (1) to assess the 20 policy options by three assessment criteria (political implementability, acceptance & feasibility and effects on environment and health), (2) to rank the eight assessment criteria used for the estimation of the total MCA results and (3) to create an ideal policy mix of a maximum of six policy measures. The web-survey was online from mid-March until mid-May 2018.

1.6. WP6, Dissemination, education and data products

The work was organized in three tasks: 1. Interaction with stakeholders, 2. Data products and dissemination and 3. Education and interaction with the general public. In the following some of the work is described in more detail.

Task 6.1: Interaction with stakeholders

BONUS SHEBA topics involved a very wide spectrum of disciplines, and because they are closely related to policy, society, and industry, the interaction with relevant stakeholders from these groups was of high importance for the project. Stakeholders were involved on two levels. First, some key stakeholders were invited to consult the project throughout its running time as members of an external advisory board. Members of the advisory board were: David Turner, Gothenburg University, Sweden; Carl Carlsson, Swedish Shipowner´s Association; Anita Mäkinen, Finnish Transport Safety Agency, Helsinki, Finland; Stefan Schmolke, Federal Maritime and Hydrographic Agency, Hamburg, Germany; and Magdalena Wesolowska, Maritime Office in Szczecin, Poland. Members of the advisory board participated in the consortium meetings.

Stakeholder workshop

A major activity at the beginning of the project was the organization and conduction of a stakeholder workshop ("1st SHEBA Stakeholder Meeting"), which was hosted by Helmholtz-Zentrum Geesthacht and took place in Hamburg, Germany, on 29 and 30 of September 2015. About 20 stakeholders of the shipping sector participated (Figure 27). The interaction with maritime stakeholders from shipping, environment and related administration was of the upmost importance for SHEBA. The aim was to consult a wide group of stakeholders about various elements of the project's research, such as input of data,- and their expectation on the results of BONUS SHEBA, to further refine the research questions.

The outcome helped very much to start the scenario development process of working package 1 by addressing technical, socio-economic and political issues and reflecting on the future of Shipping in the Baltic.

The meeting was organized in form of World cafés and outcomes have been reported in the first policy brief 'Brief from the SH meeting' **(D6.3)**.

Figure 27 Impressions from the 1st BONUS SHEBA Stakeholder-meeting in Hamburg, September 2015.

Stakeholder elicitation (including preparatory training)

To support the scenario development of WP1 an important contribution by WP6 was the preparation and conduction of a stakeholder elicitation using an objective, quantitative method. This activity was done in collaboration with a Swedish Institute (SI) financed project called "Expert elicitation". The actual elicitation took place during the SHEBA stakeholder meeting on 12 and 13 October 2016 in Tallinn, Estonia. The method chosen to assess quantitative expert judgements was the Sheffield Elicitation Framework (SHELF). A preparatory SHELF training course for SHEBA consortium members was held in May 2016 in Gothenburg, Sweden. The course was instructed by Prof. Tony O´Hagan, one of the two developers of SHELF. During the Tallinn meeting SHEBA consortium members conducted the elicitation, the experts involved were invited members of the SHEBA advisory board and the extended SHEBA stakeholder group. Main purpose of the elicitation was to support the SHEBA scenario building with quantitative information on several issues related to emission abatement in the Baltic shipping sector. The actual questions aimed at the use of Liquefied Natural Gas (LNG) as fuel, the employment of scrubbers for exhaust gas cleaning, and on the use of port reception facilities (PRF) for greywater. E.g. the expert group thinks that in 2040 about 27% of the ships sailing in the Baltic Sea will use LNG as fuel in order to reduce NO_x emissions, and it was estimated by the expert group that in 2040 about 24 % of the ships sailing in the Baltic Sea will use scrubbers to reduce sulphur emissions to air.

Conference "Shipping and the Environment" and special issue in Copernicus journals

A central activity of this task was the preparation and conduction of the conference "SHIPPING & the ENVIRONMENT -from regional to global perspectives". The conference took place on the 24th and 25th of October 2017 in Gothenburg, Sweden. It was co-organized together with the project SOLAS (International Surface Ocean - Lower Atmosphere Study) and was affiliated as the 2nd BONUS symposium. The conference addressed a wide range of aspects regarding the impact of shipping on the environment and attracted about 120 participants from all over the world (scientists, students, representatives of environmental and transport agencies as well as environmental managers) (Figure

28). The 5 major themes were: Atmospheric processes, Assessments of integrated effects on environment and climate, Marine processes, Noise and Socioeconomic aspects and policies. The conference closed with an expert panel discussion. Summaries of the conference sessions as well as major messages from the different research areas are presented in the 2nd SHEBA policy brief (**D6.8**). Some renowned scientists were invited as keynote and solicited speakers. Besides oral talks the conference also included 2 poster sessions with much appreciated "flash-talks" as introduction conference. Overall the conference was well received by the participants.

Figure 28 Impressions from the "Shipping and Environment" conference in Gothenburg, October 2017.

The conference organising committee decided to organise a special issue in scientific journal which would provide forum for scientific discussion on the topic of environmental impacts of shipping. The special issue has been opened in February 2018 as a joined special issue of Copernicus open access journals 'Atmospheric Chemistry and Physics' and 'Oceanic Science' (https://www.atmos-chem-phys.net/special_issue948.html), inviting both publications stemming from the conference contribution and from the wide scientific community. BONUS Secretariat contributes financially to the publication costs of papers originating from BONUS projects.

Networking

In 2015 BONUS SHEBA become one of the flagship projects of EUSBSR Policy Area (PA) Ship. Representatives of BONUS SHEBA were attending meetings of the international steering board of PA Ship, where they presented progress of the project and the project provided annual progress reports for the PA Ship. BONUS SHEBA coordinator Jana Moldanova, IVL, also contributed to the Joint Capacity Building Workshop of EUSBSR PA Ship and PA Safe in April 2018 in Copenhagen, Denmark.

In December 2015 BONUS SHEBA was assigned to be a Baltic Earth affiliated project. As such, SHEBA with its commitment for sustainable shipping contributed by consultancy to some of the research questions with focus on biogeochemical questions in relation to air and water pollution and their impacts on the marine ecosystem and socio-economic sectors. The SHEBA research plan and results were presented during the 1st Baltic Earth conference, June 206 in Nida, Lithuania, and the 2st Baltic Earth Conference, June 2018 in Helsingör, Denmark.

Task 6.2: Data products and dissemination

After consultation with all partners the concept for the BONUS SHEBA data-portal was finalized and a data-portal prototype has been established. A report on the data-portal was been compiled as deliverable **D6.4**. After a test phase and refinement of the general structure and THREDDS the actual data-portal has been set up as deliverable **D.6.5**.

Towards the end of the project a general concept and structure of the BONUS SHEBA information portal (**D6.9**) was defined and implemented. The BONUS SHEBA information portal has the task to inform the public, authorities and other scientists about the outcome of the project and to provide an overview which data from project will be available for further research and how to assess it. The information portal is web based and organized along the working package structure of the BONUS SHEBA project. Starting points will be the SHEBA webpage and a reserved URL. Each of the topical fields can be assessed freely chosen from an entrance tile. From there the research fields can be explored in different depths. For each topic a list of available data sets compiled during BONUS SHEBA and respective contact points will be provided. Additionally selected story lines are offered as spotlights to learn targeted about shipping and environment. The information portal will be filled with content prepared by the different working packages. Going online is planned for the end of 2018.

A general BONUS SHEBA data policy for internal and external data use has been developed within this task, which has been agreed upon by the consortium during its final meeting in Berlin in May/June 2018.

Task 6.3: Education and interaction with the general public

Dedicated outreach activities

In the beginning of July 2016 BONUS SHEBA organized during the research expedition on sailing research vessel Hrimfare af Rankie an outreach campaign in Visby, Gotland on the Swedish politicians' week in Almedalen. Researchers from BONUS SHEBA were joined by colleagues from other BONUS projects CHANGE, ZEB, BALTSPACE and ESABALT. For three days, the Hrimfare expedition sailing boat was opened for visitors and an exhibition tent provided further possibilities to discuss with BONUS experts cleaner and safer shipping. BONUS SHEBA organized also discussion panel between the BONUS research projects' experts, politicians and representatives of authorities and industry with title 'Towards safer and cleaner shipping in the Baltic Sea' in West Swedish Arena (Figure 29).

Figure 29 Panel discussion on safe and clean shipping in the Baltic Sea during the Swedish politicians' week in Almedalen. Photo: Jana Moldanova

BONUS SHEBA organized and contributed with 3 speakers to the seminar "Sustainable shipping on the Baltic Sea beyond 2020" of the 9th Annual Forum of the EU Strategy for the Baltic Sea Region in June 2018 in Tallinn, Estonia. The seminar presented the results of the BONUS SHEBA project and used the scenario work of the project as basis for an interactive dialogue on a pathway to a sustainable and competitive maritime sector in the Baltic Sea Region for the coming decades.

Scientists from Helmholtz-Zentrum Geesthacht (HZG) presented BONUS SHEBA research during several „Forschung vor Anker“-tour of the HZG-owned research vessel “Ludwig Prandtl. The tours led to several locations along the German Baltic and North Sea coasts. During the course of the project BONUS SHEBA was also topic of several other public outreach activities like talks or TV interviews.

Educational material

Partners from Chalmers, IVL and HZG have compiled a set of educational material reflecting BONUS SHEBA results, which can be used by schools, shipping related university courses and distributed to the public (**D6.6**). To give the task a wide scope three different formats were chosen to provide information to students and pupils: a reader, an interactive PowerPoint Presentation (PICO) and a short movie. The reader on featured topics addresses different problem areas by short dedicated essays written by BONUS SHEBA scientists from the different subject areas. An interactive PowerPoint Presentation (PICO) informs about the BONUS SHEBA topics along the projects working package structure by a combination of short text segments and graphics. The movie based on interviews with BONUS SHEBA scientists on the different research fields is the third format to provide educational information.
A second activity within task 6.3 was the preparation of an environmental manual, which provides the key results from the BONUS SHEBA project together with a list of policy options and recommended measures/mitigations addressed to ship-owners and ports (**D6.7**).

1.7. WP7, Project management

Before the start of the project BONUS SHEBA consortium adopted a Consortium Agreement including a Management Plan of the project and a Quality Management Plan. These documents have been maintained by the coordinator and used to guarantee an efficient and transparent management of the project, good and fair collaboration among the partners as well as a good quality of the produced deliverables. In a later phase of the project a BONUS SHEBA Data Disclaimer and document ‘Handling of data produced and exchanged within BONUS SHEBA’ have been formulated and accepted by General Assembly to guidance the data exchange within and outside the consortium.

