Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions (EMERGE)

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"Baltic and North Sea report"

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Author(s)	Erik Ytreberg, Anna-Lunde Hermansson, Ida-Maja Hassellöv (CHALMERS) Jukka-Pekka Jalkanen, Elisa Majamäki, Risto Hänninen, Jaakko Kukkonen (FMI) Maria Granberg, Kerstin Magnusson, Erik Fridell, Sara Jutterström, Emelie Johansson, Jana Moldanová (IVL) Samuel Guéret and Wilfried Winiwarter (IIASA) Göran Broström (UGOT) Ian Williams (UoS)
Other Contributor(s)	Andreas Gondikas, Vassiliki Galiotou (CNano), Mikhail Sofiev, Yulia Palamarchuk (FMI), Jane Ihrfors (IVL), Marco Picone, Loris Calgaro (UV), Manuel Aghito (MET), Ranjeet S Sokhi (UH-C3R), Ummugulsum Alyuz (UH-C3R), Saurabh Kumar (UH-C3R), Mikhail Sofiev (FMI, Risto Hänninen (FMI), Jana Moldanova (IVL), George Tsegas (AUTH), Mark Bergsma, Kent Salo (CHALMERS)
Reviewer(s)	Evangelia Fragkou (AUTH) and Elisa Giubilato (UV)
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	Name	Date
Verification Final Draft by WP leader	**Jukka-Pekka Jalkanen**	**24.10.2023**
Check before upload by coordinator	**Jukka-Pekka Jalkanen**	**31.10.2023**

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ABBREVIATIONS

AF	Assessment Factors
AFS	Anti-Fouling Systems
AIS	Automatic Identification System
AQ	Air Quality
B*a*P	Benzo[*a*]pyrene
BPR	Biocidal Products Regulation
BWMC	Ballast Water Management Convention
CO_2	Carbon Dioxide
CH_4	Methane
DAPSIR	Driver Activity Pressure State Impact Response
EC	European Commission
EC10	Effect Concentration 10%, the concentration at which 10% of the test population is affected
EC50	Effect Concentration 50%, the concentration at which 50% of the test population is affected
ECA	Emission Control Area
EEA	European Environment Agency
EGCS	Exhaust Gas Cleaning System
EMEP	European Monitoring and Evaluation Programme
EMERGE	Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions
EQS	Environmental Quality Standard
EU	European Union
GAINS	Greenhouse gas and Air pollution Interactions and Synergies
GES	Good Environmental Status
HC5	Hazardous Concentration 5%, the concentration at which 5% of species in an SSD are affected (conditioned that the SSD is based on Chronic NOEC data, which for REACH, is the only allowable one from a legal standpoint, and therefor applicable in this report)
HELCOM	The Baltic Marine Environment Protection Commission
HFO	Heavy Fuel Oil
ICES	International Council for the Exploration of the Sea
IIASA	International Institute for Applied Systems Analysis
IMO	International Maritime Organization
IPCC	The Intergovernmental Panel on Climate Change
LC50	Lethal Concentration 50%, the concentration at which 50% of the test population is dead
LNG	Liquid Natural Gas

LOD	Limit of Detection
LOEC	Lowest Observed Effect Concentration
MARPOL	The International Convention for the Prevention of Pollution from Ships
MGO	Marine Gas Oil
MEC	Measured Environmental Concentration
MEPC	Marine Environment Protection Committee
MPA	Marine Protected Area
MSFD	Marine Strategy Framework Directive
N_2O	Nitrous Oxide
NO_2	Nitrogen Dioxide
NOEC	No Observed Effect Concentration
NOEL	No Observed Effect Level
NO_X	Nitrogen Oxide
O_3	Ozone
OSPAR	The Convention for the Protection of the Marine Environment of the North-East Atlantic
PAH	Polycyclic aromatic hydrocarbons
PEC	Predicted Environmental Concentration
PLC	Pollution Load Compilation (by HELCOM)
$PM_{2.5}$	Particulate Matter < 2.5 μm
PNEC	Predicted No Effect Concentration
RCR	Risk Characterization Ratio
RID	Riverine Inputs and Direct Discharges
RoPax	Roll-on/Roll-off passenger-vessel, i.e., vessel that transports wheeled cargo and passengers
RORO	Roll-on/Roll-off cargo ship
SCR	Selective catalytic reduction
SILAM	System for Integrated modeLling of Atmospheric coMposition
SOLAS	Safety Of Life At Sea
SO_X	Sulphur Oxides
SSD	Species Sensitivity Distribution
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
STEAM	Ship Traffic Emission Assessment Model
TGD	Technical Guidance Document
UNCLOS	United Nations Convention on the Law of the Sea
US EPA	United States Environmental Protection Agency

VLSFO	Very Low Sulphur Fuel Oil
VOC	Volatile Organic Compound
WP	Work package
WWTP	Wastewater Treatment Plant
YOLL	Years Of Life Lost

EXECUTIVE SUMMARY

Shipping is responsible for a range of different pressures affecting air quality, climate, and the marine environment. However, most social and economic analysis of shipping have focused on air pollution assessment and how shipping may impact climate change and human health. This risks policies to be biased towards air pollution and climate change, while trading off impacts on the marine environment. One example is the IMO's global sulphur cap, which requires shipowners to use a compliant fuel with a sulphur content of 0.5% (0.1% in SECA regions) or use alternative compliance options (scrubbers) that are effective in reducing sulphur oxide (SO_X) emissions to the atmosphere. The scrubber process results in large volumes of acidic discharge water. Although regulations primarily target SO_X removal, other pollutants such as polycyclic aromatic hydrocarbons (PAHs) and metals are transferred from the exhausts to the wash water and subsequently discharged to the marine environment. The aim of this deliverable has therefore been to develop a holistic framework to evaluate the impacts of shipping emissions, particularly those related to scrubbers, on the marine environment, human health, climate, and economy. The structure of this deliverable follows the well-established DAPSIR (Driver-Activity-Pressure-State-Impact-Response) framework, under which information, findings and conclusions from previous work packages are synthesized and integrated, including experiments of direct emissions from shipping to the marine environment (WP2) and the atmosphere (WP3), assessment of marine environmental impacts (WP2, WP4 and WP6), as well as human health and climate change impacts (WP5 and WP6). Finally, this deliverable provides recommendations and guidance for stakeholders and policymakers.

The assessment is performed using a baseline scenario (year 2018) and three future scenarios (for year 2050) based on different projected future developments of shipping transport volumes and considering the development of ships regarding fuel efficiency and ship size. In this deliverable, we focused primarily on two of the different future scenarios, scenario 3 (high scrubber pressure) and scenario 8 (high use of liquefied natural gas (LNG) and methanol). The marine environmental risk assessment, performed in the Öresund region for the baseline scenario (2018), showed unacceptable risks when ships in the area were using open loop scrubbers. In the assessment, modelled predicted environmental concentrations (PECs) of open loop scrubber discharge water exceeded the tolerable marine threshold value (predicted no-effect concentration, PNEC) in almost the entire Öresund region. The PEC value was derived based on ship activity and discharges of scrubber water in 2018, while the PNEC value was derived based on the ecotoxicological assays

performed within the EMERGE project. Notably, the modelling of open loop scrubber discharge water was performed using the ship traffic activity in 2018 when less than 200 ships in the Baltic Sea used scrubbers, collectively releasing 192 million tonnes of discharge water. By 2022 there were approximately 800 ships equipped with scrubbers in the Baltic Sea. In the high scrubber future scenario (S3) in 2050 this led to an assumption of the considerably higher scrubber water discharge (1740 million tonnes), representing almost one order of magnitude higher compared to our baseline scenario in 2018.

In addition, our impact assessment, following Marine Environment Protection Committee (MEPC) guidelines, shows that a ban on discharge water from scrubbers should be considered in the entire Baltic and North Sea region, since all sea basins in the region fail to reach good environmental status (GES) as defined by the EU Marine Strategy Framework Directive (Directive 2008/56/EC). However, the costs of such a measure for the shipping sector (banning discharges from scrubbers, i.e., in practice a ban on scrubbers) have been questioned within the International Maritime Organisation (IMO). Therefore, EMERGE also focused on analysing to what extent the global scrubber fleet has reached break-even on their scrubber installations and the potential monetary gain of using Heavy Fuel Oil (HFO) as compared to the more expensive Marine Gas Oil (MGO) or Very Low Sulphur Fuel Oil (VLSFO). Our results showed that 51% of the global scrubber fleet had reached break-even by the end of 2022, resulting in a summarised balance of 4.7 billion €$_{2019}$. In addition, the marine ecotoxicity damage cost, by not restricting scrubbers in the Baltic Sea Area, accumulated to >680 million €$_{2019}$ from 2015 to end of 2022.

For air quality, both future scenarios showed a decrease in shipping contribution to $PM_{2.5}$ exposure by a factor of 2 to 3 compared to our baseline scenario in 2018. Scenario 8 is somewhat more efficient in decreasing the shipping originated $PM_{2.5}$ than scenario 3. Using the Greenhouse gas and Air pollution Interactions and Synergies (GAINS) model for human health impact assessment in scenario 3 revealed the loss of life expectancy in most areas around the Baltic Sea, when considering all sources, to be limited to two to four months. However, the differences in life shortening between Scenarios 3 and 8 are two to three orders of magnitude lower when compared to human health impacts resulting from all sources, indicating that scrubbers alone have a minor impact on human health in the Baltic region from air quality perspective. For Öresund case the shipping-related health impacts from PM2.5 represented approximately 10% of the total burden of air pollution, in 2050 scenario simulations this burden decreased to 7-9%. Important improvement of air quality in the scenario simulations come also from reduction of NO_2 which is a criteria

pollutant regulated by the Air Quality Directive, where the decrease is 3 to 5-fold. In relative terms the shipping contribution to NO_2 concentration levels, however, maintains similar, approximately 25%, as the land emissions are also expected to decrease. The GAINS health impact assessment for the Baltic Sea was compared to the Solent region using a statistical technique. The latter study showed that a relatively small fraction of all premature deaths in Southampton, Portsmouth, Poole, Christchurch & Bournemouth are attributable to air pollution from shipping, corroborating the conclusion that the deployment scrubbers alone has a minor impact on human life shortening through atmospheric transport.

1 INTRODUCTION & SCOPE

Shipping is an activity responsible for a range of different pressures on the marine environment, originating from a variety of sources. These include discharges of hazardous substances from greywater, sewage, bilge water, scrubber water, cooling water, tank cleaning, propeller shaft lubricants and antifouling paints. Moreover, there are emissions of nutrients from sewage, greywater, food waste and deposition of nitrogen oxides (NO_X) as well as emissions of acidifying compounds from scrubber discharge water and deposition of sulphur oxides (SO_X). Shipping is also responsible for the spread of invasive species through hulls or ballast water and has an impact on the marine ecosystem through turbulence and underwater noise (Figure 1.1).

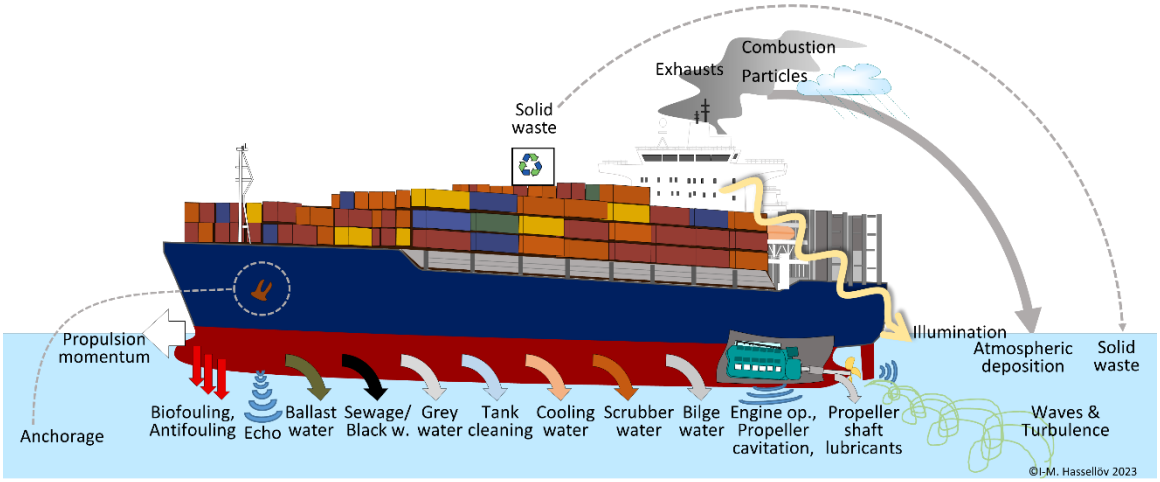


Figure 1.1: Emissions from shipping to the atmosphere and direct emissions and pressures on the marine environment.

Shipping also affects air quality and human health through emissions of fine particulate matter (PM), volatile organic compounds (VOCs), NO_X and SO_X. Emissions to air of black carbon and greenhouse gases such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) are also important because of their climate impact. The knowledge about air pollution emissions, mitigation potentials and cost for air pollution and greenhouse gases is comparatively well developed and various models exist. One example is the Greenhouse gas and Air pollution Interactions and Synergies (GAINS) model, developed at the International Institute for Applied Systems Analysis (IIASA), which has been used extensively in Europe (and elsewhere) to identify cost effective

emission control strategies of air quality and mitigation of greenhouse emissions (Amann et al. 2011). While scientific understanding of air pollution and climate change has increased substantially in recent years, the knowledge base is not the same for the pressure and impacts on the marine environment and the interaction between the different problems. Within EMERGE, we have assessed several different abatement methods, with a primary focus on the use of Exhaust Gas Cleaning Systems (EGCS), also known as (and from now on referred to as) scrubbers. The work in EMERGE includes experiments of direct emissions from shipping to the marine environment (WP2) and the atmosphere (WP3), assessment of marine environmental impacts (WP2, WP4 and WP6), human health and climate change impacts (WP5 and WP6). The overall aims of this deliverable were:

- to synthesize and integrate the information, findings and conclusions from previous work packages;
- to develop a holistic framework allowing us to evaluate the impacts of shipping emissions on the marine environment, human health, climate and economy;
- to provide recommendations and guidance for stakeholder and policymakers including to identify knowledge gaps that need to be addressed.

The deliverable focuses only on the Baltic Sea and the North Sea region, with particular interest in the respective EMERGE Case study areas located in these sea regions: Öresund (the Sound) and the Solent Strait.

1.1 Conceptual framework

DAPSIR (Driver-Activity-Pressure-State-Impact-Response) is a conceptual management framework utilized to describe the interaction and relationships between society and the environment (Borja et al. 2010). The framework is further used to analyse environmental problems (Figure 1.2) and to identify and propose measures to mitigate the problems. DAPSIR starts with identifying the driving force (***D****rivers*) that require human ***A****ctivities,* that cause specific environmental ***P****ressure(s)* on the environment. The pressure(s) can in turn change the environmental ***S****tate* in the geographic area of interest. This change in state may cause an ***I****mpact* on ecosystems and human health as well as the way humans can use the ecosystem (i.e., ecosystem services). Society can then act in different ways to reduce the pressure(s), e.g., through legislation or other measures. This is termed ***R****esponse*. The DAPSIR model has been applied to the shipping

sector in the SHEBA-project by Moldanová et al. (2022) which describes the links and relationships between shipping, society and the environment. This includes a comprehensive assessment on the different pressures caused by shipping to the atmosphere and on the marine environment, including ways with which these pressures can influence the state of the environment (e.g., pollutant concentrations in air and water) and as well as their impact on marine ecosystem services and human health. A modified version of the DAPSIR framework was developed by Ytreberg et al. (2021) allowing a quantification of the societal damage costs of shipping due to the degradation of human welfare in a Baltic Sea case study. These two versions of the DAPSIR framework were used to structure this deliverable and to fulfil the aims and objectives.