The SHEBA management team consisted of the project coordinator, the financial manager and the project manager and performed the day-to day scientific and economic management of the project. The close connection of the coordinator with the consortium has been through the steering board of the project which convened regularly every month and distributed notes of the meeting to the consortium through the project internal website which was created by coordinator at the project start.

The project has organized 2 consortium meetings annually, 7 in total. They were often organised back to back to BONUS SHEBA stakeholder events or to the conference. The consortium meetings gathered wide consortium, members of the advisory board, representatives from BONUS secretariat as well as invited guests and stakeholders. All meetings included plenary presentations on the progress in the project as well as work package meetings. Meetings of the General Assembly, the project’s highest decision body, were organised in agreement with the Management Plan at least once per year during the consortium meetings. On occasions when GA decisions were needed, these were more frequent. In total 5 GA meetings were organised. All work packages have organized additional physical meeting and regular teleconferences to coordinate the work among their partners.

2. Summary of the produced scientific and technological foreground capable of industrial or commercial application, plan for the use and dissemination of this foreground and measures taken for its protection

The project has produced substantial scientific foreground comprising of developments in the STEAM model to calculate direct shipping emissions of contaminants to water column and emissions of underwater noise, development of the model for calculation of emissions from recreational boats BEAM, quantitative emissions from shipping to air, water and of underwater noise in different scenarios, improved modelling capabilities of atmospheric, oceanic and noise propagation models regarding the shipping emissions, quantitative assessments of impacts of these emissions as well as assessment of policy options to mitigate the negative impacts. This foreground will be used by the members of the consortium in their further research and consultancy work both on national, Baltic Sea region and wider international level. However, the STEAM and BEAM models use data from AIS data collected by HELCOM member states as well as from commercial providers. The use of STEAM is restricted for research purposes only and aggregated output data is available. The BONUS SHEBA results are public and majority will be published in scientific journals, allowing access to wide scientific community in agreement with the grant agreement of the project. Consortium has formulated a data exchange policy disclaimer to guideline use and publication of the data produced in BONUS SHEBA.

3. Further research needed in the field

The project ambition to develop an assessment framework for ecological, economical and societal impact of shipping embedded wide analyses of available data and knowledge as well as the gap analysis. The BONUS SHEBA assessment framework needs to be seen as a basis which will be continuously developing as new knowledge is becoming available. Below the most important areas where research effort is needed are described, following the work package structure of the project:

3.1. WP1, Policies, activity data and scenarios

- Ships are becoming more diverse and there is an ongoing need on detailed description of ships in the traffic models. This may concern fuel type, use of engines in different modes and the use of abatement measures.
- The model for leisure boats is a first attempt and there are several research needs associated with it. The traffic from other countries (i.e. Norway) should be incorporated. The description of the engines in the fleet should be verified. The amount of fuel use should be verified. The emissions should be verified by dispersion modelling and air quality measurements.
- There is a continued need for assessing policies as they develop. During the course of SHEBA several instruments have been introduced (NECA, GHG-policies, Ballast water convention).

- Scenarios can be further developed as new information becomes available on socioeconomic developments and policy measures as well as regarding the availability of different fuels.

3.2. WP2 Air pollution

- The amount of gases and particles emitted by ships still contains uncertainties. Although accurate information exists about shipping routes, their speed and the technical information about the ships, emission factors for NOx and PM depend on real operation conditions and are therefore hard to predict. In addition, the NO2/NO ratio, emissions of VOCs, including information on the exact species, and PM composition are uncertain. More observations of real world emissions on board of ships would help reducing these uncertainties.
- Port emissions are even more uncertain than those from sailing ships. Detailed investigations about the fuel use of ships in ports covering a large number and type of ships would be an urgent research need in order to assess the impact of ship emissions on air quality in ports with higher accuracy.
- Model results of the impact of shipping on air quality and deposition are connected with uncertainties that could be reduced if more research would be performed on the dispersion of the plumes from ships and on the non-linear in-plume transformation processes. The application of several atmospheric chemistry transport models would reduce the uncertainty inherent in every model system. In addition, simulations of multiple years with varying meteorological conditions could reduce the uncertainty connected with specific weather conditions in the simulated years.
- Similar to the regional models, city scale chemistry transport models need further development for an improved representation of ship plume dispersion and in-plume chemistry. In addition, the effects of complex buildings and structures in port areas might cause disturbances in the exhaust gas propagation that are not well represented in current model systems.
- It is difficult to validate the model results for atmospheric deposition (both wet and dry) because this is either hard to measure (dry deposition) or spatially very inhomogeneous (wet deposition). However, this is a problem that is not solely related to shipping emissions.
- Assessments of health impacts and impacts on natural land ecosystems were performed along the methodology used in EU Thematic Strategy on Air Pollution (TSAP) and it is important to keep the methodology updated as more knowledge is continuously included in the TSAP. Uncertainties in deposition of nitrogen could be better assessed if the model results were compared to more wet and dry deposition data, e.g. from Swedish monitoring networks. Effects of ozone on crops and forests were not evaluated due to limitation of resources for the land impacts assessment in the project. Completion of the assessment framework with these effects is rather straight forward.

3.3. WP3 Water pollution

Reflections, challenges and obstacles identified:

- Uncertainties in the assessments - assumptions in the indata regarding:
  - Waste stream concentrations are variable and today few data sets are available
  - Ballast water discharge patterns are not very well described for different types of ships
  - Emission factors for grey, black water and food waste multiplied by no of persons onboard
  - Particle assessment; too little data available, standardized potential risk
- Modelling is used to distinguish the shipping from other sources, but validation is often not possible in nature e.g. for nutrients, also impacting monitoring possibilities
- Improved pH-measurements in the Baltic Sea, BONUS PINBALL, will increase reliability of future measurements

- It is still a challenge to get access to sample waste streams on board
- It is also a challenge to sample ship lanes and to consider the natural and ship induced hydrography
- In D3.9 ship lanes were distinguishable with respect to temperature and sometimes hydrocarbon concentrations. What implications/biases could this cause for ferry-boxes measurements in ship lanes?
- Assumptions regarding illegal emission are extremely difficult to make with an appropriate degree of certainty.

Future outlook from WP3 perspective:

- Zero discharge to water, e.g. black water 2021/2023 reduce need further research related to that specific waste stream
- Reduce uncertainties in the assessments through:
  - Reports of positioning during discharge operations ballast water
  - Environmental conditions and speed of vessel for leakage rate
  - Sampling/database on characterization of waste streams
    - Scrubber water (work already started by BSH German Federal Maritime and Hydrographic Agency)
    - Grey water
    - Treated ballast water
  - Improve biogeochemical modelling
    - Missing link between concentrations (state) and effects on biogeochemical processes (impact)
    - Increased focus on process modelling, local/regional cases,
    - Synergistic effects of e.g. different contaminants and acidification
- Include physical effects of induced mixing in ship lanes
- Design and establishment of monitoring programs, difficult but necessary

3.4. WP4 Underwater noise

- The Wittekind noise model was developed for larger cargo vessels which typically travel in the Baltic Sea area and the applicability is less well known to passenger and feeder vessels which also appertain to the Baltic Sea fleet. The development of noise source model to cover also the fleet using two stroke engines and vessels with controllable pitch propellers needs further attention.
- This issue has clear links with maritime spatial planning, which was not extensively covered in this project. Allocation of sea areas for specific purposes needs to consider also noise in the future.
- Regular monitoring of underwater noise needs to be developed. Currently, there exists only scattered research projects which do noise monitoring, but there is a clear need for an observation network, which is similar to the coverage required of the monitoring of atmospheric pollution.
- It is difficult to conduct impact assessment of noise if only some of the relevant sources of noise pollution are known. This inevitably leads to the situation where noise exposure is incomplete and needs further work to cover all sources.
- The knowledge of technical noise reduction measures needs to be collected and communicated to research and ship building communities. Lack of noise signature measurement data from ships prohibits the analysis of potential reduction measures and needs further attention.

3.5. WP5 Assessments

A number of challenges and further research needs occurred during the assessments:

- The design of the overall DPSIR framework means that while linkages can be identified it was not possible to fully identify feedback loops within the system and account for their effects on human wellbeing.
- Lack of data was a major challenge regarding links between various elements of the assessment
  - The *pressures-state* link is still missing for underwater noise and work done in BONUS SHEBA need to be seen as a first attempt. Also for other *pressures* there are still challenges as specified above.
  - Linkages between *state* of *level 1* and *level 2* (from environmental concentrations of pollutants/contaminants/noise energy levels to environmental changes such as changes in biodiversity) are quantitative only in few cases and a focused effort is needed both in the marine and terrestrial ecosystem research. This is a wide topic not limited to shipping, however, the important impacts identified in BONUS SHEBA framework has been mapped.
  - Links between the *state* and *impacts*, i.e. the linkage to ecosystem services, is in most cases only qualitative and not well understood. There is also a lack of economic data e.g. for monetization of benefits of policy options.
- Further research is needed on comparison studies including all Baltic Sea countries on economic valuation of ecosystem services, e.g. stated or revealed preference studies. As benefit transfer from one country to the other is always including uncertainties and shortcomings, country comparison studies are valuable for the further improvement of ecosystem services assessment.
- Cost and especially benefit assessments in monetary terms per policy option have as well further research needs. Further steps could include case studies or detailed studies on specific components of ecosystem services or for specific policy options in which aspects can be analysed in more detail.

4. Summary of the promoted and effective science-policy interface to ensure optimal take up of research results

4.1. Project's contribution to the development and implementation of 'fit-to-purpose' regulations, policies and management practices on international, European, the Baltic Sea region or national level (Performance statistics item no. 1)

Throughout the project duration BONUS SHEBA contributed to implementation of two important IMO regulations. Both the IMO revisions of Baltic Sea and North Sea NECA applications and the agreement on the sulphur cap of 0.5% for global shipping have benefitted from SHEBA contributions through contribution of partner FMI, who presented analyses of impacts of these regulations at IMO MEPC70 meetings (documents IMO MEPC70/5/1 AND IMO MEPC70/INF.34). Although the BONUS SHEBA project cannot take credit of all this work conducted over the past years, the revisions of Baltic Sea and North Sea NECA applications have benefitted from BONUS SHEBA contributions.

The SHEBA project was highlighted in the Proposal for a work plan on underwater noise at the Heads of Delegation (HoD) meeting of HELCOM in Tallinn, Estonia, 10-11 June 2015. Also, the work carried out in SHEBA was noted in the HELCOM Maritime 18 meeting in Hamburg, Sep 25th-27th 2018.