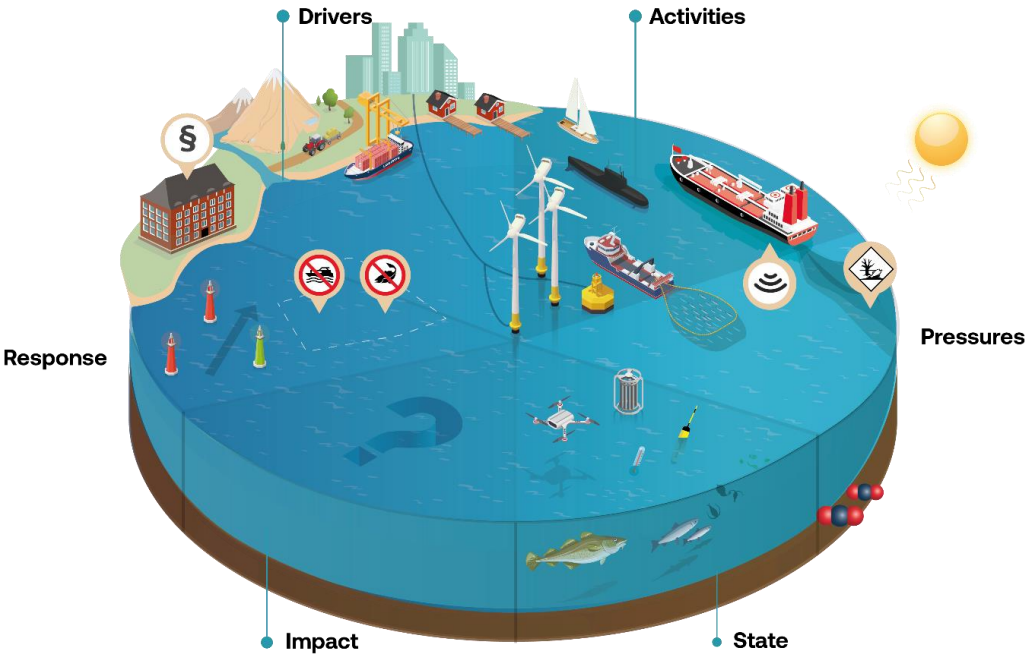


Figure 1.2: Illustrative description on how the DAPSIR framework has developed in EMERGE to assess pressures from shipping and impacts on air quality (health), climate and the marine environment.

1.2 Regulatory landscape

The United Nations Convention on the Law of the Sea (UNCLOS, 1982) is a comprehensive international agreement that establishes a legal framework for all marine and maritime activities. One part of UNCLOS, and in particular PART XII, is especially dedicated to shipping. Protection

and preservation of the marine environment is applicable on pollution prevention from shipping. Beyond UNCLOS, the regulatory landscape concerning environmental pressure, impact and response to reduce adverse effects from shipping on the marine environment can be viewed from two perspectives; the ship pollution prevention perspective, and the environmental (and sometimes health) management perspective (Table 1.1). Environmental pressures from international shipping are most often directly targeted through international conventions on ship pollution prevention, primarily through the International Maritime Organization (IMO). International shipping is defined as the share of shipping occurring between two different countries, whereas domestic shipping is considered to happen inside a country. These route-based definitions come from the Intergovernmental Panel on Climate Change (IPCC (2006)) and the distinction is important because the rules for domestic shipping can be defined regionally (e.g., EU), or even by some individual countries.

The IMO's most comprehensive environmental framework is the International Convention for the Prevention of Pollution from Ships (MARPOL, 1973, as modified by the Protocol of 1978 relating thereto and by the Protocol of 1997). MARPOL consists of six annexes, targeting I) oil pollution, II & III) harmful substances in bulk and packaged form respectively, IV) sewage, V) solid waste and VI) air pollution. Additional aspects, such as antifouling and ballast water handling are covered by the AFS convention and BWMC, respectively. There are also nine other conventions that cover other aspects, e.g., dumping at sea, however they will not be discussed here in further detail (APPENDIX II - Regulatory landscape). Issues related to MARPOL are handled within the IMO Marine Environment Protection Committee (MEPC) and its subcommittees. Specifically, the Pollution Prevention Response (PPR) addresses issues such as the development of e.g. guidelines for scrubber discharge water (MEPC 2022a). The impact assessment described in section 7.4 of the guidelines stipulates that the adoption of restrictions or a ban on discharge water from scrubbers should be considered in areas where any of four indicative criteria are fulfilled. The first criterion is

"7.4.1 environmental objectives in the areas are not met, e.g. good chemical status, good ecological status or good environmental status are not achieved under applicable legislation;"

In Europe, marine environmental objectives, mentioned in indicative criteria 7.4.1, are defined by the Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC) that aims to achieve Good Environmental Status (GES) in all the European marine waters. The MSFD is described more in depth later in this chapter.

In general, environmental protection can benefit from increased safety at sea, which is why both the International Convention for the Safety of Life at Sea (SOLAS, 1974, as amended) and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW, as amended, including the 1995 and 2010 Manila Amendments), can be claimed to be of importance. Finally, the IMO can designate Particularly Sensitive Sea Areas (PSSAs) based on an area's established ecological, socio-economic or scientific value. Within the PSSA specific measures can be used, e.g., routeing measures. Another option is to designate Special Areas, which are linked to the MARPOL Annexes, which enables possible stricter regulations with respect to the specific Annex. The Baltic Sea is designated Special Area under Annexes I, IV, V and VI, and the North Sea for Annex V and VI.

Table 1.1. Overview of regulations of shipping subsystems targeting different on-board operations (sources) and the targeted pressures, expressed in terms of state descriptors of the EU directives. XX = well known and quantified, X = well recognised, h = hypothesised significant. Modified from Moldanová et al. 2021.

Response	*Pressure*	Environmental regulatory framework							
Shipping regulatory framework	Source	MSFD D2 Invasive Species	MSFD D5 Nutrients	MSFD D8 Contaminants	MSFD D7[a] Hydrography	MSFD D10 Litter	MSFD D11 Energy	Air poll.:Land ecosystems & crops AAQD	Air poll.:Human health AAQD
MARPOL Annex VI	Emissions of air pollutants		XX[b]	X[b]	X[b]	X[b]		X	X
IMO MEPC 304(72)	Emissions of GHG		XX	XX		XX	XX	X	XX
MARPOL Annex I	Bilge water		X	X		X			
-	Stern tube oil			X					
MARPOL Annex IV	Sewage	h	X	X		h			
IMO AFS convention EU BPR, EU REACH	Antifouling paints	X		XX					
BWMC	Ballast water	X	h	h					
-	Biofouling	X							
MARPOL Annex V	Food waste (solid)		X			X			
MEPC voluntary guidelines on reducing underwater noise from shipping	Propulsion, vibrations and cavitation						X		

[a]Acidification is not generally included in D7, although many countries assess the acidification in relation/beyond D7.
[b]Pressures from discharge of scrubber wash water; use of exhaust gas scrubbers is an alternative to use of fuels with low sulphur content.

To become legally binding, the IMO conventions must be incorporated in national law, and in the case of EU, they need to be incorporated in European law. The primary EU-directives targeting ship pollution prevention are the EU Sulphur Directive (Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels) and the Ship-source pollution prevention (Directive 2005/35/EC of the European Parliament and of the Council of 7 September 2005 on ship-source pollution and on the introduction of penalties for infringements). In addition, the use of biocides for antifouling purposes, such as those found in antifouling paint products, is regulated (or granted exception) under the EU REACH (Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency), and the EU BPR (Regulation (EU) No 528/2012 of the European Parliament and of the Council of 22 May 2012 concerning the making available on the market and use of biocidal products Text with EEA relevance).

Similarly to the global, EU and national regulatory frameworks aimed at preventing ship pollution, the environmental management perspective for ship pollution spans from global to national levels. At a global level, the Agenda 2030 and the UN Sustainable Development Goals (SDGs), especially SDG 14, *Life below water*, sets out ambitions to reduce marine pollution, while prevention of biodiversity losses in marine ecosystems is targeted by SDG 15, *Life on land.* While the SDGs are not legally binding, a new treaty under UNCLOS was adopted in 2023 on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ treaty or the High Seas Treaty). The BBNJ is in line with the UN Convention on Biological Diversity (CBD) with the target to protect 30% of land and sea by 2030. Moving from a global to a regional scale, the Regional Seas Conventions and Action Plans (RSCAPs), in the Baltic Sea and North Sea areas, HELCOM and OSPAR respectively, focus on the promotion of regional cooperation for sound management of the coastal and marine environment. OSPAR has five Annexes within which, measures can be adopted in the form of OSPAR Decisions that are legally binding under international law. However, there is yet no Annex exclusively targeting ship related pollution, other than the prevention of pollution by dumping and incineration at sea. HELCOM, on the other hand, works with recommendations, which can then be implemented by the contracting parties through their national legislation. Both HELCOM and OSPAR have close interaction with pollution prevention and marine environmental management at an EU level.

The most extensive environmental EU framework is the Marine Strategy Framework Directive (MSFD, 2008/56/EC), built around eleven descriptors, for which environmental quality targets are defined as good environmental status (GES). Shipping may directly affect at least Descriptors 2, 5-11, and indirectly 1, 3-4.

- Descriptor 1: Biodiversity is maintained
- Descriptor 2: Non-indigenous species do not adversely alter ecosystems
- Descriptor 3: Populations of commercial fish and shellfish species are healthy
- Descriptor 4: Food webs ensure long-term abundance and reproduction of species
- Descriptor 5: Eutrophication is reduced
- Descriptor 6: Sea floor integrity ensures the proper functioning of ecosystems
- Descriptor 7: Permanent alteration of hydrographical conditions does not adversely affect ecosystems
- Descriptor 8: Concentrations of contaminants give no pollution effects
- Descriptor 9: Contaminants in seafood are at safe levels
- Descriptor 10: Marine litter does not cause harm
- Descriptor 11: Introduction of energy (including underwater noise) does not adversely affect the ecosystem

Shipping activities in coastal and port areas may affect the environmental status indicators of both good chemical and good ecological status as defined in the Water Framework Directive (WFD, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy). WFD and MSFD overlap in their spatial coverage and the indicators set by the WFD (e.g., EQS of priority substances) also apply to the assessment within MSFD. The Habitats and Birds Directives (Habitats Directive - Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, and the Birds Directive - Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds) are the cornerstones of the EU's biodiversity policy and therefore relevant for shipping pressures e.g. related to spreading of non-indigenous species. With respect to air quality, the Air Quality Directive (2008/50/EC) is of relevance for assessing pollutant levels caused by ship emissions. Finally, the

European Green Deal embraces several strategies and policies relevant to shipping environmental pressures and impacts, such as the EU Biodiversity strategy for 2030, the Integrated Maritime Policy, the Blue Economy Strategy, the Chemicals Strategy, and the Zero Pollution Strategy.

1.3 Description of study area

The Baltic Sea and the North Sea are emissions control areas (ECAs), as designated MARPOL Annex VI, for both SO_X (2006-) and NO_X (2021-) (Figure 1.3). Regional features include winter navigation, low water volume exchange, special regulations, large human populations, and features of dense ship traffic, which warrant a regional focus.

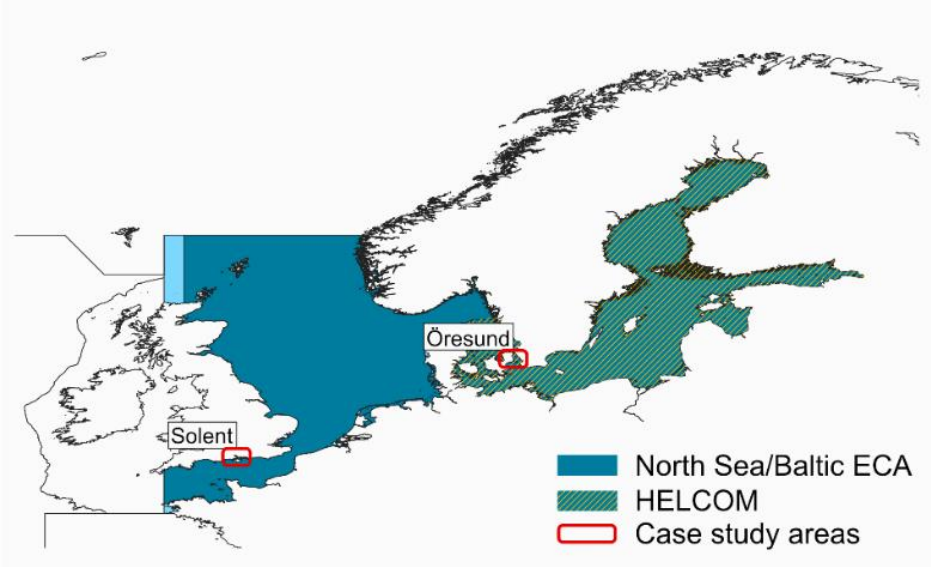


Figure 1.3: The study area included in EMERGE deliverable 6.1. North Sea area (including the English Channel) is blue and the Baltic Sea Area (i.e., HELCOM area) is green-dashed. Solent and Öresund case study areas are marked with red rectangles.

The Baltic Sea is a semi-enclosed inland sea with a large catchment area. The input of freshwater from land and the low water exchange through the Belt and Öresund Strait result in a salinity gradient from south (more marine conditions, ~25 ‰) towards the north where the salinity is very low (almost fresh-water conditions, ~2 ‰). The brackish character of the Baltic creates a unique environment that is inhabited by sensitive marine and limnic species. The large catchment area also

contributes to a high nutrient load and contaminant input in the Baltic Sea area. The Baltic Sea has been designated as a Particularly Sensitive Sea Area (PSSA) by the IMO.

The North Sea and the English Channel contain significant hubs of intercontinental shipping activity. In addition to intense ship traffic, the North Sea also holds a large and important fishing sector, offshore wind farms and oil platforms. The current environmental policies for air emissions are like those for the Baltic Sea area, but discharge rules are not as strict due to the lack of Special Area status with respect to some of the MARPOL Annexes. The North Sea area is not classified as a PSSA.

The Öresund region case study (Sweden/Denmark) provides a closer look on the impacts of ship traffic in the busiest part of the Baltic Sea while the Solent Strait (including Southampton) case study addresses impacts of ship generated air/water pollution in a major UK shipping hub. Both case study regions are near Natura 2000 areas.

The Öresund strait is one of the two connections between the North Sea and the Baltic Sea and has one of the busiest shipping lanes in the world. The case study provides an analysis of the impacts of current and abatement scenario shipping in the strait on water and air quality. The area is a transit fairway for all traffic entering or exiting the Baltic Sea, with several medium-size ports located in a high densely populated area but also integrated in a high ecological valuable area (both Natura 2000 and nature reserves). A detailed description of Öresund hydrodynamics can be found in EMERGE D.4.3. Main environmental issues include impact on water and air quality, adverse effects on marine ecosystems, eutrophication and human health impacts from air pollution.

The Solent Strait region, including the ports and cities of Southampton and Portsmouth, separates the Isle of Wight from the mainland of England. It is a major shipping lane for passenger, freight and military vessels and an important recreational area for water sports, particularly yachting. The Solent Strait has a complex tidal pattern that provides a "double high tide" that extends the tidal window during which deep-draught ships can be handled. Hence the port of Southampton is the UK's number one vehicle handling port and Europe’s leading turnaround cruise port. The Solent region has a population of >1 million, >50,000 businesses and a local gross value added (GVA) of £25 billion (Xiong *et al*, 2023). The area is of great ecological and landscape importance with much of its coastline being designated as a Special Area of Conservation according to the European Union's Habitats Directive.

Identified main environmental issues of the Solent Strait area include impact on water and air quality, adverse effects on marine ecosystems and human health impacts of air pollution. An important international port, Southampton is the largest city in the region and is served by an international airport and major rail and road networks. The concentration of atmospheric pollutants to which individuals in a port city are exposed to is dependent on emissions, meteorological conditions, dilutions, and transformations. Significant short-term variations of water pollutant concentrations may conceal long-term trends of water pollution or make analysing them difficult. It is therefore crucial to understand how drivers influence atmospheric pollution in port cities, and the aspects of the ports that are the most detrimental to atmospheric pollution in comparison with emissions associated with activities related to the city itself. Hence as part of EMERGE, an investigation of the long-term trends and drivers of atmospheric pollution in Southampton (2000-2019) was undertaken to provide context (Owusu-Mfum *et al*, 2023). Further, the Solent Strait is bordered by agricultural land and urban areas with wastewater treatment plants, and hosts an annual international regatta, all of which result in adverse impacts on marine water quality. Consequently, long-term historical analyses of: i) general water quality in the Solent (May *et al*, 2023), and ii) the specific impacts of recreational boating on marine surface water quality (Xiong et al, 2023) were carried out as part of the EMERGE project to provide crucial historical context.

2 SYNTHESIS OF PREVIOUS WORK WITHIN EMERGE

This deliverable aims at condensing and synthesizing the outcomes of previous work within the EMERGE project (Figure 2.1), both from previous deliverables and peer-reviewed scientific papers published as part of EMERGE (APPENDICES

APPENDIX I – Synthesis of previous work). The overall concept is based on the DAPSIR framework, where drivers are represented by the different future scenarios presented in EMERGE D1.4. Based on the 8 scenarios, including baseline conditions for year 2018 (EMERGE D4.2 and D5.1), the Ship Traffic Emission Assessment Model (STEAM) provide activity data for ships which can be used, in combination with emission factors (EMERGE D2.1, D2.2 and D3.3), to quantify pressures, i.e., contaminant loads, to the environment from ship activities. By applying transportation and chemical fate models for both atmosphere and marine environment, also simulating deposition of a selection of contaminants, the state, i.e., air and water quality, can be estimated for each scenario. The assessment of state and state change will enable an integrated impact assessment, including marine environmental quality and human health aspects. In addition, the contaminant load of metals and PAHs from ship activities are compared to the loads derived from other natural and anthropogenic sources for a more holistic assessment (Ytreberg et al. 2022).

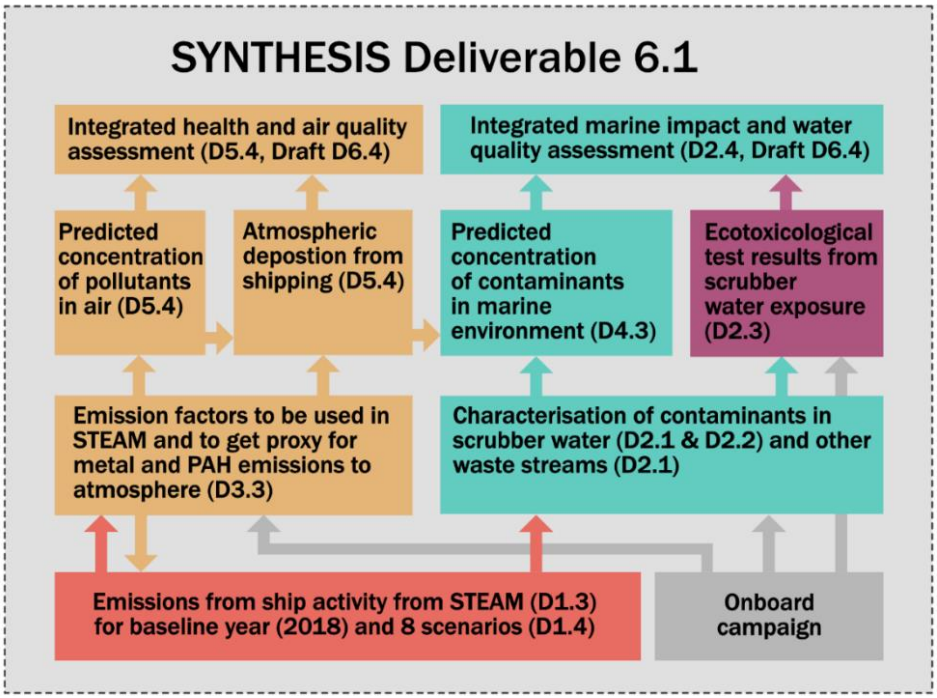


Figure 2.1: Workflow of deliverable 6.1 and connections between EMERGE WPs and previous deliverables.

The use of scrubbers as an abatement system to comply with the global sulphur cap has introduced a new contamination source to the marine environment from ships. An initial attempt to model the discharge and dilution of scrubber water once discharged is used to assess the risks of scrubber water exposure to marine organisms by consulting new evidence from ecotoxicological studies carried out within EMERGE, where early life stages have shown to be very sensitive to scrubber water exposure (EMERGE D2.3).

Implications of different responses are represented in the results of the different scenarios which act as basis for discussion on remaining knowledge gaps and recommendations to policy makers.

3 RESULTS

The main outcomes of the previous EMERGE work packages are structured and sectioned according to the DAPSIR framework, namely Driver, Activity, Pressure, State and Impact. The Response section provides a summary and recommendations based on the current scientific knowledge while addressing important knowledge gaps. The different aspects of DAPSIR are assessed at different spatial scales, from regional to case study level, depending on data availability. The outcomes from previous EMERGE deliverables have been complemented by scientific publications, additional data collection from ICES Dome (https://www.ices.dk/data/data-portals/Pages/DOME.aspx) (State) and a new approach of assessing the environmental risk associated with open loop scrubber water discharge (Impact).

3.1 Driver

Eight scenarios were developed in EMERGE D1.4 to calculate future emissions from shipping to air and water in 2050. The scenarios build on two different projected future developments of shipping transport volumes and consider the development of ships regarding fuel efficiency and ship size. The established EMERGE scenarios account for the use of abatement equipment and different fuels (Table 3.1). The use of scrubbers is modelled through an economic model, i.e., ship owners use scrubbers when it is profitable, accounting for potential future restrictions on the use of scrubbers. Since the installation and use of scrubbers is linked to strong financial incentives, an ongoing study is investigating the economic aspects of scrubber installations, both in relation to the shipowner perspective, i.e., financial gain and payback time, and in relation to the costs of not restricting, assessing the damage cost on marine ecotoxicity due to scrubber water discharge in the Baltic Sea area (Lunde Hermansson et al. in prep).

For the scope of deliverable 6.1, scenarios 1 and 3 are in terms of emissions the same since the Baltic Sea and the North Sea area already are designated ECAs. In terms of State, the scenarios are almost the same for the Baltic Sea, where impact of NOx emitted outside the current ECA does not have any negligible influence. For the North Sea the NOx emissions emitted in the Atlantic Ocean outside ECA have quite significant influence - this is both for atmospheric concentrations and for N deposition.

Two scenarios (number 3 and 8) were selected in EMERGE to primarily be used in model simulations for State and Impact assessment:

Scenario 3 is a high-pressure scenario, where the maritime transport development is high, there are no further measures to reduce the use of fossil fuels in shipping other than those already in place, there is significant use of open-loop scrubbers and high use of selective catalytic reduction (SCR) in NECA and it is assumed that sulphur and nitrogen oxide emission control zones are introduced in all European seas from 2030 onwards. A variation of this scenario (scenario 3b), assuming all scrubbers are operating in closed loop mode, was also used in this analysis. Scenario 3b is in terms of pressures equivalent to scenario 2 in already designated ECAs such as the Baltic Sea and North Sea areas.

Scenario 8 assumes a high development in ship traffic, measures in place to reach the 2018 IMO initial strategy to reduce GHG emissions with 50% by 2050 compared to 2018, no use of open loop scrubbers and low use of SCRs. It also assumes a high use of LNG and methanol as alternative fuels to HFO.

Table 3.1: Overview of the scenarios in the EMERGE project.

Scenario number	Ship traffic development	Number of scrubber installations	SCRs in use	Low sulfur required	Ambition to reduce GHG emissions	Alternative fuel
1	High growth	High (open loop)	NECA	SECA	No ambition	
2	High growth	High (closed loop)	NECA	SECA	No ambition	
3	High growth	High	Everywhere	Everywhere	No ambition	
4	Low growth	High	NECA	SECA	No ambition	LNG
5	Low growth	No scrubbers	None	SECA	50% reduction	Methanol
6	High growth	High	NECA	SECA	50% reduction	Methanol
7	High growth	Low	None	SECA	50% reduction	Methanol
8	High growth	No scrubbers	None	SECA	50% reduction	LNG & Methanol

3.2 Activity

Shipping activity was tracked globally using Automatic Identification System (AIS) data, a system which is mandatory for all vessels over 300 gross tonnage (GT) limit as defined in the SOLAS convention (SOLAS 2014). For other vessels, use of AIS is optional. AIS data was obtained from Orbcomm Ltd (data obtained for the period 2014 - the current date, from other projects), and it consisted of position reports of over 610,000 vessels globally, of which over 85,000 were sending out the IMO registry number which can be used to reliably identify ships that are counted as part of the global shipping fleet. The remaining half a million AIS targets represent other waterborne traffic, like fishing vessels and recreational craft. The temporal coverage of AIS is good, for 2018 in the Baltic Sea area, the availability of the AIS service was 97.2%, with intermittent data gaps between February 2nd-7th and October 16th, 2018 (Figure 3.1 left). For the North Sea area, the temporal coverage of AIS was 99%, with one data gap between July 24th-25th 2018 (Figure 3.1 right).

The global AIS data are a synthesis of messages received by both terrestrial and satellite AIS networks. Of these 610,000 AIS targets, including both big and small vessels, 16,687 and 8,931, represent IMO registered ships operating in the North Sea and the Baltic Sea area, respectively. In this assessment, the North Sea also includes the English Channel. The overall development of the number of ships observed for the period 2014-2022 can be found in (Figure A.III- 1).

For the impact analysis in EMERGE, the year 2018 was chosen as the baseline, because this represented the best compromise considering the availability of weather, oceanographic, air emission and water discharge data. However, it should be noted that the selection of 2018 as the baseline year reflects the situation before the significant adoption of scrubbers in the global ship fleet which happened in 2019-2021 when ship owners adjusted their compliance strategy for the global 0.5% Sulphur cap (Figure A.III- 2).

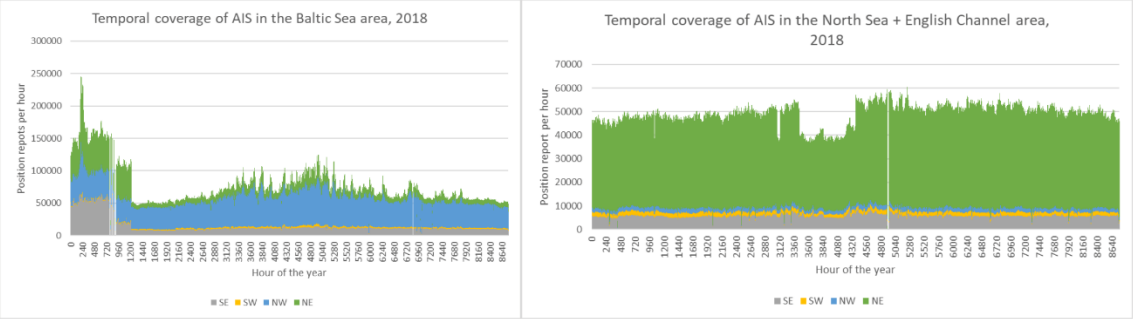


Figure 3.1: Temporal coverage and data flow of AIS in the Baltic Sea (left) and North Sea, incl. the English Channel, (right) in 2018. The numbers reported here are hourly received AIS position reports. Different colours represent the quadrants of the study domain (SE=South-East, SW=South-West, NW=North-West, NE=North-East).

The number of ships equipped with scrubbers and sailing in the Baltic Sea has increased significantly over the last few years and reached 781 ships in 2022. In 2018, which is the baseline study year of EMERGE, only 178 scrubber vessels were identified (Figure 3.2 left). Based on these numbers, it can be concluded that the Baltic Sea scrubber fleet has more than quadrupled in size since 2018. A similar increase was observed for the North Sea fleet (Figure 3.2 right). The global scrubber fleet is over 4000 vessels (Figure A.III- 2). For the Baltic Sea fleet, most scrubbers have been installed on oil tankers and bulk cargo vessels (Figure A.III- 3), which have less than 20 MW (Figure A.III- 4) of main engine power and surprisingly low annual fuel consumption of 500 tonnes (Figure A.III- 5). However, it should be remembered that the shipping activity in the regional seas, like the Baltic and the North Sea, does not necessarily reflect the global ship activity because vessels can sail out from these sea areas. This means that any cost calculation of economic viability of scrubbers should be done at global level and include all routes, regardless of location. Usually, the incentive to install and use a scrubber regard the cost savings, which can be achieved by using cheaper high-sulphur HFO instead of switching to more expensive low sulphur distillate fuels. The price difference between the 0.1% distillate fuel and the high sulphur residual fuel oil was about 300 USD/tonne in October 2023 (Ship & Bunker, 2023).

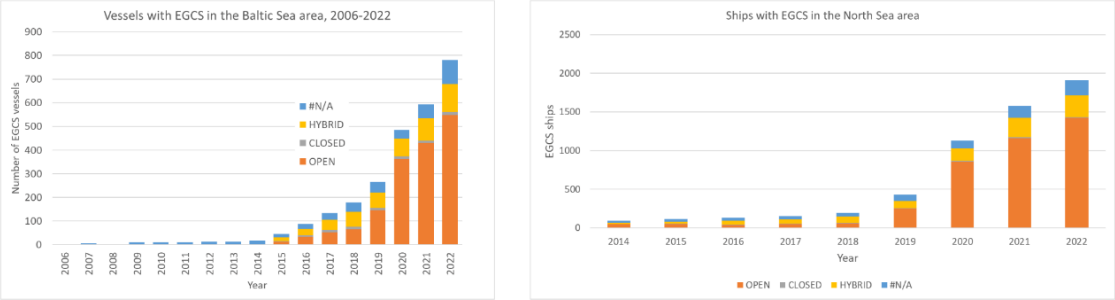


Figure 3.2: Scrubber (EGCS) installations in the Baltic Sea (left) and North Sea/English Channel (right) fleet by equipment type. For unknown equipment type, an open loop system is assumed, because this is the most common option.

During 2018, the scrubber installations in the Baltic Sea area were mostly dominated by scrubber installations on RoPax, RoRo and Cruise vessels (Figure A.III- 3). As shown in the "Pressures chapter" (Chapter 3.3), most of the effluent release in the Baltic Sea area comes from RoPax and RoRo ships. For the North Sea, the dominant scrubber discharge sources were the containerships.

EMERGE scenarios 3, 3b, and 8 all assume that ship traffic will grow significantly in the coming decades. Same traffic development assumptions are used in all three scenarios and therefore, the number of ships operating in the Baltic Sea and the North Sea remains constant for all scenarios. In scenarios 3 and 3b, it is assumed that the price difference between HFO and low sulphur fuels is high, and that it is profitable to install a scrubber on all vessels that consume more than 2,500 tonnes of fuel annually. The use of scrubbers is also at a high level as it is assumed that a new SECA is implemented in Europe within 200 nautical miles from the coastline starting in 2030. In scenario 8, it is assumed that HFO is no longer used in shipping and therefore, there are no scrubbers in use. The number of ships operating in the Baltic Sea and the North Sea, and the respective number of scrubbers in use for the baseline year and the selected scenarios are shown in Table 3.2.

Table 3.2: The total number of ships (including ships with open-loop and closed-loop scrubbers) operating in the Baltic Sea and the North Sea in EMERGE scenarios for 2050.

	Scenario 3	Scenario 3b	Scenario 8
Baltic Sea			
Ships Total	32 290	32 290	32 290
Open loop scrubbers	9460	0	0

Closed loop scrubbers	0	9460	0
North Sea			
Ships Total	185 930	185 930	185 930
Open loop scrubbers	22 710	0	0
Closed loop scrubbers	0	22 710	0

3.3 Pressure

Within EMERGE, direct shipping emissions of NO_X, SO_X, PM and CH_4 to the atmosphere were derived (see example in Figure 3.4 left which shows total emissions from shipping for the baseline year 2018). All calculations of emissions and discharges from shipping are produced using the Ship Traffic Emission Assessment Model (STEAM) (Jalkanen et al. 2009, Jalkanen et al. 2012, Johansson et al. 2017, Jalkanen et al. 2021). International shipping in the Baltic Sea area is responsible for 64% of the shipping total CO_2 emissions to the atmosphere (Figure 3.3 left), but also for 75% of the scrubber effluent discharges in the sea (Figure 3.3 right).