These contributions are described in documents Maritime 18/12-2.INF, Maritime18/12.4-INF and Maritime18/11-2.INF.

4.2. Suggestions for designing, implementing and evaluating the efficacy of relevant public policies and governance on international, European, the Baltic Sea region or national level originating from the work of the project (Performance statistics item no. 2)

BONUS SHEBA has contributed to the work concerning the writing of the HELCOM indicator for underwater noise, where in the assessment protocol the BONUS SHEBA methodology is incorporated as approach number 3. If accepted, the SHEBA approach will be used as a methodology for assessing GES for underwater noise in low density areas.

BONUS SHEBA activities have contributed in several ways to the ship emission reporting to HELCOM in the Baltic Sea area with results and tools developed within the project. From 2018 the annual ship emission reporting of Finland to the HELCOM member states will include underwater noise and emissions of contaminants to water from ships, both developed within the BONUS SHEBA project. SHEBA emission modelling capabilities were also introduced at a meeting of European Sustainable Shipping Forum, Air Emissions subgroup in Brussels, June 2018. Further, BONUS SHEBA contributed to HELCOM assessments concerning the share of small boats in emission totals and regional assessments and to State of the Baltic Sea and OSPAR's Intermediate Assessment 2017.

Members of consortium also responded on several requests from Swedish agencies concerning e.g. national assessments of impacts from shipping, knowledge support for new schemes for environmentally differentiated fairways, assessment of a research funding program and suggestions on how to improve antifouling paint regulation in the Baltic Sea region. The impact of emissions from shipping on land was assessed using the methodology of UN ECE Convention on Transboundary Air Pollution and brought the Convention's attention.

4.3. Scientists working in the project have served as members or observers in stakeholder committees (Performance statistics item no. 3)

Scientists involved in BONUS SHEBA have served as members and representatives of a number of expert and working groups and committees on international, EU, macro-regional and national levels, including the ICES-Working Group on Ballast Water and Other Ship Vectors, the IQOE Working group on Arctic Acoustic Environment (SCOR), the European Sustainable Shipping Forum, Air Emissions from Ships –subgroup, the EC TG Noise Expert Group, HELCOM Network of Noise Experts, the Technical Committee of Clean Shipping Index and the Program Committee for the Competence Centre Lighthouse.

BONUS SHEBA has been a flagship project of EUSBSR Policy Area Ship. The project partners have regularly attended semi-annual meetings of the international steering board of PA Ship, where they presented progress of the project and the project provided annual progress reports for the Policy Area as well as have contributed to the Joint Capacity Building Workshop of EUSBSR PA Ship and PA Safe in April 2018 in Copenhagen, Denmark.

Scientists involved in BONUS SHEBA have participated in a number of meetings and events with stakeholder groups, such as e.g. the Swedish Zero-Vision Tool organisation and the Marine Spatial Planning 2050 workshop. Members of BONUS SHEBA have been very active in developing underwater noise indicators in the HELCOM Baltic Boost expert group and in the MSFD Common Implementation Strategy Technical Group on Underwater Noise (EC TG-NOISE).

4.4. International, national and regional stakeholder events organised by the project

BONUS SHEBA organised a number of stakeholder events throughout its duration:

During the first year the major stakeholder event organised by the project was the First BONUS-SHEBA stakeholder meeting which took place in Hamburg 28-30 September 2015. In total 18 stakeholders and external guests from 6 different countries participated in the meeting. Representatives of authorities, ship-owners, cruise companies, harbours, leisure-boat association, NGOs and research organisations were present

In July 2016 the project invited Swedish politicians and representatives of authorities and industry to take part in a panel discussion at the West Swedish Arena on Swedish politician week in Almedalen. The topic of the discussion was about how citizens, boat owners, harbour operators, shipping partners, authorities and politicians can help to decrease undesired environmental impact caused by shipping and boating in the Baltic Sea. In the panel, moderated by Anna Jöborn from Swedish Agency for Marine and Water Management (SWAM).

In September 2016 expert elicitation meeting was held in Tallinn. There were in total 40 participants of whom 14 were expert stakeholders from different maritime authorities around the Baltic Sea and invited guests from BONUS and HELCOM secretariats. Highlights of the results achieved in the project were presented and the invited experts helped to estimate a number of parameters needed in development of the BONUS SHEBA shipping scenarios using the Sheffield expert elicitation method (SHELF).

In October 2017 a stakeholder panel discussion was organised at the Shipping and the Environment conference, event co-organised by the BONUS SHEBA project and the project SOLAS (International Surface Ocean - Lower Atmosphere Study). It included 8 panellists from research, national and local authorities, industry and HELCOM secretariat. The number of conference participants was approximately 117 persons with different background; from research, authorities and industry.

In October 2017 IVL, BONUS SHEBA partner, organised a panel discussion 'Så når vi en hållbar sjöfart i Östersjön' at annual stakeholder event 'Östersjöseminarium' arranged by IVL in Stockholm. The panellists were from two Bonus projects, politicians, representatives from the Swedish shipowners' association, Swedish ports' association, SWAM and Västra Götaland Region Administration. The audience amounted to about 100 from all backgrounds.

The development of SHEBA D5.3 included stakeholder engagement via a web-survey.
The stakeholder perspective was included in the integrated assessment of policy options, a web-survey was designed, with the goal to obtain more information on the stakeholder's own weighting of assessment criteria. The web-survey went online in mid-March and continued until mid-May 2018. By the end of this period, a total of 63 stakeholders had responded to the questionnaire. The most responses came from public authorities (13), science (11), businesses (8) and NGOs (7).

In June 2018 BONUS SHEBA organised a discussion panel on the 9th EUSBSR annual forum in Tallinn. The panellists were from HELCOM, BONUS SHEBA and the industry (Tallink, Port of Gdynja). The audience amounted to about 50 people.

4.5. List of peer-reviewed publications arising from the project research and defended PhD dissertations'

Published publications:

- Zetterdahl, M., Moldanová, J., Pei, X., Pathak, R.K., Demirdjian, B. (2016). Impact of the 0.1% fuel sulfur content limit in SECA on particle and gaseous emissions from marine vessels. Atmospheric Environment 145, 338-345.
- Jalkanen J.-P. et al., Modeling of ships as a source of underwater noise, Ocean Science Discussions, https://doi.org/10.5194/os-2018-48, *in review for Shipping and Environment Special Issue in Ocean Science*
- Karasalo, I., Östberg, M., Sigray, P., Jalkanen, J.-P., Johansson, L., Liefvendahl, M. and Bensow, R. Estimates of source spectra of ships from long term recordings in the Baltic sea. Frontiers in Marine Science, 4 (2017) 164. https://doi.org/10.3389/fmars.2017.00164
- Magnusson K., Jalkanen J.P., Johansson L., Smailys V., Telemo P., 2018. Winnes H. Risk assessment of bilge water discharges in two Baltic shipping lanes. Mar. Pollut. Bull. 126, 575-584. doi: 10.1016/j.marpolbul.2017.09.035.
- Wilewska-Bien, M., L. Granhag, J-P, Jalkanen, L. Johansson and K. Andersson. (2018) Phosphorus flows on ships: Case study from the Baltic Sea. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, https://doi.org/10.1177/1475090218761761

Submitted publications, not yet accepted:

- Jalkanen et al., Modeling of ships as a source of underwater noise, Ocean Science Discussions, https://doi.org/10.5194/os-2018-48, in review for Shipping and Environment Special Issue in Ocean Science
- Marianne Zandersen, Sampo Pihlainen, Kari Hyytiäinen, Markus Meier, Anna-Kaisa Kosenius, Päivi Haapasaari, Jørgen E. Olesen, Jens Christian Refsgaard, Martin D.A. Le Tissier, Barbara Bauer, Maciej T. Tomzcak, Erik Fridell, Detlef van Vuuren, Bo G. Gustafsson, Extending Shared Socioeconomic Pathways for the Baltic Sea region for use in studying regional environmental problems, Submitted to Regional Environmental Change
- Wilewska-Bien M., L. Granhag and I. Maljutenko. Nutrient contribution from cruise ships´waste and importance for algal blooms. Submitted to Boreal Environment Research.

Defended PhD dissertations:

- Magda Wilewska-Bien, Chalmers. Management of ship-generated waste - illustrated from the Baltic Sea perspective. ISBN 978-91-7597-624-2. Successfully defended September 29th 2017. Chalmers University of Technology. Opponent: Dr. Merica Sliskovic, Faculty of Maritime Studies, University of Split, Croatia.
- MSc. Marje Prank, worked for SHEBA until end of March 2017 (Defence 13.1.2017, but SHEBA was only one of the FMI projects where Marje was involved). Thesis "Identification of pollution sources and characteristics of atmospheric composition via forward and inverse dispersion modelling", FMI contributions, #128.
- MSc. Joana Soares, FMI, until end of 2016 (Defence 27.5.2016, but SHEBA was only one of the projects where Joana was involved). Thesis "Emission and dispersion modelling of aerosols and human exposure to particulate matter", FMI contributions #121.

5. Overview of the collaboration with relevant research programmes and the science communities in the other European sea basins and on international level (Performance statistics item no. 5)

Through its project partners BONUS SHEBA had a direct collaboration with a number of national and international research projects including German project MeRamo supporting public authorities dealing with the Marine Strategy Framework Directive, EMISSHIP project (Portuguese science foundation) aimed at shipping near the Iberian Peninsula, AIRCOAT H2020 project on developing new antifouling surface for hulls, EPITOME project (Nordic council of ministers) on Arctic shipping and Copernicus Atmospheric Monitoring Services 81, on emission inventories. SHEBA partners joined several consortia preparing proposals for further research submitted or under development to INTERREG (one proposal) and to H2020 (three proposals). SHEBA participants took part in scientific meetings including 2018 ITM meeting in Canada and more. To reach outside the Baltic region co-operation has been established with research institutions in Portugal, France, Germany, Norway and USA. BONUS SHEBA collaborated closely with international project SOLAS (International Surface Ocean - Lower Atmosphere Study) on organisation of an international conference Shipping and the Environment – From local to global perspective (2017) and project partners participated actively on SOLAS workshop organised back to back to the conference and on drafting of a report from this workshop.