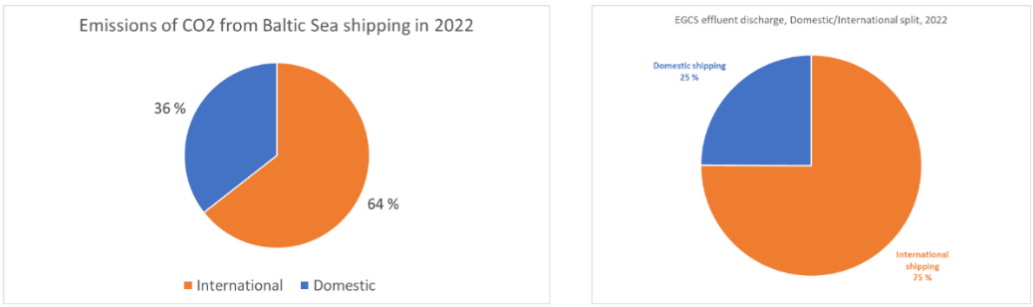


Figure 3.3: Left: Division of CO_2 emissions from ships to International and Domestic navigation contributions. Right: Share of scrubber effluent release from International and Domestic shipping in the Baltic Sea area.

Existing SECAs require a reduction of SO_X which has also influence on PM emissions from ships. These requirements can be met by either switching to low sulphur fuels, or by using scrubbers to remove SO_X from the exhaust, and the resulting lower emissions are visible in Figure 3.4, where the boundary between North-East Atlantic and the North Sea SECA is sharp when ships are required to reduce their SO_X emissions. Both the Baltic Sea and the North Sea are also ECAs for NO_X, but this requirement became effective later (2021) and was not in force during the baseline

year 2018. Further, NECA requires only for the new ships to comply with the IMO NO_X Tier III emission levels, and therefore this is does not apply to the existing vessel fleet. This means that the full effect of NO_X reduction from ships in the NECAs is expected to be visible after the fleet has undergone one renewal cycle, which usually takes 25-30 years. Total emissions of SOx, NOx $PM_{2.5}$ and NH_3 in the Baltic Sea and the North Sea in year 2018 and in scenarios 3 and 8 in year 2050 are shown in Figure AIV-5. in Appendix IV.

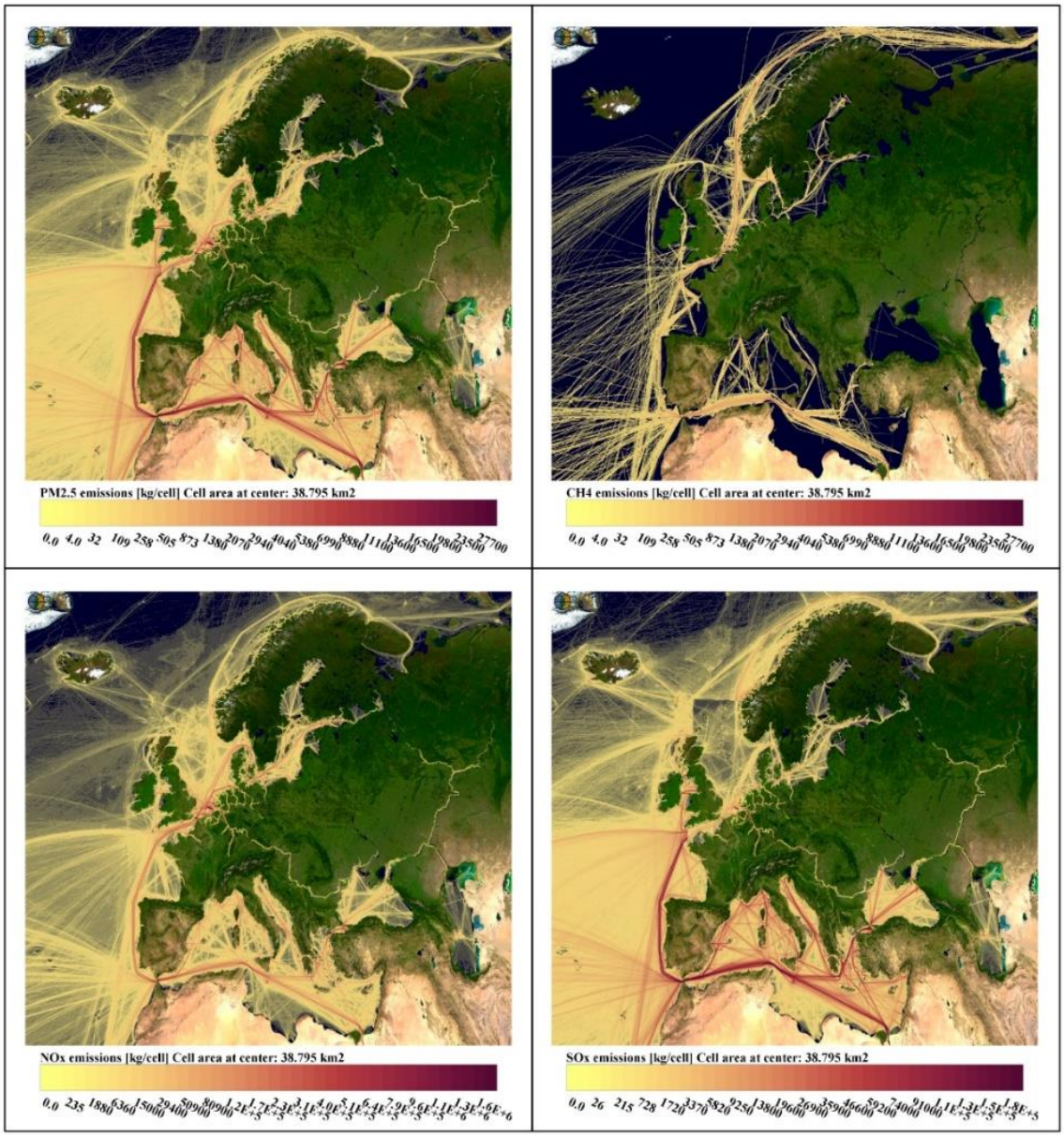


Figure 3.4: Emissions of $PM_{2.5}$(top left), CH_4 (top right), NO_X (bottom left) and SO_X (bottom right) from shipping in 2018 (EMERGE baseline year). Data from STEAM.

Since EMERGE primarily focuses on scrubbers, special attention has been given to emissions, discharges and impacts on the marine environment (Figure 3.5 and Figure A.IV- 3) related to scrubber equipped vessels. Hence, one important task has been to estimate the load of metals and PAHs from ships equipped with scrubbers and compare the load from scrubbers with the load from other natural sources and human activities. Within EMERGE, we decided to use two key metals (Cd and Pb) and two key PAHs (fluoranthene and benzo[*a*]pyrene) in our assessments. These substances were selected since they are known to be toxic, are regularly monitored in the marine environment, threshold values exist, and background knowledge of inputs from other sources is accessible in our case study regions. However, since both nickel (Ni) and vanadium (V) are signature elements in HFO (Corbin et al., 2018), a load compilation was also made for these two metals in the Baltic Sea region.

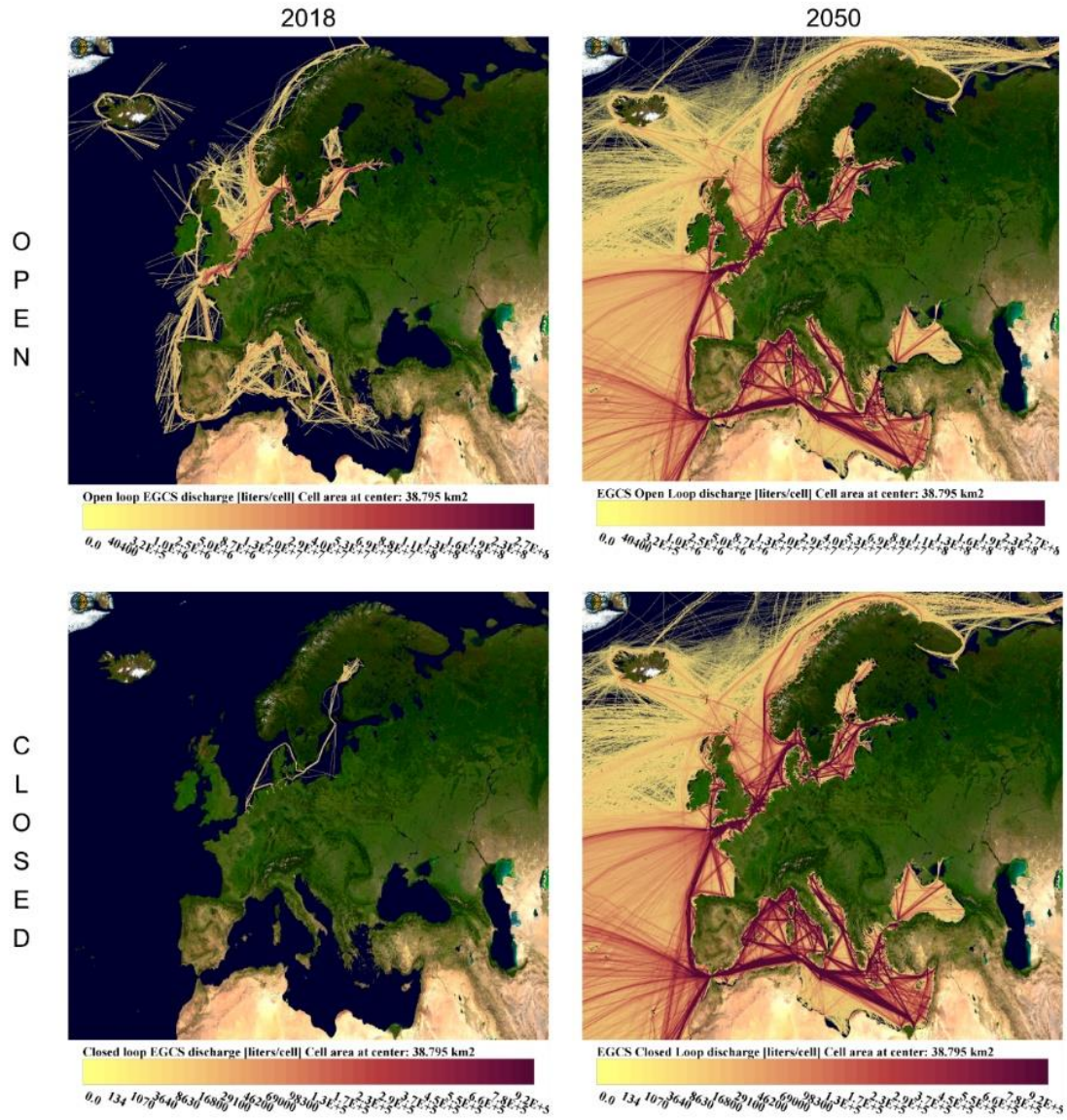


Figure 3.5: Discharges of open (top panel) and closed (bottom panel) loop scrubber water in baseline scenario (2018) and scenario 3 (open) and 3b (closed) for 2050. Data from STEAM.

The loads of metals and PAHs from shipping were calculated by multiplying the total volumes of open- and closed loop scrubber wash water, bilge water, greywater, and sewage for the different scenarios (exemplified in Figure 3.5 for 2018 scrubber discharge and Figure A.IV- 3 for other liquid waste streams) with the corresponding average concentrations of the contaminants present in the respective waste stream (obtained from EMERGE D2.1).

Scenarios 3 and 3b represent a future situation with a high number of scrubbers used in shipping and therefore, pressures from scrubber discharge waters are also high. Figure 3.5 shows the distribution of scrubber water discharge in 2050 following scenarios 3 and 3b. Both scenarios assume that only one type of scrubber is used and therefore, results for scenario 3 (Figure 3.5 top right) only show discharges from open loop scrubbers and results for scenario 3b (Figure 3.5 bottom right) only for closed loop scrubbers. Total discharges of scrubber water in the Baltic Sea are 1.74×10^9 m^3 from open loop scrubbers (scenario 3) and 8.76×10^6 m^3 from closed loop scrubbers (scenario 3b). In the North Sea, total discharges of scrubber water are 2.13×10^9 m^3 from open loop scrubbers (scenario 3) and 1.12×10^7 m^3 from closed loop scrubbers (scenario 3b).

Loads of metals and PAHs to the Baltic Sea from shipping relative to other sources

The load of PAHs (16 US EPA priority PAHs) and metals (As, Cd, Cr, Cu, Pb, Hg, Ni, V and Zn) from atmospheric deposition, riverine inputs, point sources (coastal industries and wastewater treatment plants), maritime shipping and leisure boating to the Baltic Sea were calculated based on data from various sources (see Figure 3.6 and Ytreberg et al. (2022) for a thorough description on data sources used and methodology applied). A simplified extrapolation method was used to estimate loads of atmospheric emissions and deposition fluxes since only Cd, Cu, Hg, Pb and benzo[*a*]pyrene are included in EMEP chemistry transport model on the Baltic Sea scale (EMEP 2021, HELCOM 2021a). Hence, annual atmospheric loadings of metals and PAHs to the surface water of the Baltic Sea were calculated by extrapolating the deposition fluxes of 9 metals (including Pb, Cd, V and Ni) and 12 PAHs (including fluoranthene and benzo[a]pyrene) at Swedish background stations to the surface area of the Baltic Sea subbasins (see Ytreberg et al. 2022). National data of riverine input of metals reported by the HELCOM contracting parties to HELCOM PLC Annual was collected for the period 2015–2017 (HELCOM 2021b).

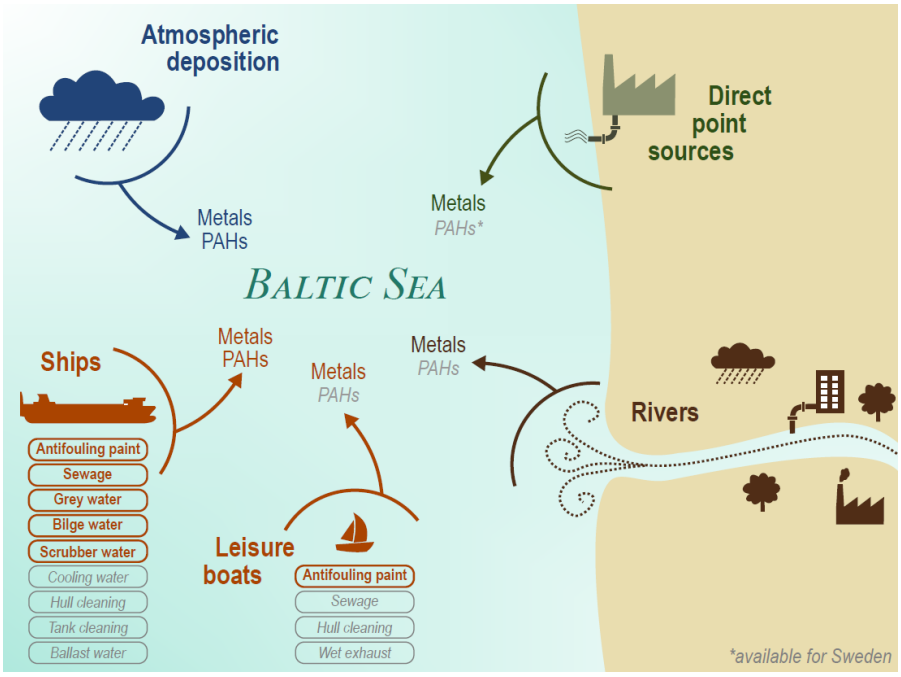


Figure 3.6: Direct discharges and atmospheric deposition of metals and PAHs to the Baltic Sea. Grey text in italic indicates substances and sources where data is lacking and thus not included. (From Ytreberg et al. (2022))

The loads of metals from point sources with outlets directly to the coast were compiled from (HELCOM 2021a). The data includes loads from industrial point sources and larger coastal municipal wastewater treatment plants (WWTPs) during the period 2016–2018. In the load compilation, all inputs from atmospheric deposition, rivers and point sources are expressed as annual inputs and represent the period between 2015 and 2018. This implies that in all future EMERGE scenarios for 2050, the loads the atmospheric deposition, rivers and point sources will remain the same as in 2015–2018 while the emissions from shipping will change due to different policy measures and assumptions in shipping development.

The total annual load of Ni to the Baltic Sea region in 2018 was 700 tonnes (Figure 3.7A), of which direct discharges from open loop scrubbers accounted for 11.4 tonnes (1.7%). The input from scrubbers is considerably higher in scenario 3 (2050), accounting for 84 tonnes of Ni (or 10.5% of the total input). For Cd (Figure 3.7 B), the total annual load to the Baltic Sea region in 2018 was estimated to be 26 tonnes and the contribution from scrubber discharge water was 0.2 tonnes (0.7%). Similarly to Ni, the share of Cd from scrubbers compared to the total input increased significantly in Scenario 3 from 0.7% to 5.2%. For Pb (Figure 3.7C), less than 1% of the total input originated from scrubbers in 2018. The share from scrubbers increased to 5.3% in scenario 3 (2050).

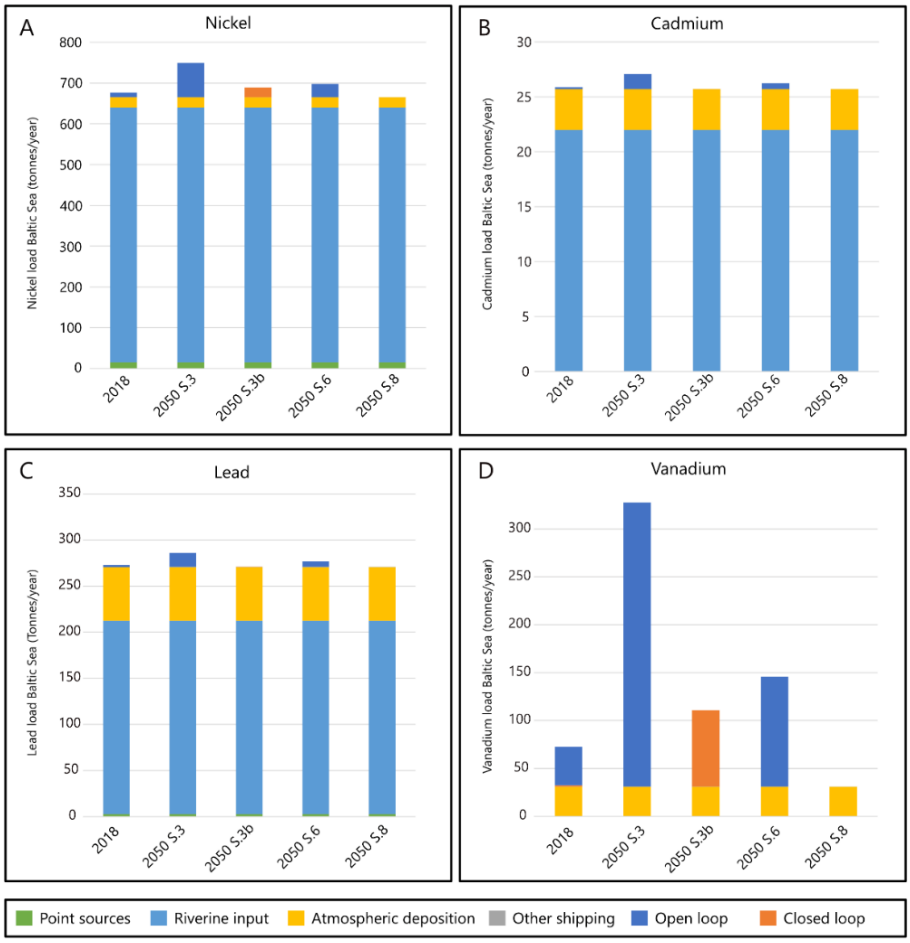


Figure 3.7: Comparison of loads (tonnes/ year) of Ni (A), Cd (B), Pb (C) and V (D) from rivers, atmospheric deposition, direct point sources, open loop scrubbers, closed loop scrubbers and other sources of shipping (bilge water, sewage and greywater) to the Baltic Sea region in 2018 and different shipping scenarios for 2050. For V, riverine input and point sources were excluded due to insufficient data coverage (only Sweden).

For V (Figure 3.7D), riverine input is only available from Swedish rivers and no country reported inputs from coastal point sources. Thus, a thorough load compilation was not possible to perform since the assessment is limited to inputs from shipping and atmospheric deposition. Nonetheless, open loop scrubbers were found to discharge 41 tonnes of V in 2018, which is higher compared to the atmospheric deposition (31 tonnes) and similar to the riverine input from Swedish rivers (47 tonnes). The load in 2050, according to scenario 3 from open loop scrubbers, is as high as 297 tonnes of V, while the closed loop mode scenario (scenario 3b) showed lower inputs (80 tonnes). The environmental load of fluoranthene and benzo(a)pyrene (B*a*P) to the Baltic Sea in 2018 from shipping and atmospheric deposition is shown in Figure A.IV- 4.

Loads of metals and PAHs to the North Sea from shipping relative to other sources

Inputs of metals and PAHs from shipping to the North Sea were estimated using STEAM, i.e., the same methodology as described above. Load of metals and PAHs in riverine input and direct discharges from industries and WWTPs to the North Sea was compiled from the Riverine input and direct discharges programme (RID) from OSPAR (https://www.ospar.org/work-areas/hasec/hazardous-substances/rid). RID aims to monitor and assess all inputs and discharges of selected contaminants to the OSPAR maritime area and its regions that are carried via rivers into tidal waters or are discharged directly into the sea. Monitoring and reporting of the concentrations and loads of relevant metals such as Cd, Cu, Pb, Hg and Zn is mandatory for OSPAR member states. However, no country reports inputs of V or PAHs. Here, we used the average yearly load of riverine input during a three-year period (2018 - 2020). The annual load of Pb and Cd to the North Sea is shown in Figure 3.8, and similarly to the Baltic Sea an increase of open loop scrubber related load is estimated in scenario S3, while the scrubber load in Scenario S3b is very low (<0.1 tonnes/year).

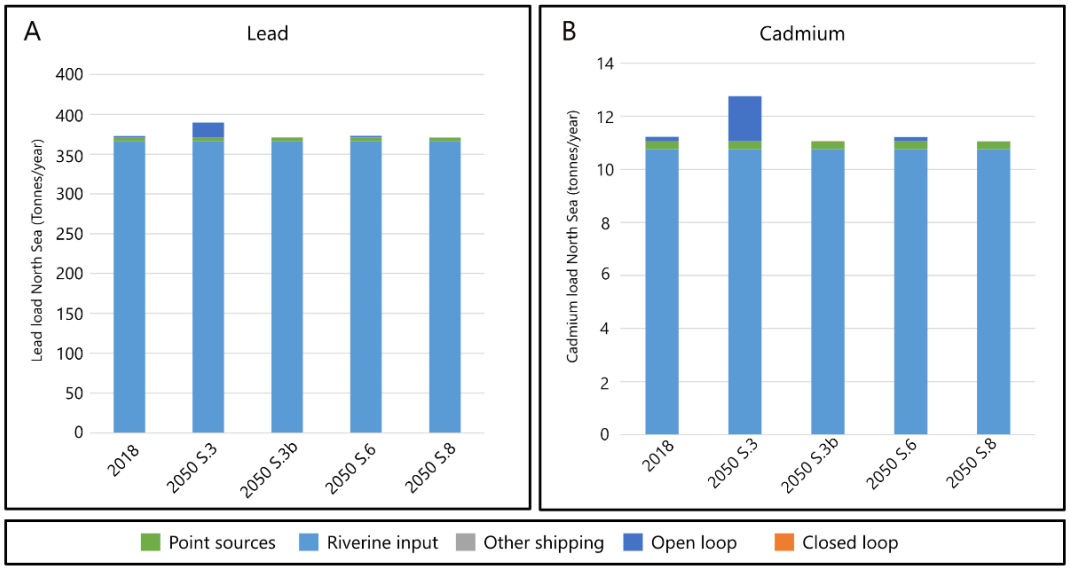


Figure 3.8: Comparison of loads (tonnes/ year) of Pb (A) and Cd (B) from rivers, direct point sources, open loop scrubbers, closed loop scrubbers and other sources of shipping (bilge water, sewage and greywater) to the North Sea (OSPAR region) in 2018 and different shipping scenarios for 2050.

3.4 State

The assessment of environmental status of European sea areas is based on Member State reporting on MSFD indicators and descriptors. Here, the results from Member States' 2018 reporting on their progress to achieve GES were collected from WISE Marine (https://water.europa.eu/marine). WISE Marine is an EU platform hosted by the European Commission and the European Environmental Agency (EEA) that offers access to information and data on the state of Europe's Sea. The aggregated assessment (Figure 3.9 Left) includes all the reported data and was organized per indicator, per descriptor, and considering all descriptors using the One Out All Out–Principle. In this principle, the descriptor score defines the overall status of the whole sea area.

The aggregated assessment, including all descriptors, show that almost all water basins to fail to achieve GES. Especially northern Europe waters fail to reach GES with respect to descriptor D8, Contaminants (Figure 3.9 Right). On a European scale, out of the 21 indicators included in the high-resolution evaluation of D8, only six had no detected failures to reach GES. This means that >70% of the indicators have at least one basin where the status is assigned "not good" by one or more contaminants.

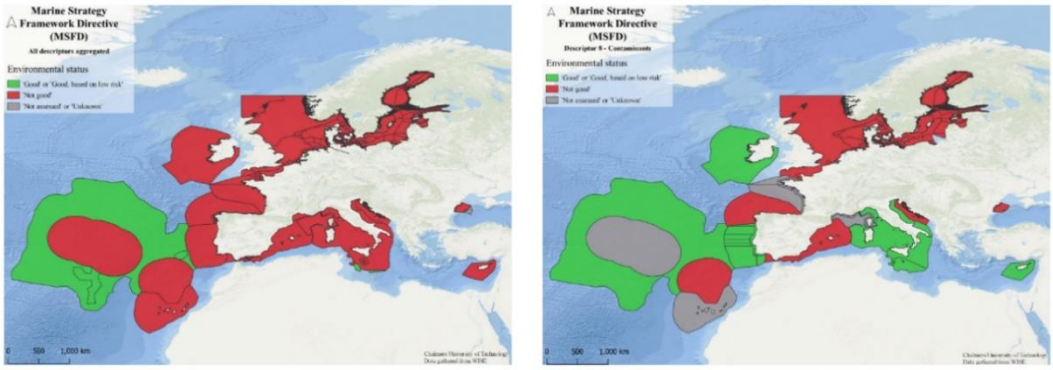


Figure 3.9: Environmental status of European sea areas as reported by EU Member States in 2018 according to the Marine Strategy Framework Directive (2008/56/EC). Left panel shows the overall environmental status considering all descriptors and the right panel shows the result for D.8 (contaminants).

Since the status assessment reported by EU Member States does not include information on actual water concentrations (all data is reported in the format GES achieved or GES failed), additional monitoring data for Ni, Cd, Pb, V, B*a*P and, fluoranthene was gathered from ICES DOME

(https://www.ices.dk/data/data-portals/Pages/DOME.aspx). All data used came from water samples taken at 0-5 m depth during the period 2015-2022. If samples had been collected more than once from the same sample station, an average value was used. The monitoring stations reported in ICES DOME are almost exclusively from coastal regions (Figure 3.10). For comparison, the monitoring data are also presented in comparison to threshold values for each substance according to the relevant Directive (WFD, Annual Average Environmental Quality Standard – AA-EQS presented as current and newly proposed by new dossiers (https://circabc.europa.eu/ui/group/9ab5926d-bed4-4322-9aa7-9964bbe8312d/library/69579412-bcc1-4740-b14b-88980756e6c3?p=1&n=10&sort=modified_DESC) (Table 4)), or to the predicted no effect concentration (PNEC) obtained from the scientific literature.

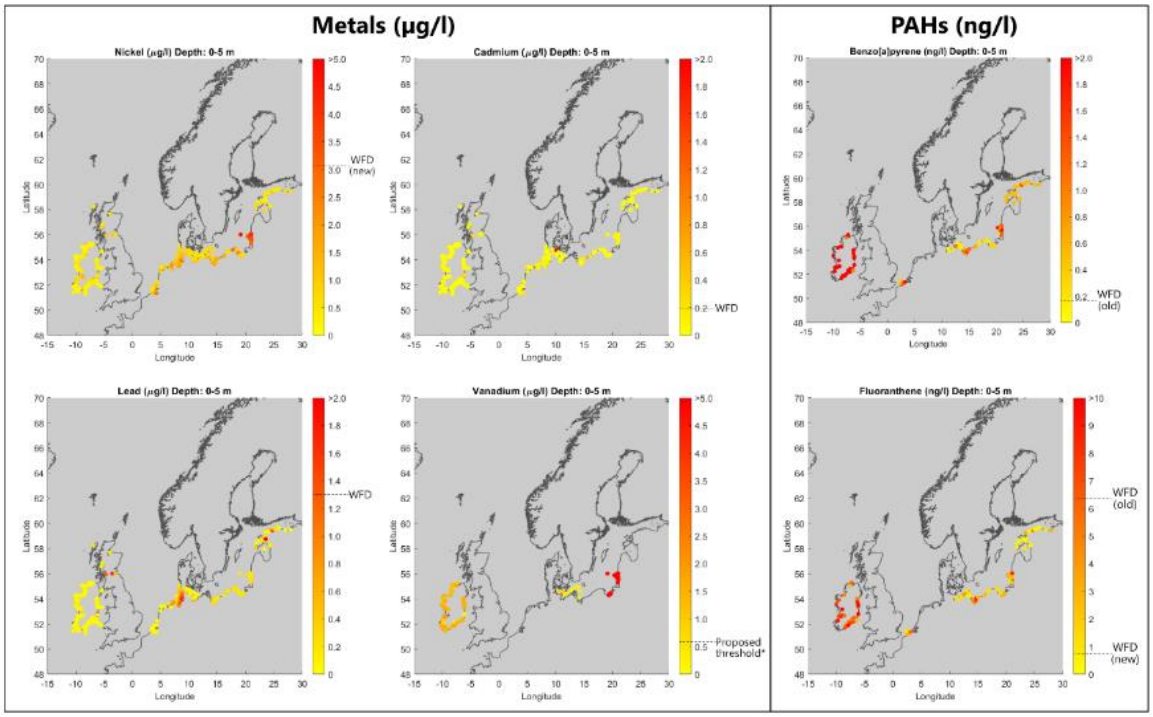


Figure 3.10: Environmental concentrations from monitoring data of 4 metals (Ni, Cd, Pb and V) and 2 PAHs (fluoranthene and benzo[a]pyrene) from surface water (0-5 m) in Baltic and North Sea region collected between 2015-2022 (https://www.ices.dk/data/data-portals/Pages/DOME.aspx)

The results show 1% of the stations to exceed the AA-EQS with respect to Ni (n_{tot}=1319) (newly proposed AA-EQS) and Cd (n_{tot} =1255). For Pb (n_{tot} =1149) and V (n_{tot} =482), the corresponding percentage of stations that exceeded the AA-EQS (Pb) and proposed PNEC (V) was 2% and 90%, respectively. For benzo[*a*]pyrene (n_{tot} =185) none of the stations exceeded the new proposed AA-

EQS but >90% exceeded the current AA-EQS. For fluoranthene (n_{tot} =160), almost 40% of the stations exceeded the current AA-EQS and 84% exceeded the newly proposed AA-EQS.