6. Progress in comparison with the original research plan and the schedule of deliverables

By its end, the BONUS SHEBA has completed all originally planned deliverables. Few exemptions experienced has been amended to the original plan and approved by the BONUS secretariat. These changes were caused by practical reasons as e.g. the original location of a test study was less suitable than the one eventually investigated or that the original timing of opening of information portal was before important outcomes of the project were in place. The overall achievements of BONUS SHEBA were well in line with the original plan and number of highly innovative outputs has been produced.

BONUS SHEBA put substantial effort into communication with stakeholders on different levels which led to additional activities associated to the project. During the 1st BONUS SHEBA stakeholder meeting a need for additional meetings to elicitate information from stakeholders was identified. This led to a grant application for support of additional meetings applying the Sheffield expert elicitation framework (SHELF). The application was led by Chalmers and sent to Swedish Institute. The application was successful and additional financial support was granted, enabling training of consortium members in the SHELF method, organisation of an expert elicitation workshop and invitation of additional stakeholders also to other meetings originally planned in the DoW. Further, the project has arranged two outreach campaigns and several lectures and discussions, including the panel discussion at Swedish politicians' week in Almedalen and at EUSBSR 9th Annual Forum in Tallinn to disseminate the project results and to raise public awareness of the environmental impact of shipping in the Baltic Sea Region.

A number of project deliverables experienced a delay, however in most cases not exceeding few months. In many cases there were personal reasons such as parental or sick leave behind the delay. Also a rather tight schedule of deliverables put some stress on timely delivery, at the same time it contributed to high engagement and interaction among the partners throughout the entire project. The delays as well as the large amount of new and highly innovative outputs worth publishing led to extension of BONUS SHEBA with 4 months to allow for further analysis and synthesis of the results and work on scientific publications.

7. Wider societal implications. Please cover in this chapter also gender equality actions, ethical issues and efforts to involve other actors and spread awareness

The BONUS SHEBA project has advanced the understanding of shipping related impact on the environment in the Baltic Sea Region. The holistic approach of looking at the impacts of operational shipping on atmospheric, marine and underwater noise pollution simultaneously have significantly improved the general understanding of shipping related impact, based on efficient transfer of knowledge and concepts previously applied on assessments of air pollution to assessments of marine pollution and underwater noise. The work started from a classical *DPSIR* framework, Driver-Pressure-State-Impact-Response. In combination with evaluation of different future scenarios, it also enables possibilities to test options for regulations and other policy measures that aim at the reduction of pressures, improvements of the state and minimized impacts on human health and the ecosystem.

The new capabilities for modelling of shipping-related water contaminants and underwater noise were developed and implemented into the Ship Traffic Emission Assessment Model (STEAM) setting up one of the cornerstones of assessment framework for the impacts of shipping. The achievements in modelling of emissions of water contaminants is pioneering and the very first complete inventory and calculation of load factors of waste streams and the sum of pollutants from all waste streams, available for shipping. The development of underwater noise source module of STEAM is the first attempt to indicate the levels of noise emitted by ships, advancing our knowledge of spatio-temporal variation of shipping noise and increases general knowledge of ships as source of noise pollution. Further, a completely new model was developed to describe small boats, The Boat Emissions and Activity siMulator (BEAM) and has been applied to the Baltic Sea. All these developments facilitate regular annual reports of shipping-related emissions of air pollutants, water contaminants and underwater noise energy for HELCOM member states. Results from BEAM contributed to HELCOM State of the Baltic Sea and OSPAR’s Intermediate Assessment 2017. The emission framework facilitates also for further developments, both in terms of expanding the regional coverage to European and global as well as in terms of updating and improving the emission factors of the different pollutants and contaminants as the new data are becoming available.

The second cornerstone of the BONUS SHEBA assessment framework is the scenario work which advanced our understanding of impacts of the main drivers of shipping on its environmental sustainability in upcoming decades. The project produced predictions of emissions to air and water as well as of underwater noise for present time and for a number of scenarios for years 2030 and 2040 for shipping in the Baltic Sea, giving us insight to the sensitivity of the trends in emissions to the development of shipping activities, legislation and uptake of new fuels and exhaust and waste cleaning technologies. The extensive atmospheric chemistry and coupled ocean dynamic – biogeochemistry modelling as well as the case-study of noise propagation modelling performed in SHEBA laid the third cornerstone of the framework connecting the pressures from shipping to the environmental impacts in terms of spatio-temporal distributions of concentrations of pollutants and their impacts on ecosystems. The impact of shipping has been analysed in relation to the three European Commission Directives; Air Quality Directive (AQD), MSFD and WFD. These analyses identified the main areas of environmental degradation caused by the shipping currently and potential improvements or lack of these in different future scenarios. They also helped to identify uncertainties and knowledge gaps in a fully quantitative assessment framework. The fourth cornerstone of the BONUS SHEBA assessment framework is the linkage from the pressures of shipping in the Baltic Sea to its effects on ecosystem services and human wellbeing and assessment of policy options with multidimensional framework includes a number of assessment criteria ranging from political implementability, acceptance & feasibility to environmental and health outcomes and efficiency. The assessments developed in BONUS SHEBA has been already used by several national agencies for evaluations of the environmental goals and are timely for the upcoming update of the Baltic Sea Action Plan as recognised at the 18th meeting of the HELCOM Maritime Working Group in Hamburg. Further, analyses of impacts of the NECA and global 0.5% sulphur fuel content cap legislations presented by partner FMI at IMO MEPC70 meetings benefited from the BONUS SHEBA assessment work and the methodology for assessment of underwater noise from shipping has been recognised by HELCOM. As a flagship of the EUSBSR Policy Area Ship BONUS SHEBA became part of the Interreg clean shipping platform CSHIPP facilitating further synthesis and dissemination of BONUS SHEBA outcomes along with results of other shipping projects active in the Baltic Sea region.

BONUS SHEBA has established interaction with stakeholders on different levels. Stakeholders were consulted for dedicated topics in order to support especially the scenario building process of BONUS SHEBA in two stakeholder elicitation events and in a web questionnaire. The project organised a number of outreach activities oriented to different stakeholders, among these: 1. Exhibition and seminar of cluster of 5 BONUS shipping projects on Swedish politicians' week in Almedalen in 2016, 2. Several contributions to the "Forschung vor Anker" events of HZG at the Baltic coast, 3. A conference on "Shipping and the Environment", jointly organized with the project SOLAS (International Surface Ocean - Lower Atmosphere Study), brought together about 120 scientists and stakeholders of the shipping sector from all over the world. Through these activities the project helped to raise awareness and knowledge on the wide environmental impacts of shipping and pathways to achieve sustainability of this important economic sector and facilitated exchange and collaboration within the wide international scientific community.

Impacts of the project are not limited to the scientific results and their implementation in society. Also the teamwork on the way to achieve these results affects a large number people at the professional and private level, both those directly involved in the project and by being a good model for the upcoming generation. To promote the gender equality in research the BONUS SHEBA consortium involved research partners strictly on professional merits which led to a balanced team. Another aspect is to provide opportunity to combine the professional and the family life. Also here, even though a lot of responsibility lies at the partners' organisations, the consortium had full understanding and acceptance of leaves for family matters and a number of young scientists, both men and women, went on parental leaves continuing their work in the project upon their return.

The BONUS SHEBA fish experiment performed at the Tvärminne zoological station where fish are exposed to noise were carried out in compliance with EU legislation covering the use of animals for scientific purposes. The welfare of the fish was ensured through providing them as natural conditions as possible and the applied noise levels were well below the levels where physical injury could take place as the experiments aimed at establishing the threshold noise levels were behavioural changes could take place.

Supplement

Table S1. Annual emissions to air (in g), discharge volumes to the water column (in l) and amount of Cu released from antifouling paint on ship hulls from scenario runs for emissions from all shipping in the Baltic Sea in 2040 (except where indicated)

Scenario	CO_2 eq[a] (g)	NO_x (g NO_2)	SO_2 (g)	PM (g)	Sewage (l)	Grey water (l)	Stern tube lubricant (l)	Bilge water (l)	Scrubber water open (l)	Scrubber water closed (l)	Ballast water (l)	AFP CuO (g Cu)	Food-waste N (g)	Noise energy 125Hz[b] (J)
Reference year 2012	1.47E+13	3.29E+11	7.31E+10	1.49E+10	1.35E+09	5.40E+09	2.47E+06	2.01E+08	6.83E+09	2.69E+07	4.36E+08	2.76E+08	8.62E+07	5.08E+10
BAU (2030)	1.25E+13	1.61E+13	7.38E+09	2.72E+09	3.54E+08	6.40E+09	2.69E+06	1.73E+08	5.88E+10	2.62E+08	5.37E+08	3.09E+08	1.02E+08	5.60E+10
BAU (2040)	1.14E+13	6.80E+10	6.44E+09	2.41E+09	3.74E+08	7.05E+09	2.83E+06	1.57E+08	7.17E+10	3.19E+08	6.09E+08	3.31E+08	1.12E+08	6.22E+10
EEDI	1.65E+13	9.41E+10	8.55E+09	2.40E+09	3.74E+08	7.05E+09	2.83E+06	1.57E+08	7.17E+10	3.19E+08	6.09E+08	3.31E+08	1.12E+08	
No NECA	1.41E+13	1.66E+11	6.44E+09	2.41E+09	3.74E+08	7.05E+09	2.83E+06	1.57E+08	7.17E+10	3.19E+08	6.09E+08	3.31E+08	1.12E+08	6.22E+10
No emissions to water	1.41E+13	6.80E+10	6.44E+09	2.41E+09	0	0	1.66E+06	0	0	6.38E+08	6.09E+08	2.86E+08	0	6.22E+10
LNG	1.12E+13	5.29E+10	4.58E+09	1.97E+09	3.74E+08	7.05E+09	2.83E+06	1.57E+08	7.17E+10	3.19E+08	6.09E+08	3.31E+08	1.12E+08	6.22E+10
Scrubber open	1.41E+13	6.80E+10	6.44E+09	2.41E+09	3.74E+08	7.05E+09	2.83E+06	1.57E+08	5.39E+11	0	6.09E+08	3.31E+08	1.12E+08	6.22E+10
Scrubber closed	1.41E+13	6.80E+10	6.44E+09	2.41E+09	3.74E+08	7.05E+09	2.83E+06	1.57E+08	0	2.4E+009	6.09E+08	3.31E+08	1.12E+08	6.22E+10
Slow Steaming	9.84E+12	5.86E+10	5.55E+09	2.08E+09	3.93E+08	7.36E+09	2.97E+06	1.27E+08	5.81E+10	2.58E+08	6.38E+08	3.41E+08	1.17E+08	6.52e+10
SSP1	6.43E+12	2.61E+10	3.09E+09	5.72E+08	0	0	4.03e+05	0	0	0	6.42E+08	2.96E+08	0	3.94e+10
SSP3	1.88E+13	3.12E+11	2.29E+10	6.29E+09	1.51E+09	6.2e+09	2.49e+06	2.48e+08	8.59E+11	0	5.36E+08	3.07E+08		6.34e+10