Table 3.3: Current and proposed threshold values (e.g., Annual Average Environmental Quality Standard (AA-EQS) for 4 metals and 2 PAHs. Proposed AA-EQS collected from dossiers published here: https://circabc.europa.eu/ui/group/9ab5926d-bed4-4322-9aa7-9964bbe8312d/library/69579412-bcc1-4740-b14b-88980756e6c3?p=1&n=10&sort=modified_DESC

Substance	Current AA-EQS	Proposed AA-EQS	Reference**
Nickel	8.6 µg/l	3.1 µg/l	Directive 2008/105/EC
Cadmium	0.2 µg/l	N/A	Directive 2008/105/EC
Lead	1.3 µg/l	N/A	Directive 2008/105/EC
Vanadium*	N/A	0.57 µg/l	Tulcan et al. (2021)
Fluoranthene	6.3 ng/l	0.76 ng/l	Directive 2008/105/EC
Benzo[*a*]pyrene	0.17 ng/l	22 ng/l	Directive 2008/105/EC

*vanadium threshold value is obtained from Tulcan et al (2021) who derived a predicted no-effect concentration (PNEC) value based on a chronic species sensitivity distribution curve.

** proposed EQS values from dossiers: https://circabc.europa.eu/ui/group/9ab5926d-bed4-4322-9aa7-9964bbe8312d/library/69579412-bcc1-4740-b14b-88980756e6c3?p=1&n=10&sort=modified_DESC

3.4.1 Marine Modelling

Modelling of contaminant concentration because of ship emissions and atmospheric deposition is conducted on regional scale using ChemicalDrift model (described in EMERGE D4.1 and D4.2) and on case study level using MITgcm model (described in EMERGE D4.3). Figure 3.11 shows a regional break-down of the modelled predicted environmental concentrations in the upper 5 m of the water column of the compounds Ni, Cd, Pb, V, B*a*P and fluoranthene originating from open loop scrubber water discharges. Figures are presented for the 2018 baseline year, and for 2050 scenario 3. For this deliverable, the model runs of ChemicalDrift delivered predicted environmental concentrations from single sources and the concentrations should thus be interpreted as added concentrations in the environment due to a certain activity. The concentrations for metals (Figure 3.11) are expressed in dissolved fraction while the concentrations of PAHs (Figure A.V- 1) are based on the sum of dissolved fraction and fraction adsorbed to suspended particulate matter (SPM). The results obtained using ChemicalDrift show, for most substances, highest concentrations in the Southern Baltic Sea region (Bornholm basin and Arkona basin). As expected, the modelled concentrations are higher in S3 (2050) as compared to the baseline scenario of 2018. The highest

modelled detected concentrations in S3 (2050) of Cd and Ni was 0.0005 µg/L and 0.02 µg/L, respectively. For Pb and V the corresponding maximum concentrations were 0.001 µg/L and 0.05 µg/L, respectively.

At the Öresund case study level, the difference between scenario 3 (2050) and the baseline (2018) shows a similar trend where the marine surface water concentration of the selected metals (Cd and Pb) and PAHs (fluoranthene and benzo[a]pyrene) increase (Figure 3.12) For scenario 8, where no scrubbers are in operation, the concentrations are expected to decrease (EMERGE D4.3). The model outputs on regional and case study level from 2018 simulations are compared in Table 3.4 where the concentrations are estimated in orders of magnitude level in the Öresund area. The MITgcm model includes several waste streams from ships and atmospheric deposition while the ChemicalDrift model output only predicts environmental concentrations due to open loop scrubber discharge. Therefore, any comparison of the model simulations should be treated as indicative. The dilution approach (second column, Table 3.4), described in section 3.5.1, is based on a modelling exercise where the distribution and dilution of open loop scrubber water are modelled using MITgcm, and the final concentrations of Cd, Pb, Fla and B[*a*]P are estimated from initial scrubber water concentrations in EMERGE D2.1. As a final comparison, the measured concentrations from ICES Dome exceeding the limit of detection (>LOD) in the region (mainly Denmark and Germany) are also added (Figure 3.10).

The modelling efforts of ChemicalDrift and MITgcm also suggest that a substantial fraction of the contaminants will accumulate at the seafloor, in the sediment (EMERGE D4.3).

Table 3.4: Comparison between regional scale and local scale modelling results and monitoring data from ICES Dome. All units are µg/l. Comparison limited to Öresund Case study. The dilution approach is based on modelling described in section 3.5.1 where the distribution of open loop scrubber water is modelled using MITgcm and final concentrations estimated from initial scrubber water concentrations in EMERGE D2.1. NOTE: different activities are included in the model simulations and any comparison should be treated as indicative.

	ChemDrift2018 (only open loop scrubber water discharge)	**Dilution approach (only open loop scrubber water discharge)**	**MITgcm 2018 (annual average from shipping and atmospheric deposition)**	**ICES DOME (monitoring data, selection Figure 3.10)**
Cadmium	2×10^{-5}	0.9×10^{-5}	0.03	0.02-28
Lead	2×10^{-4}	9.2×10^{-5}	0.1	0.02-8.3

Fluoranthene	1.5×10^{-6}	0.2×10^{-5}	1.5×10^{-3}	0.002-0.0085
Benzo[*a*]pyrene	2×10^{-7}	5×10^{-7}	0.2×10^{-3}	0.0022-0.002

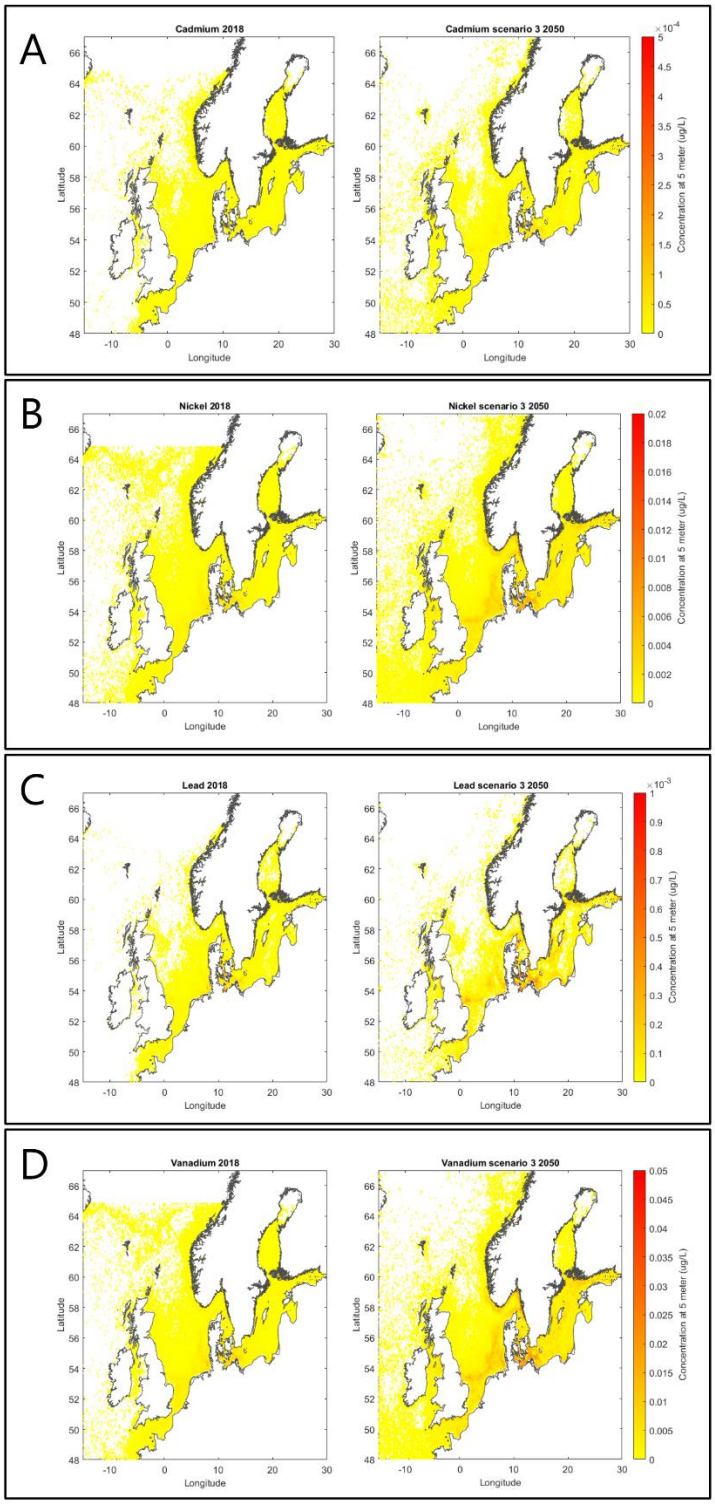


Figure 3.11: Example from ChemicalDrift output comparing 2018 with scenario 3 for 2050 (concentrations from OL scrubber water discharge in upper 5 meters).

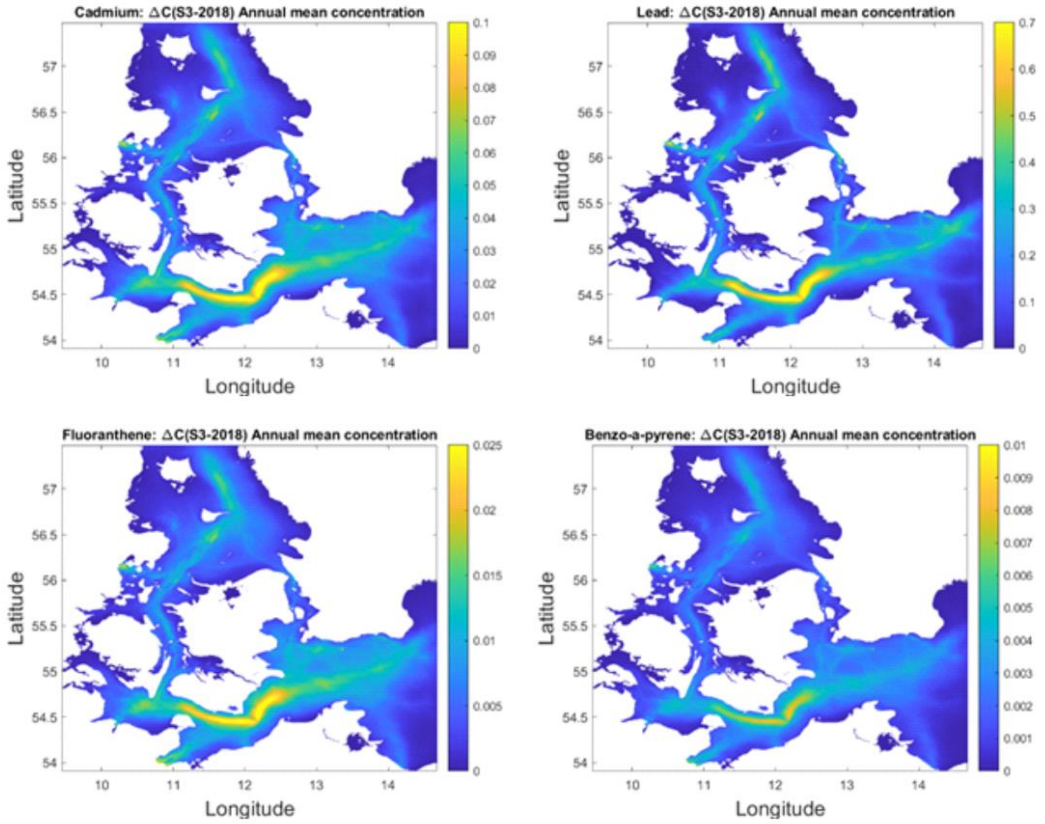


Figure 3.12: The difference between Scenario 3 and baseline year 2018 for Cd, Pb, B*a*P, Fluoranthene at 5 m depth. Concentrations are in µg/l.

3.4.2 Atmospheric modelling

The top-left panels of Figure 3.13 and Figure 3.14Figure 3.14 illustrate the current (2018) surface concentration levels for $PM_{2.5}$ and NO_2, respectively, when using the SILAM chemistry transport model at the nominal resolution of 5 km (description of SILAM model in EMERGE D5.2). The same figures also show the contribution from shipping (top-right panel), and the change compared with the current situation (top-left panel) if the shipping emissions are changed as estimated in scenario 3 (bottom-left) or in scenario 8 (bottom right), while keeping the other anthropogenic and natural emissions unchanged. As expected, the shipping contribution to $PM_{2.5}$ and NO_2 levels is not a dominant part, but rather an important source for air pollution, especially along the ship lanes and near the harbour areas, but sometimes also deeper inland. The values should be compared with the EU air quality standards that limit the annual mean concentration of $PM_{2.5}$ below 20 µg/m^3, and

NO_2 levels below 40 µg/m^3 (EC 2008). Additional maps and charts on modelling results are available in previous reports: D5.2, D5.3, and D5.4.

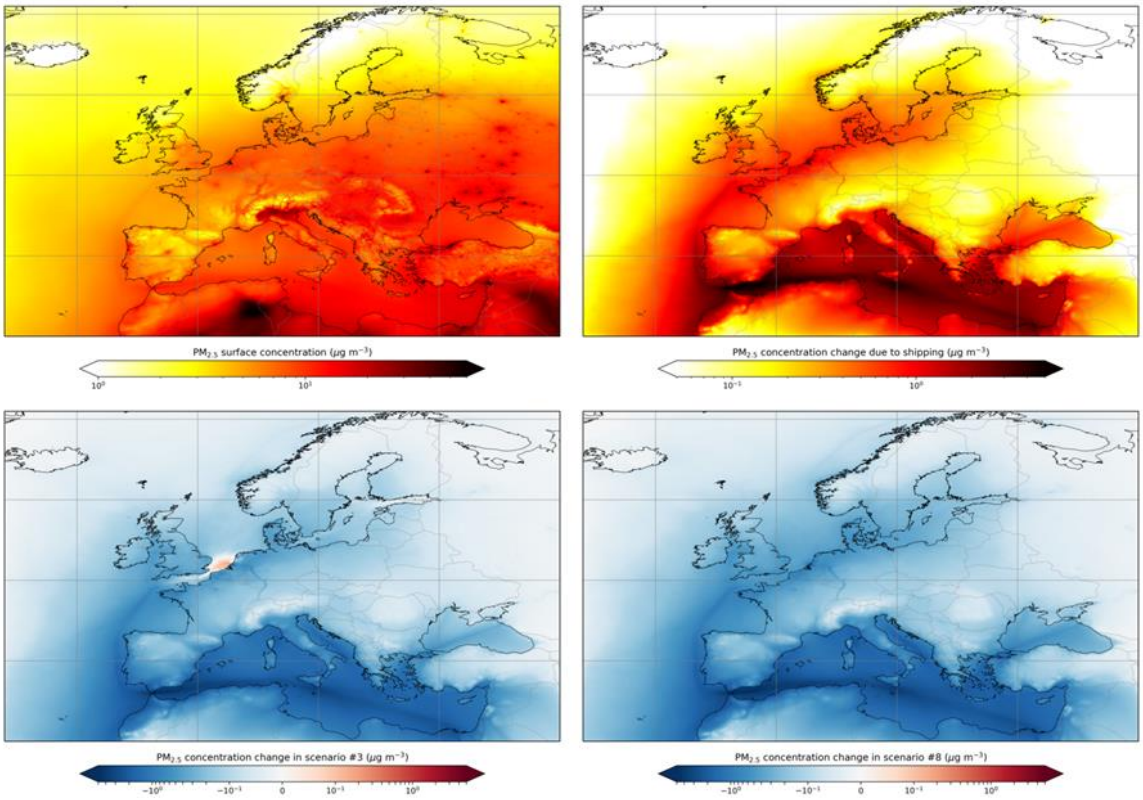


Figure 3.13: $PM_{2.5}$ concentration and contribution from shipping according to SILAM modelling. Top-left panel illustrates the total $PM_{2.5}$ concentration when including all the anthropogenic and natural emissions (e.g., dust and sea-salt). The top-right panel illustrates the shipping contribution when using the STEAM emission for 2018. The left-bottom and right-bottom panels illustrate the changes in concentrations if shipping emissions are adjusted as in scenario 3 and 8, respectively.