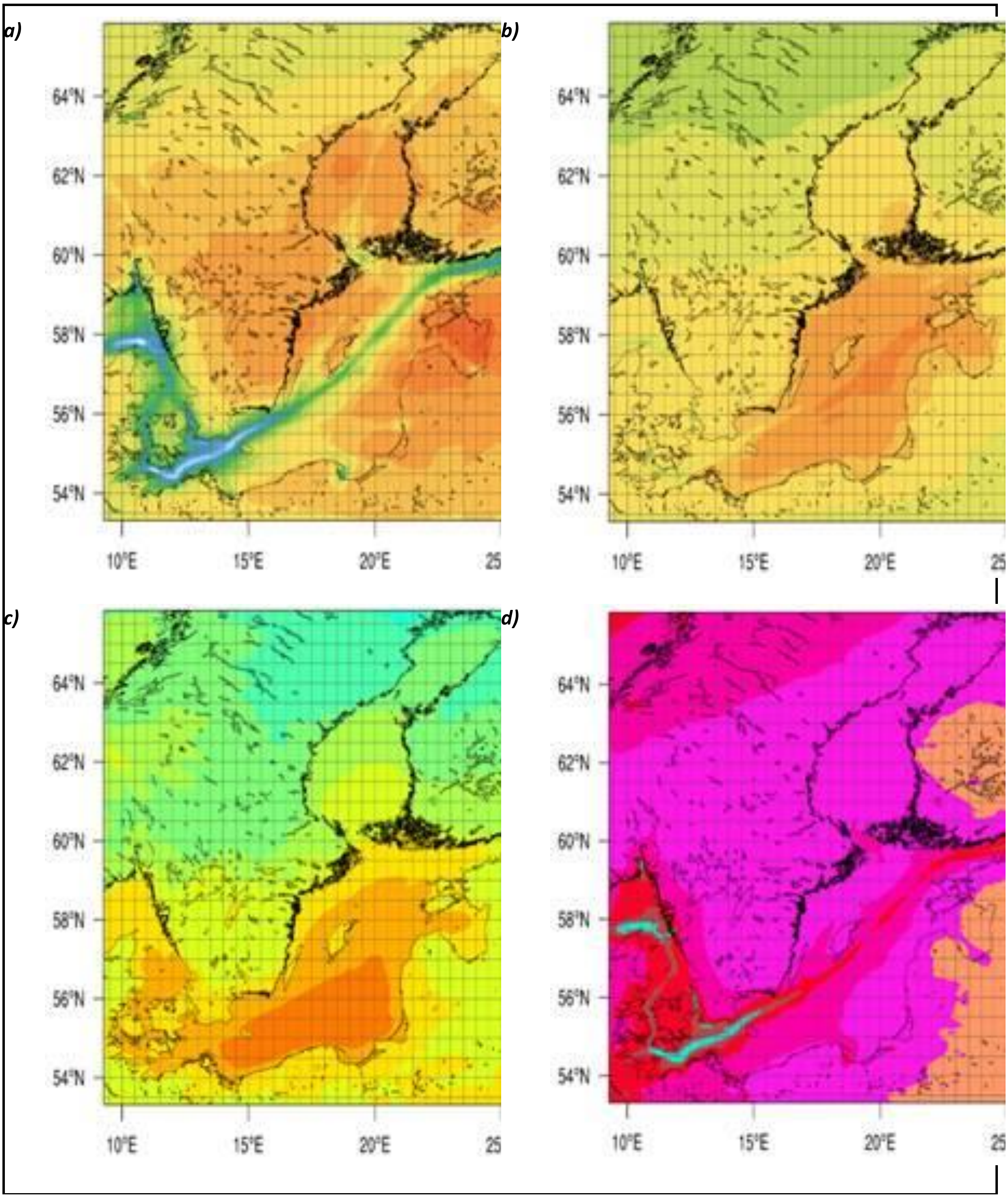
[a] CO_2 eq includes climate impact of N_2O and methane as GWP_{100}
[b] Three frequencies calculated, 63, 125 and 2 000 Hz, 125 Hz shown as an example, all data presented in D1.5

Table S2 Total emissions of copper, zinc, dibromochloromethane, naphthalene and pyrene to the Baltic Sea for the reference year and the different scenarios.

Scenario	Copper (g)	Zinc (g)	Dibromochloro-methane (g)	Naphthalene (g)	Pyrene (g)
Reference year 2012	3.02E+08	6.38E+07	6.04E+04	1.51 E+04	2.44 E+03
BAU 2030	3.18E+08	7.50E+07	3.92E+04	7.60 E+03	7.49 E+04
BAU 2040	3.42E+08	8.20E+07	4.32E+04	7.06 E+03	9.13 E+04
Zero emissions to water 2030	2.67E+08	5.15E+07	1.08E+04	0	0
Zero emissions to water 2040	2.86E+08	5.53E+07	1.22E+04	0	0
Scrubber scenario 2030 All open loop	3.79E+08	1.67E+08	3.92E+04[a]	7.60E+03[a]	7.49 E+04
Scrubber scenario 2030 All closed loop	3.13E+08	6.55E+07	3.92E+04[a]	7.60E+03[a]	4.00E+02[b]
Scrubber scenario 2040 All open loop	3.95E+08	1.63E+08	4.32E+04[a]	7.10E+03[a]	6.84E+05
Scrubber scenario 2040 All closed loop	3.35E+08	7.02E+07	4.32E+04[a]	7.06E+03[a]	3.50E+02[b]

[a] Due to absence of data on concentrations of dibromochloromethane and naphthalene in open and closed loop scrubber water, specific estimations for the scrubber scenarios could not be made for these compounds.

[b] Due to absence of data on concentrations of pyrene in closed loop scrubber water, estimations for the closed loop scenarios could not be made for pyrene. Values labelled [a] and [b] are hence underestimations of the loads.


a)
b)
c)
d)
64°N
62°N
60°N
58°N
56°N
54°N
10°E
15°E
20°E
25

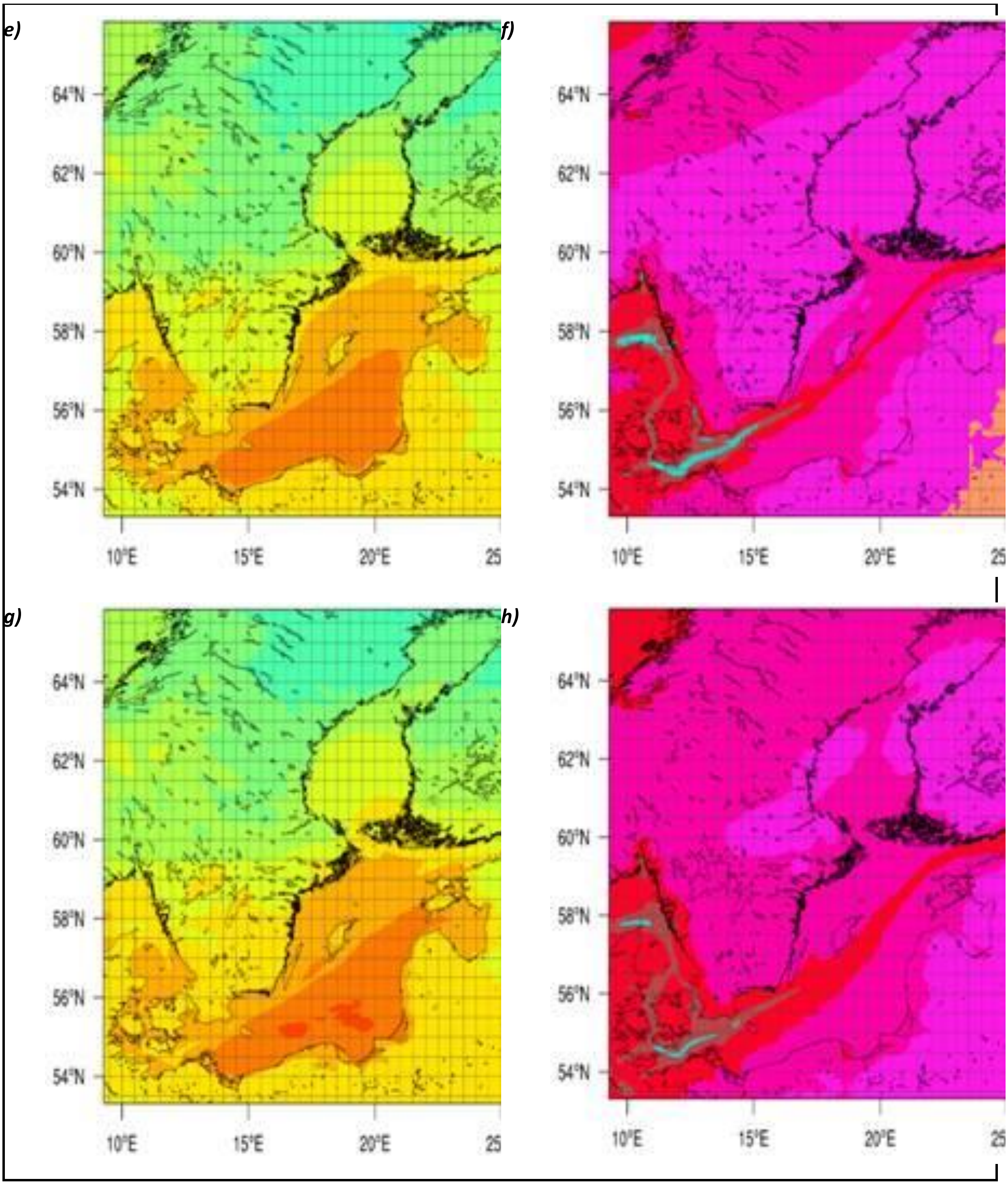
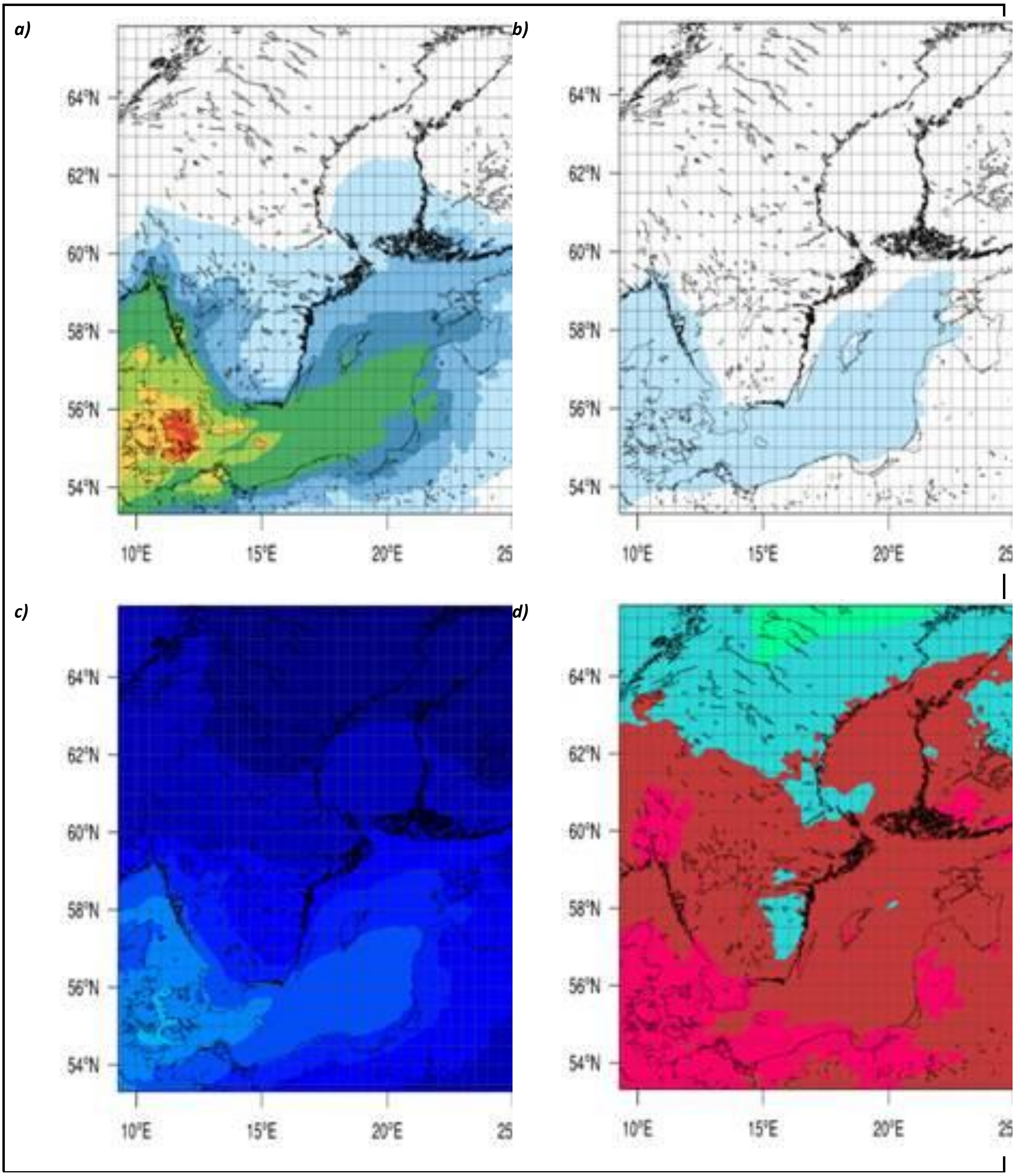


Figure S 1: Air concentration of O3 as mean of summer months, JJA (unit: ppbV): future changes in the Baltic Sea region compared to present-day (2012) for three future scenarios. (a) Present-day ship contribution, (b) BAU scenario (2040) future ship contribution, (c) BAU scenario (2040) future situation, (d) relative change (%) of BAU scenario (2040) compared to present-day, (e) EEDI scenario (2040) future situation, (f) relative change (%) of EEDI scenario (2040) compared to present-day, (g) NoNECA scenario (2040) future situation, (h) relative change (%) of NoNECA scenario (2040) compared to present-day.


a)
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64°N
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10°E
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20°E

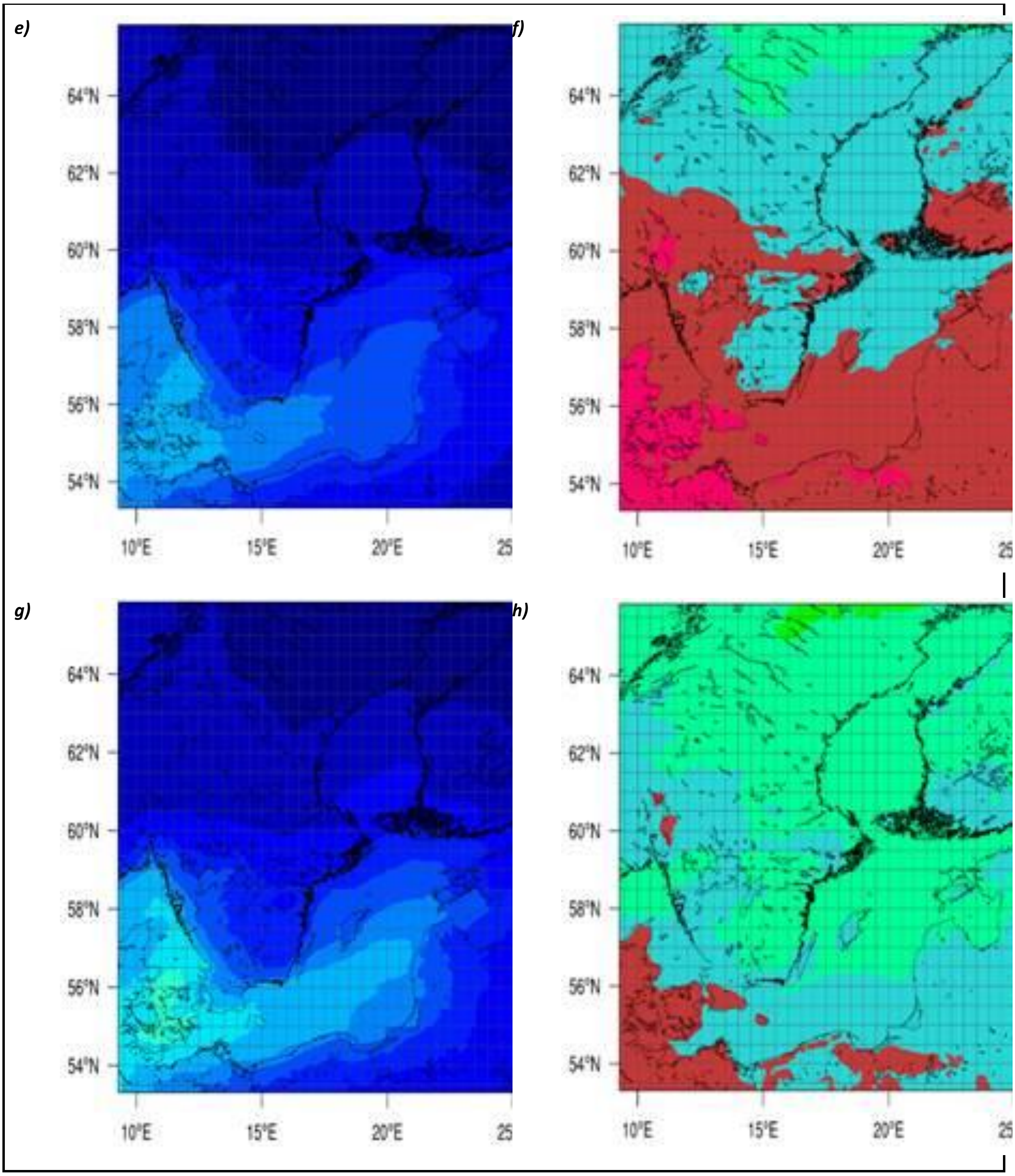
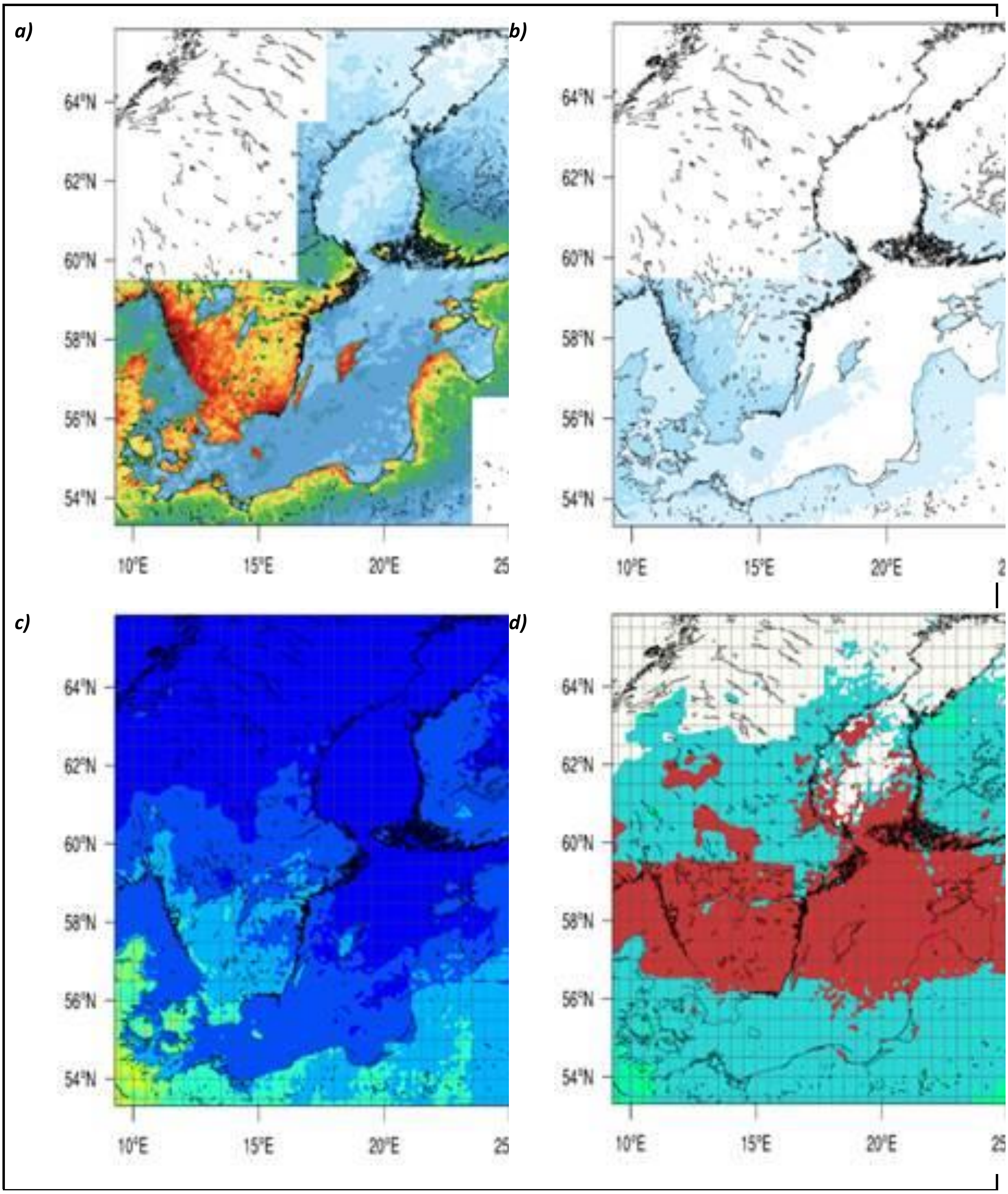