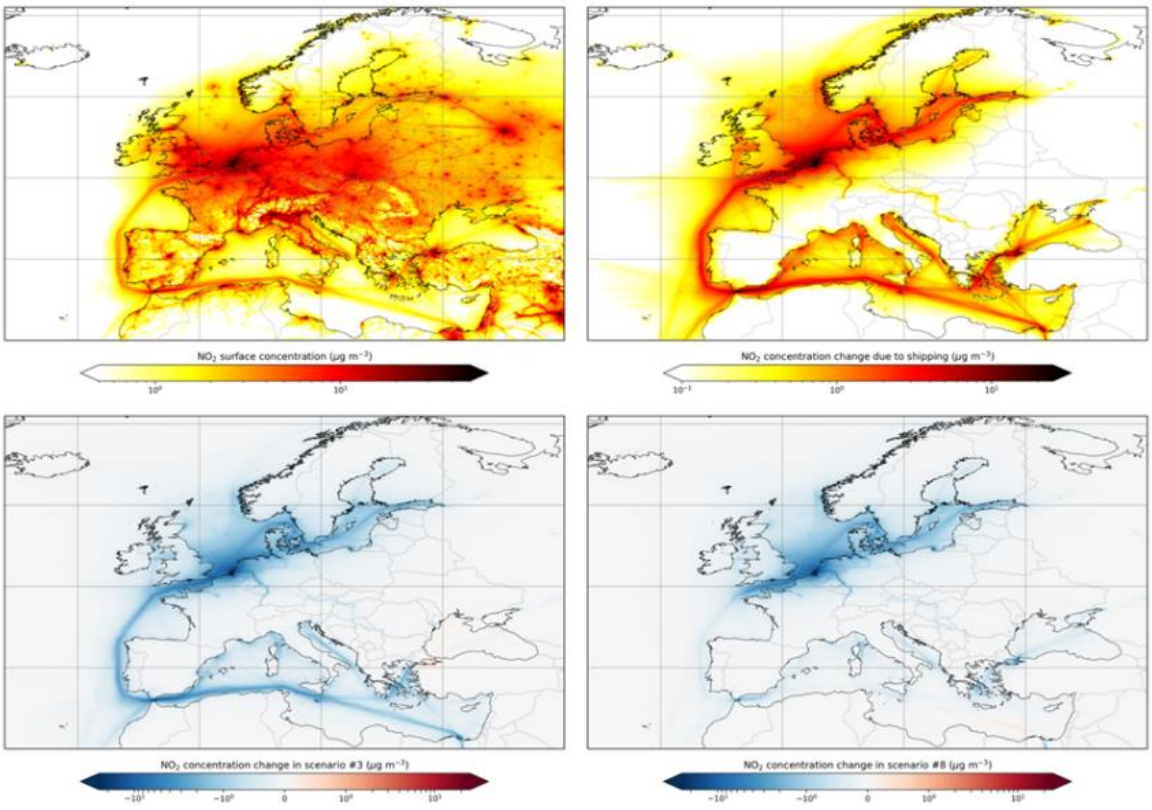


Figure 3.14: NO_2 concentration and contribution from shipping according to SILAM modelling. Top-left panel illustrates the total NO_2 concentration when including all the anthropogenic and natural emissions (e.g., dust and sea-salt). The top-right panel illustrates the shipping contribution when using the STEAM emission for 2018. The left-bottom and right-bottom panels illustrate the changes in concentrations if shipping emissions are adjusted as in scenario 3 and 8, respectively.

High-resolution simulations for the Case Study with SILAM and EMEP model

The Öresund region generally has higher shipping contribution with respect to reduced air quality. The impact of shipping emissions to NO_2, SO_2 and $PM_{2.5}$ concentrations is larger in July 2018 compared to January 2018 in the two EMERGE case study regions which clearly points to higher shipping activity during summer. Although models predict different shipping contributions in each case study region, the general summer increasing trend is predicted similarly by all models for all pollutants in all case study regions (Figure A.V- 2).

During the month of July 2018, the Community Multi scale Air Quality (CMAQ) model and the SILAM model projected an average reduction of NOx from shipping emissions exceeding 38% across all case study regions. In contrast, the reduction in NOx was estimated to be approximately

18% for both models during January 2018. In the absence of shipping emissions, it is generally observed that predicted ozone levels exhibit an increasing trend across all case study regions.

According to model predictions from the SILAM and CMAQ models, the responses are similar for the Solent and Öresund case study regions except for SO_2 where the shipping contributions during the summer at the Öresund region are higher due to stricter controls in the Solent area.

Most of the negative effects on air quality due to shipping appear above open sea areas, but people in coastal areas and around harbours are also affected. Table 3.5 summarizes the exposure to $PM_{2.5}$, NO_2, and O_3 in the case study areas based on the SILAM model results. The concentration maps in the case study regions are weighted with population density in order to obtain a characteristic number for exposure/concentration for that specific area. The calculated values from SILAM are annual averages, but it should be noted that maximum daily mean contribution from shipping can often be 3-8 times higher than the annual average. The shipping contribution to annual mean population weighted exposure in the different case study areas varies between 0.6-1.4 $\mu g/m^3$ for $PM_{2.5}$ and between 0.3-4.2 $\mu g/m^3$ for NO_2. Locally (near the harbours/shipping lanes), the exposures can be noticeable higher. In the case of ozone concentrations, shipping can have either positive or negative impact, depending on whether the region is located at the low NO_X area (where an increase of NO_X emissions will increase ozone), or in the high NO_X area where the titration effect dominates and an increase in NO_X emissions will typically decrease the ozone levels.

When comparing the future scenario emissions from SILAM to the calculated exposures in the different case study areas (see Table 3.5) one may notice that both scenarios, 3 and 8, decrease the shipping contribution to $PM_{2.5}$ exposure by a factor of three. Scenario 8 is slightly more efficient in decreasing the shipping originated $PM_{2.5}$ in Öresund and Solent regions than scenario 3. For NO_2, scenario 3 provides better reduction of NO_2 exposure than scenario 8. In scenario 3 the shipping contribution to NO_2 exposure would be dropped by a factor between two and seven, when compared to the 2018 baseline case. Exact numbers are visible in Table 3.5, which additionally illustrates that both future scenarios tend to increase ozone in the two case-study areas considered in the present deliverable.

The contributions of shipping to concentrations of $PM_{2.5}$, NO_2 and ozone calculated with the EMEP model for the year 2018 and the year-2050 scenarios S3 and S8 were combined with JRC-GEOSTAT 2018 population density data on 1x1 km grid (Batista e Silva et al. 2021) to calculate person-weighted concentrations ($\mu g/m^3$, for ozone also Sum Of Means Over 35 ppb (daily 8-hour maximum), SOMO35, in ppb-days). The person-weighted concentrations are calculated by first

calculating product of concentration and population in each grid-cell of the model domain, these products are aggregated and divided by the total population in the domain of the CS. Simulation NoShips exclude shipping in all 3 nested simulations of EMEP and hence, the impact of shipping emissions is from all shipping in European waters. Exposures in year-2050 scenarios S3 and S8 with year-2050 land emissions are presented along with those with year-2018 land emissions to show impact of change in land emissions on sipping-related exposures.

Table 3.5: Annual mean population weighted exposure (concentration) generated by SILAM to $PM_{2.5}$, NO_2, and O3, in five different case study regions, and shipping contribution to the exposure according to SILAM modelling at a nominal resolution of 5 km. The "Baseline" column is the total exposure when the 2018 STEAM shipping emissions are included. The "NoShip" column is the exposure without shipping emissions, "Ship2018" is the shipping contribution with 2018 shipping emissions, and ShipS3 and ShipS8 correspond to shipping contribution to exposure when the shipping emissions correspond to scenario 3 and 8 emissions in 2050, respectively. For the Öresund case study, results of 1-km resolution simulations calculated with EMEP model are presented as well. Exposures calculated for S3 and S8 scenarios with year-2050 scenario land emissions are presented along with the results from scenario simulations consistent with SILAM and marked with *.

	Baseline	**NoShip**	**Ship2018**	**ShipS3**	**ShipS8**
	Annual mean population weighted exposure/concentration for **$PM_{2.5}$** ($\mu g/m^3$)				
Öresund (SILAM)	7.18	6.56	0.62	0.34	0.19
Öresund (EMEP)	7.87	6.97 3.84*	0.90	0.35 0.39*	0.27 0.31*
Solent (SILAM)	7.09	6.24	0.85	0.48	0.30
	Annual mean population weighted exposure/concentration for **NO_2** ($\mu g/m^3$)				
Öresund (SILAM)	10.75	8.14	2.60	0.52	0.74
Öresund (EMEP)	8.47	6.13 2.02*	2.34	0.46 0.46*	0.68 0.69*
Solent (SILAM)	14.18	10.00	4.18	0.62	1.08
	Annual mean population weighted exposure/concentration for **O_3 (**$\mu g/m^3$)				
Öresund (SILAM)	54.76	55.87	-1.11	0.40	0.42
Öresund (EMEP)	63.03	64.39 66.63*	-1.35	0.25 0.48*	0.25 0.58*
Solent (SILAM)	51.70	54.85	-3.15	0.51	0.45

	Annual mean population weighted exposure/concentration for SOMO35 (ppb*days)				
Öresund (EMEP)	1 787	1 652 1 478*	135	107 146*	137 194*

**** Exposure based on EMEP simulations with year-2050 land emissions***

High-resolution simulations for the Öresund Case Study with EMEP model

Impacts of shipping emissions in the Öresund Case Study region have been simulated on high resolution (1 km x 1 km) with EMEP Open-Source model (APPENDIX V - Description of the model system used for simulations of air quality in Öresund Case Study). Likewise in the regional-scale model simulations performed with SILAM, the year-2018 situation has been assessed together with the year-2050 situation regarding shipping emissions in scenarios S3 and S8. In this Case Study the difference in between the 2 future scenarios regarding emissions to air comes from the fuels and abatement measures used in these scenarios: while in S3 most of the ships use HFO, MD and LSFO fuels combined with open-loop scrubber and SCR, in S8 scenario MeOH, MD and LNG are used without SO_x aftertreatment and with other NO_x aftertreatment but SCR. This leads to lower emissions of SO_x, PM and NH_3 in S8 compared to S3.

In the next the S3 and S8 scenario simulations kept the year 2018 land emissions and only differences in contributions from shipping to concentrations and deposition of pollutants are shown along with the year 2018 total concentrations/depositions and shipping contributions. Simulations with scenario land emissions for year 2050 are shown further down as a sensitivity study. Figure 3.15 shows concentrations of $PM_{2.5}$ in the Öresund CS region (Panel a). In the same figure, panel b shows contribution of shipping in year 2018 and panels c and d show contribution in scenario S3 and S8 in year 2050, respectively. Differences between $PM_{2.5}$ concentrations are driven by lower emissions of primary PM as well as by lower emissions of SO_x and NH_3, both contributing to formation of secondary PM. Comparison of the shipping contributions to $PM_{2.5}$ concentrations in year 2018 and in the 2050 scenarios shows decrease from contributions >1 μg/m^3 in large parts of the Öresund Case Study domain to contributions above 1 μg/m^3 limited only to vicinity of the Helsingborg harbour and shipping lanes in scenario S3. Further decrease in contributions to $PM_{2.5}$ concentrations can be seen in scenario S8 where the only place with contriburions above 1 μg/m^3 is around Helsinborg and Helsingör.

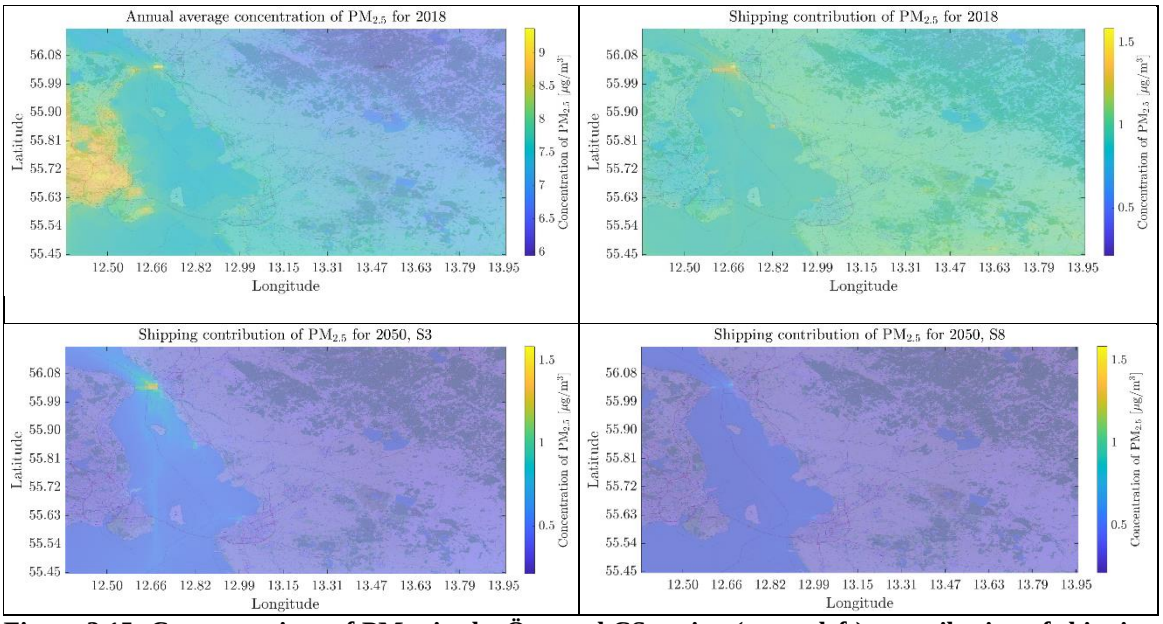
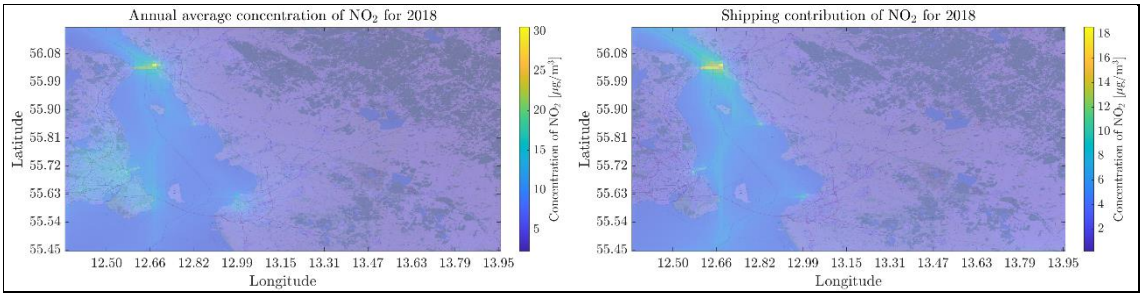


Figure 3.15: Concentrations of $PM_{2.5}$ in the Öresund CS region (upper left), contribution of shipping in year 2018 (upper right), contribution of shipping in scenario S3 in 2050 (lower left) and contribution of shipping in scenario S8 in 2050 (lower right).

Figure 3.16 shows year-2018 concentrations and year-2018 and year-2050 scenario S3 and S8 contributions of shipping to NO_2 concentrations. The figure shows high contribution of shipping to current NO_2 levels in the region. In 2050 scenario simulations the contribution from shipping dropped from up to 16 μg/m3 in 2018 to 1.5 $\mu g/m^3$ in maximum in 2050 S3 scenario. Further decrease in NO_2 contributions from S3 to S8 scenarios can be seen in the bottom panels of Figure 3.16.