Figure S 2: Air concentration of particulate nitrate (NO3-) as mean of summer months, JJA (unit: µg/m³): future changes in the Baltic Sea region compared to present-day (2012) for three future scenarios. (a) Present-day ship contribution, (b) BAU scenario (2040) future ship contribution, (c) BAU scenario (2040) future situation, (d) relative change (%) of BAU scenario (2040) compared to present-day, (e) EEDI scenario (2040) future situation, (f) relative change (%) of EEDI scenario (2040) compared to present-day, (g) NoNECA scenario (2040) future situation, (h) relative change (%) of NoNECA scenario (2040) compared to present-day.


a)
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64°N
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56°N
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10°E
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20°E

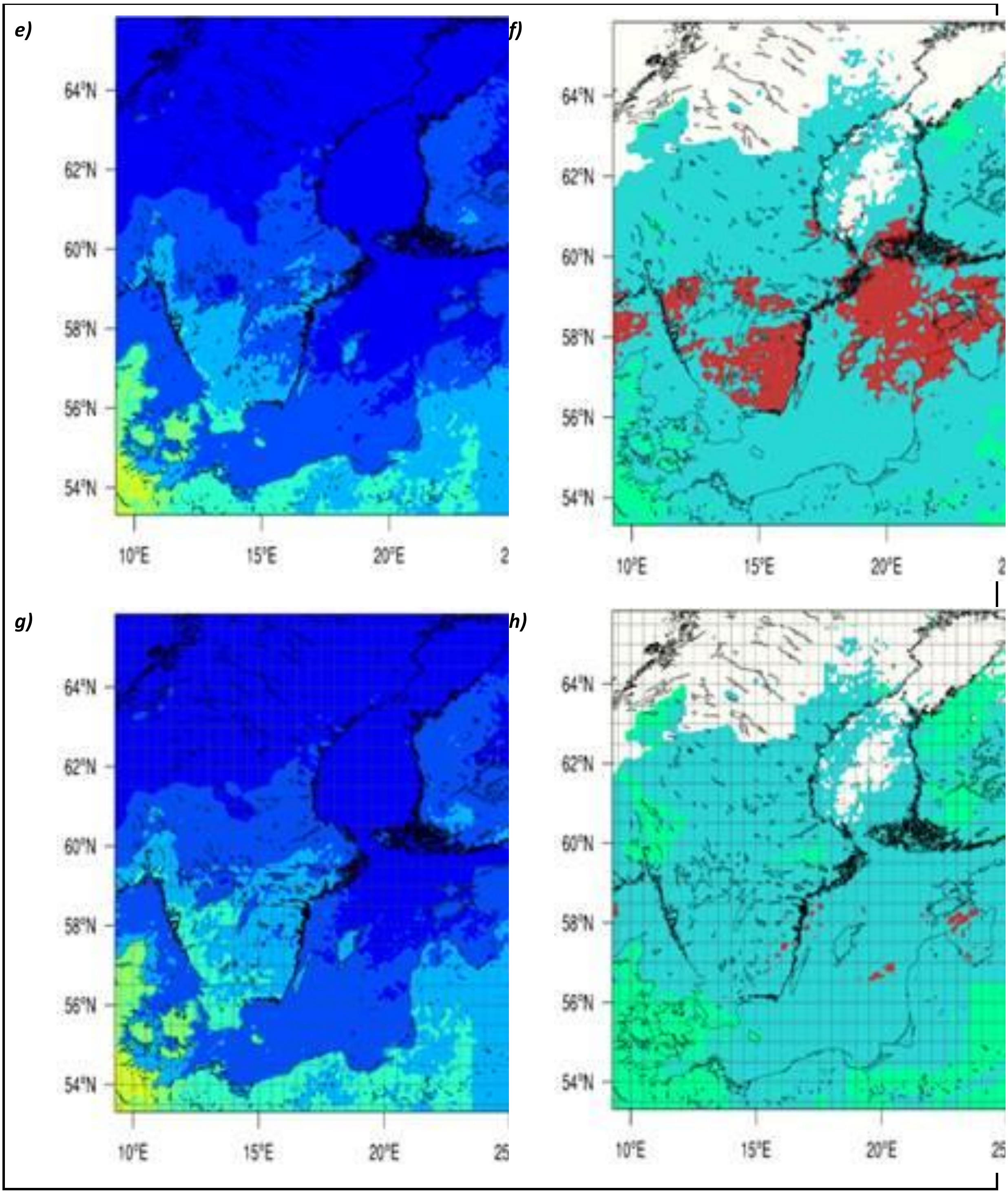

Figure S 3: Atmospheric deposition of total nitrogen accumulated over summer months, JJA (unit: kgN/ha): future changes in the Baltic Sea region compared to present-day (2012) for three future scenarios. (a) Present-day ship contribution, (b) BAU scenario (2040) future ship contribution, (c) BAU scenario (2040) future situation, (d) relative change (%) of BAU scenario (2040) compared to present-day, (e) EEDI scenario (2040) future situation, (f) relative change (%) of EEDI scenario (2040) compared to present-day, (g) NoNECA scenario (2040) future situation, (h) relative change (%) of NoNECA scenario (2040) compared to present-day.

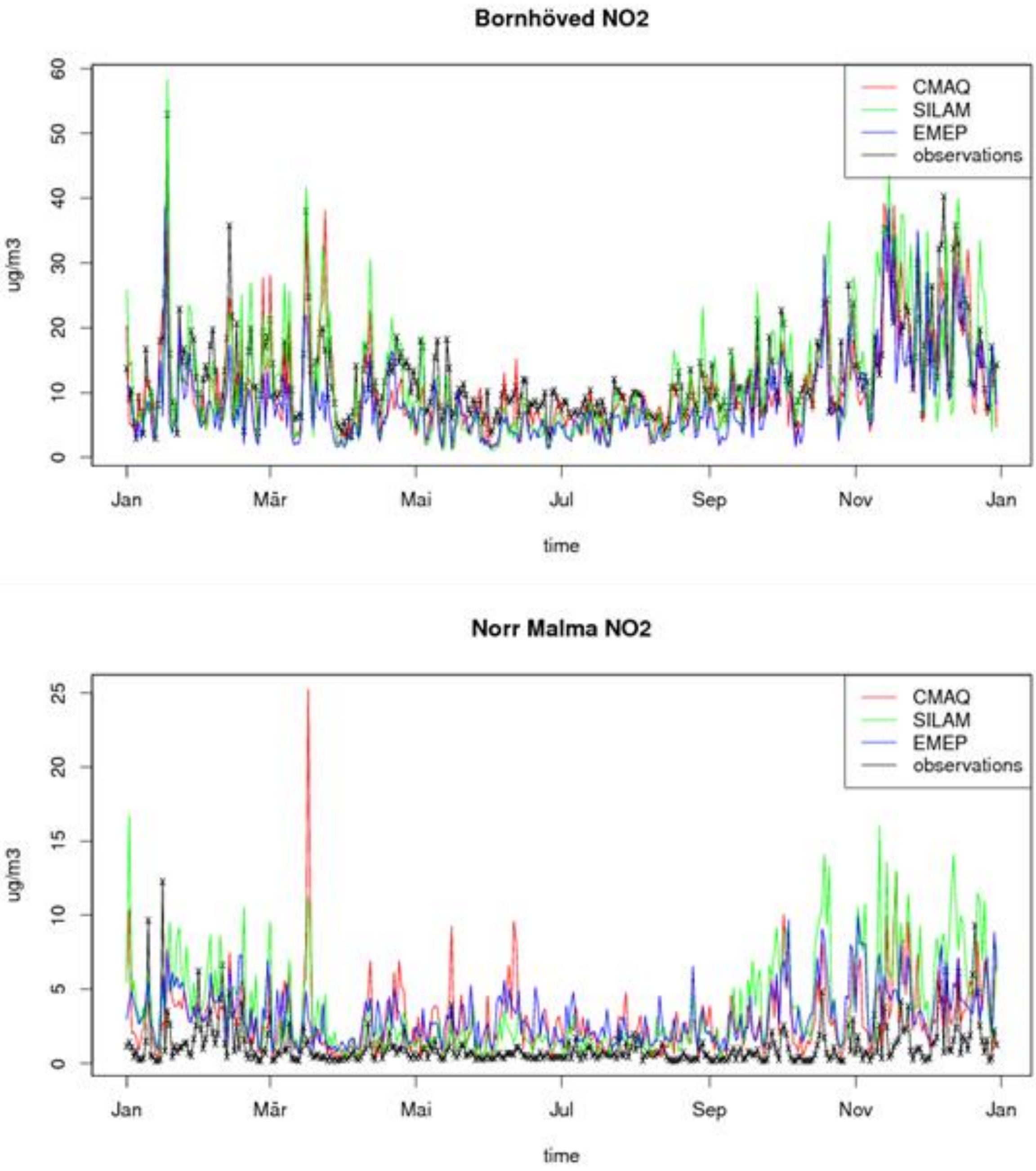

Figure S 4: Comparison of the modelled NO2 concentrations from CMAQ, SILAM and EMEP for the year 2012 with observations at Bornhöved, Germany and Norr Malma, Sweden.

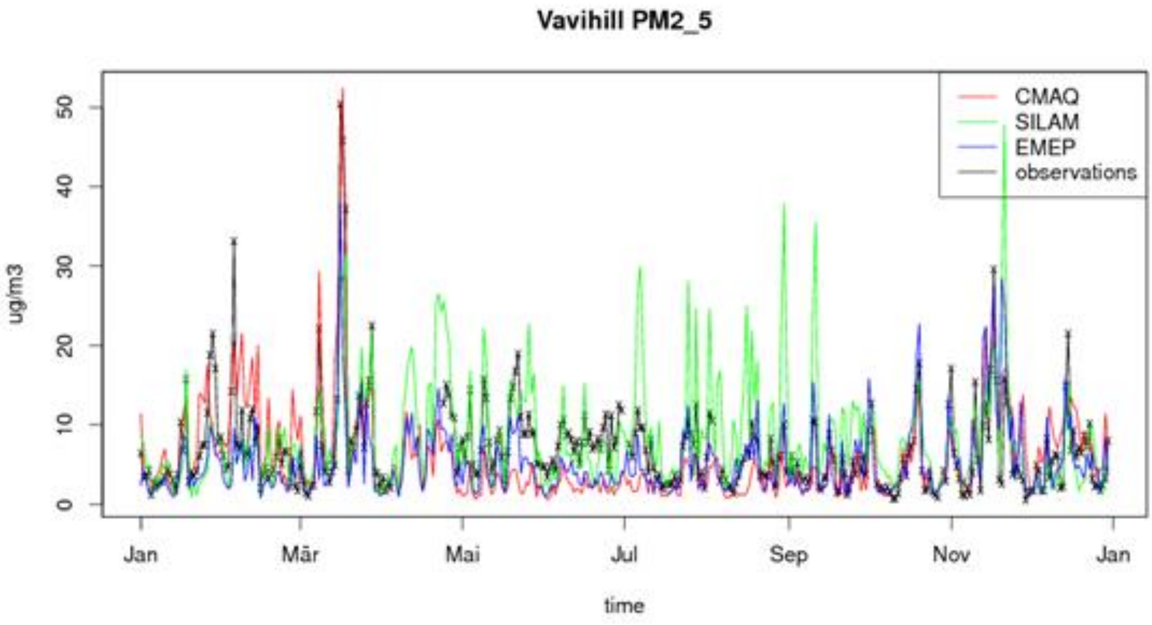

Figure S 5: Comparison of the modelled PM2.5 concentrations from CMAQ, SILAM and EMEP for the year 2012 with observations at Vavihill, South Sweden and Aspvreten, East Sweden.

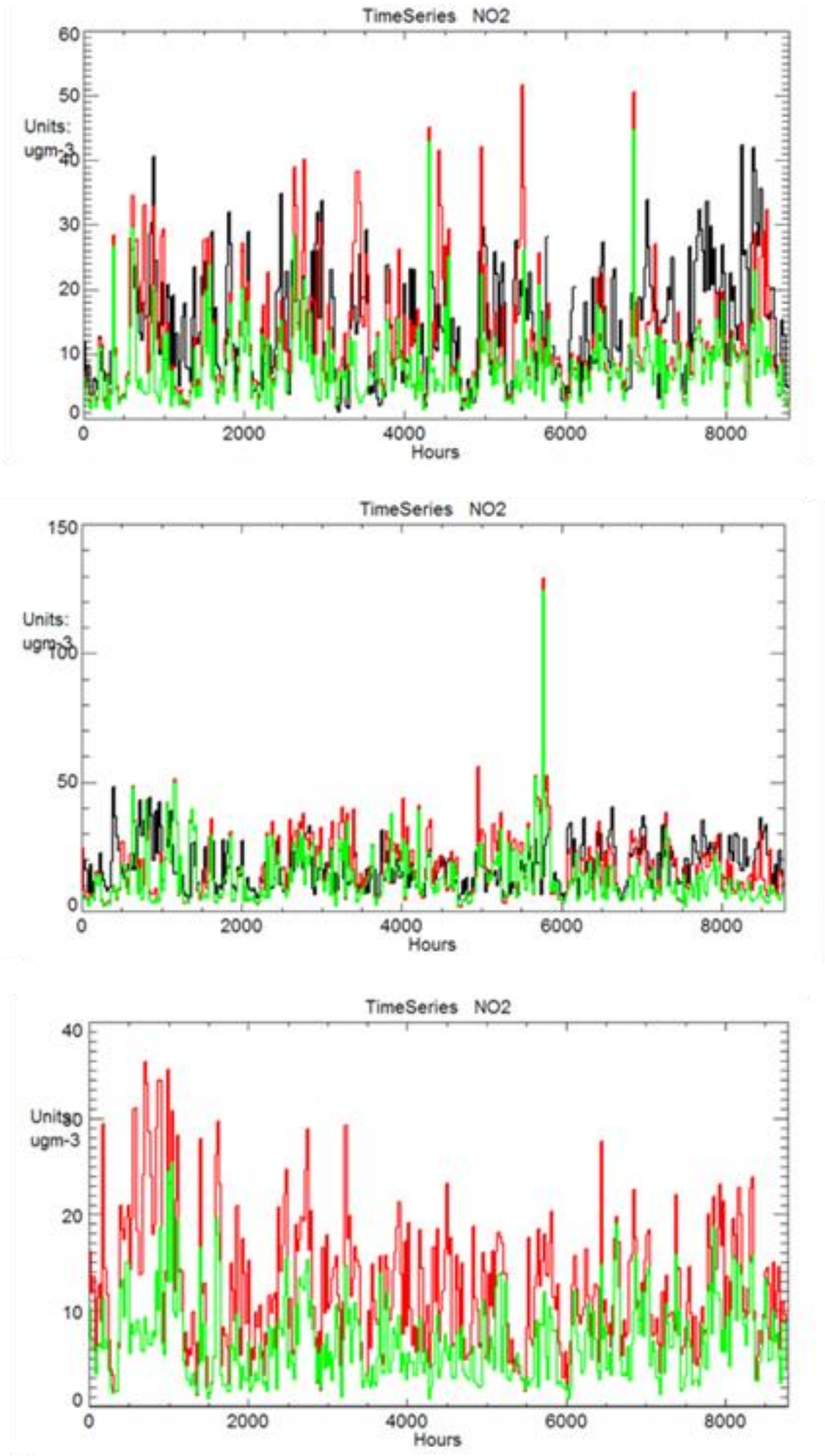

Figure S 6: Modelled time Series of NO2 concentrations at Rostock Warnemünde, Gdansk Noviport and Riga Vecmilgravis in 2012. Displayed are the simulations including all sources (red) and without ships (green). Observations are shown for comparison in black for Rostock and Gdansk.

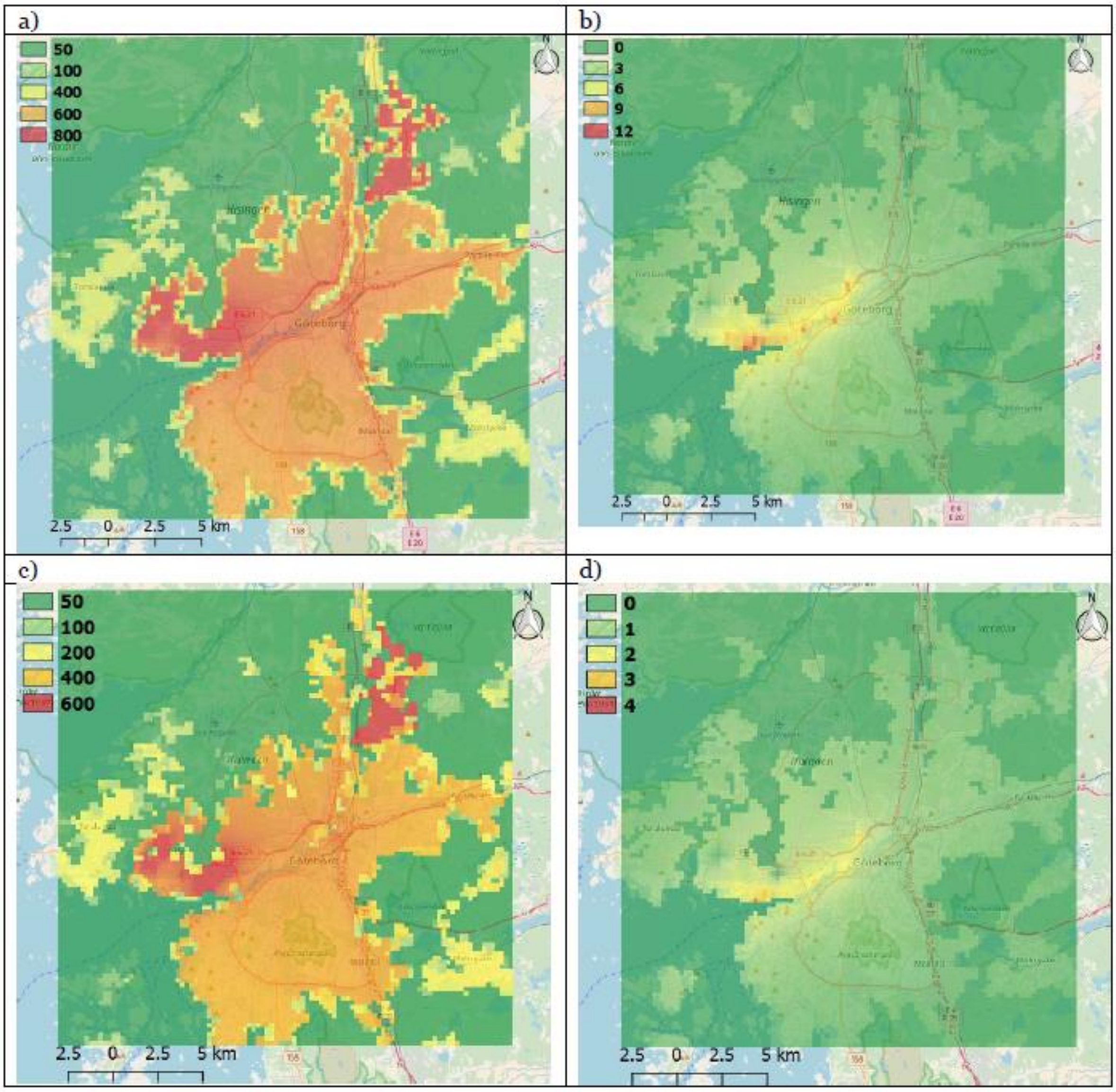

Figure S7: Exposure to PM2.5 concentrations of the population in Gothenburg in 2012 (a,b) and in 2040, BAU scenario (c,d). The total exposure in ?g*m^{-3}*capita/grid square is shown on the left (a and c), relative contribution of the local shipping to the total exposure (in %) on the right (b and d).