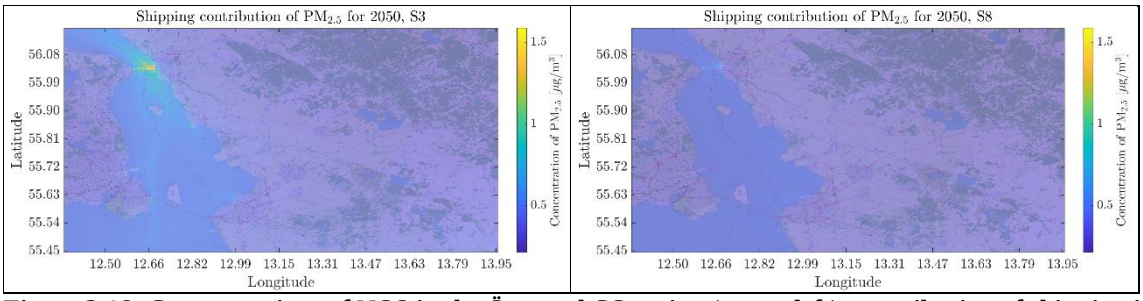


Figure 3.16: Concentrations of NO2 in the Öresund CS region (upper left), contribution of shipping in year 2018 (upper right), contribution of shipping in scenario S3 in 2050 (lower left) and contribution of shipping in scenario S8 in 2050 (lower right).

Figure 3.17 shows year-2018 deposition of total nitrogen (reduced and oxidised) and year-2018 and year-2050 Scenario S3 and S8 contributions of shipping to the deposition of N. The simulations have shown widespread contribution of shipping to deposition of nutrient nitrogen both to the sea surface and on land areas for year-2018 situation. The nitrogen deposition in S8 scenario is lower by approximately factor of 4 compared to year 2018. N deposition in S3 is significantly lower than in S8.

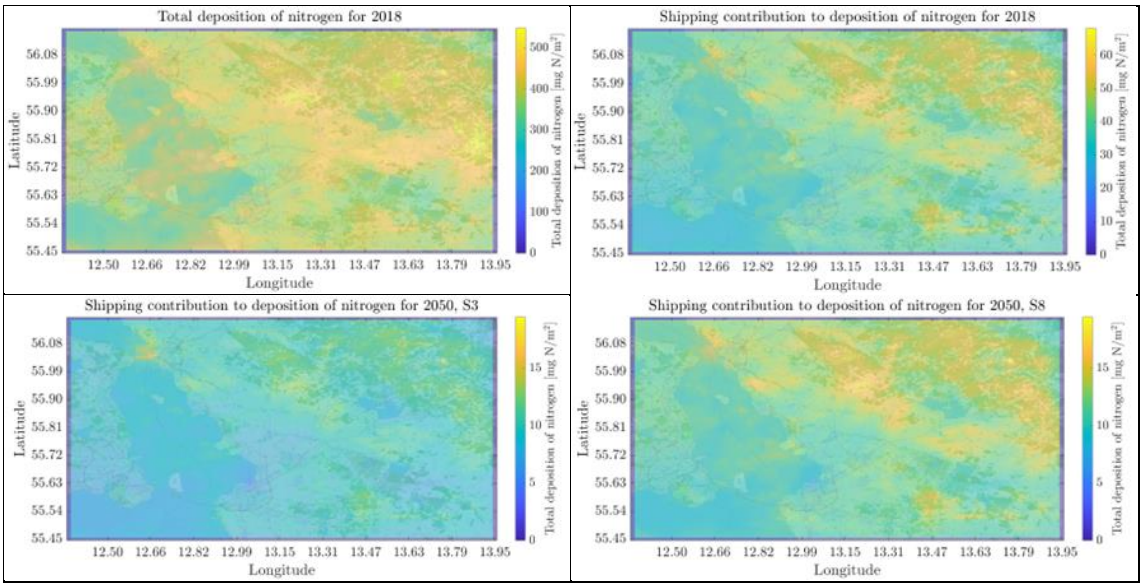


Figure 3.17: Deposition of total nitrogen (oxidesed and reduced) in the Öresund CS region (upper left), contribution of shipping in year 2018 (upper right), contribution of shipping in scenario S3 in 2050 (lower left) and contribution of shipping in scenario S8 in 2050 (lower right). The colour-scale for the 2050 shipping contributions is different from year-2018 contributions

Deposition of metals related to the shipping emissions is assumed to be directly proportional to the ash particles (Table 3-1 in EMERGE D3.2 report: Ni 4.1E-2 g/g ash, Cd 6.3E-6 g/g ash, Pb 1.2E-4 g/g ash, V 8.3E-2 g/g ash). Deposition of metals from land sources is not considered in EMEP simulations. Figure 3.18 shows year-2018 and year-2050 Scenario S3 and S8 contributions of shipping to deposition of ash particles associated with deposition of metals. The simulations show deposition of metals-containing ash particles both on the sea surface in the vicinity of emission hotspots and on land, where increased deposition around the emission hotspots and over forested areas can be seen. A large increase in metal emissions in scenario S3 compared to year-2018 emissions is clearly reflected also in deposition maps. Deposition map for the S8 scenario shows a large decrease in deposition of ash particles compared to S3.

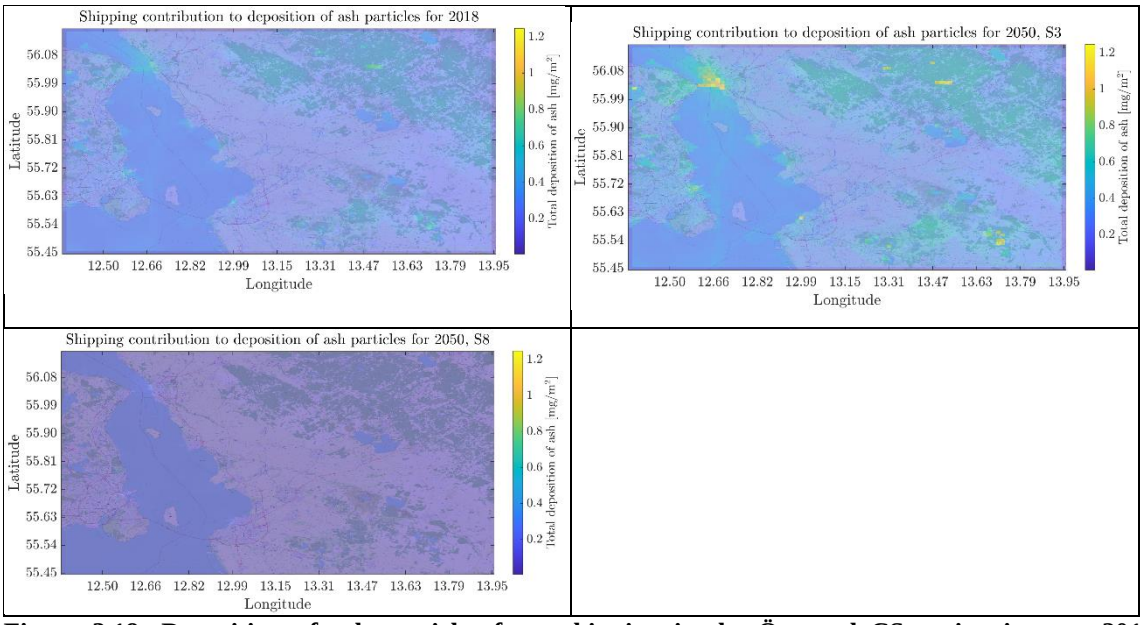


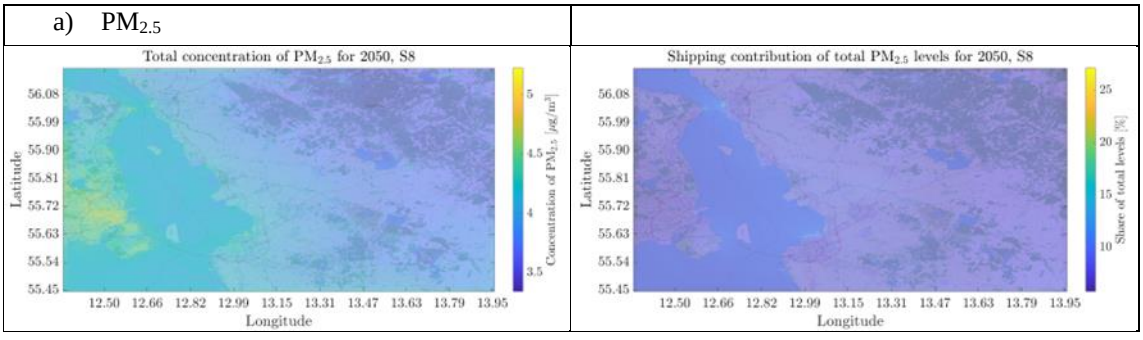
Figure 3.18: Deposition of ash particles from shipping in the Öresund CS region in year 2018 simulation (upper left), in scenario S3 for year 2050 (upper right) and in scenario S8 for year 2050 (lower leftt). The ash particles are proportional to metals as following: Ni 4.1E-2 g/g ash, Cd 6.3E-6 g/g ash, Pb 1.2E-4 g/g ash, V 8.3E-2 g/g ash (EMERGE D3.2)

The year-2050 land emissions used in the sensitivity scenario simulations were calculated by scaling emissions from the CAMS REG -v2.2.1 dataset for year 2015 with emission trends between years 2015 and 2050 in the ECLIPSE v6b global emission scenarios (Klimont et al. 2017, Höglund-Isaksson et al. 2020). The MFR (Maximum Feasible Reduction) scenario has been selected, which assumes that in addition to current policies, additional measures are taken to reduce air pollutant

emissions which are both technically available and cost-effective. The STEAM model was used to calculate both the shipping emissions in year 2018 and the future scenarios S3 and S8 in year 2050 (EMERGE D4.2 and D5.1).

In the next the S3 and S8 scenario simulations with year-2050 land emissions are shown. The simulated air quality situation in the scenario simulations is shown along with the relative contribution of shipping emissions in the scenario and the relative difference of the shipping contribution to concentration of air pollutants between simulations with year-2050 land emissions and year-2018 land emissionsFigure 3.18 (Figure 3.19). Comparing the concentration levels in S8 with those in 2018, concentrations of $PM_{2.5}$ in the hotspots have decreased by approximately factor of 2 and factor of 2-3 for NO_2. In S8 shipping contribution to $PM_{2.5}$ is up to 15% with maxima in the ports, over the exposed coastal areas the contributions are approximately 10%. In S3 the relative contributions to $PM_{2.5}$ in ship-emission hotspots reach up to 25% (Figure 3.19a). For NO_2, the relative contribution of shipping to the concentration levels is dominated by shipping in sea areas with heavy ship traffic but also some in exposed coastal areas contributes shipping to NO_2 concentrations is more than 50% (Figure 3.19b). Comparison of scenario simulations with year 2018 and year 2050 land emissions shows differences in shipping contributions between these simulations. For $PM_{2.5}$ the differences are largest in areas with high land emissions, which are the urban areas of Copenhagen and Malmö, where the simulation with year-2018 land emission show lower contribution of the same shipping emissions by up to 20 – 30 %. For NO_2, the differences are the largest in ship emission hotspots. In Helsingborg harbour the NO_2 concentration levels in simulation with the year-2018 land emissions is about 15% lower compared to simulations with the year-2050 land emissions.

a) $PM_{2.5}$



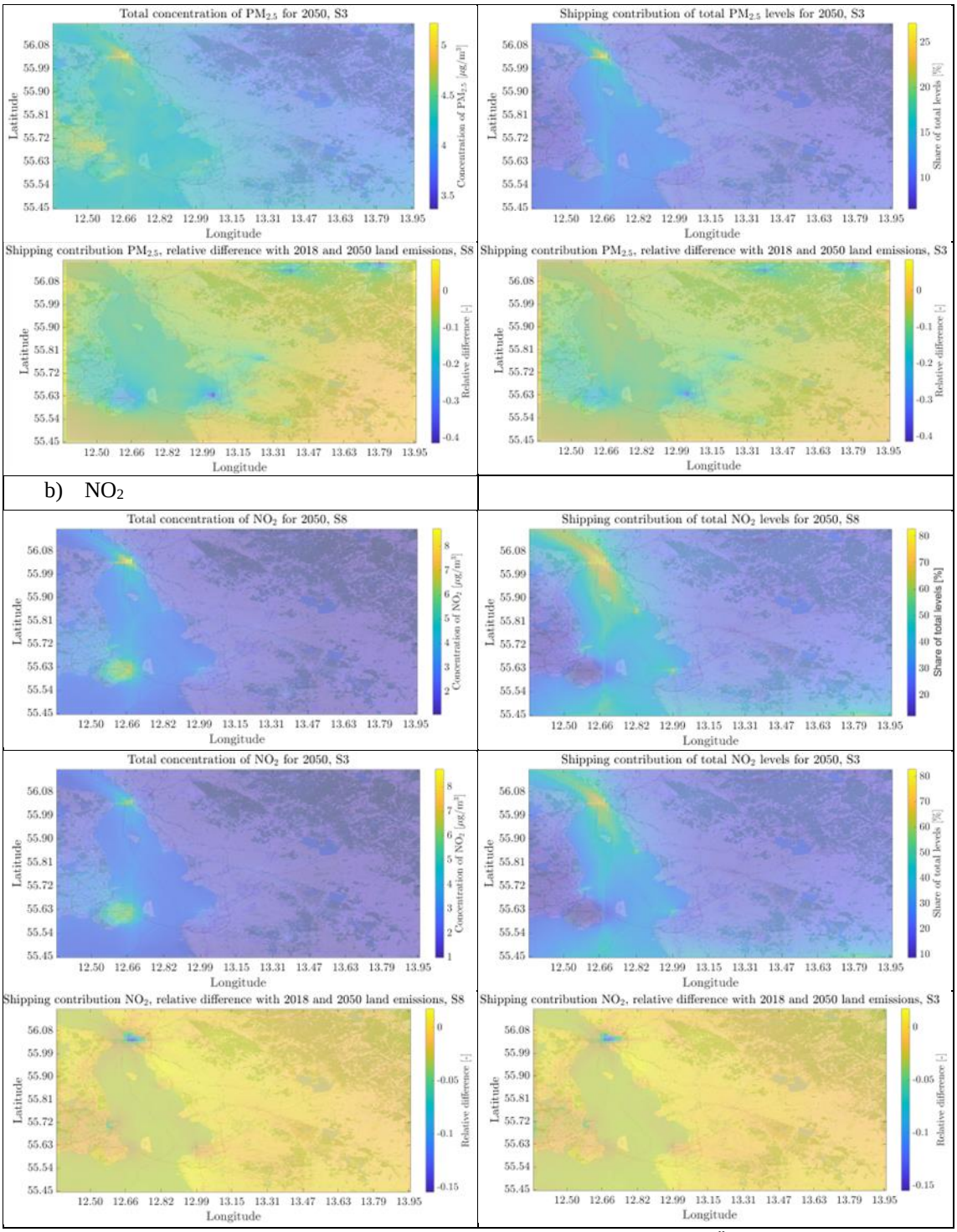


Figure 3.19: (a) Concentrations of $PM_{2.5}$ in scenario S8 in year 2050 in the Öresund CS region (upper left), relative contribution of shipping in scenario S8 in 2050 (upper right), concentrations of $PM_{2.5}$ in scenario S3 in year 2050 in the Öresund CS region (middle left), relative contribution of shipping in scenario S3 in 2050 (middle right), difference between contribution of shipping emissions in scenario S8 to $PM_{2.5}$ with year-2050 land emissions and with year-2018 land emissions relative to the shipping contribution with year-2050 land emissions (lower right), d.t.t.o. for S3 (lower left). (b) Concentrations

of NO_2 scenario S8 in 2050 (upper right), concentrations of NO_2 in scenario S3 in year 2050 in the Öresund CS region (middle left), relative contribution of shipping in scenario S3 in 2050 (middle right), difference between contribution of shipping emissions to NO_2 in scenario S8 with year-2050 land emissions and with year-2018 land emissions relative to the shipping contribution with year-2050 land emissions (lower right), d.t.t.o. for S3 (lower left).

3.5 Impact

The current environmental state, from monitoring data, and the future State change, based on pressures derived from scenario 3 and 8, can be further analysed with respect to potential impact on the marine environment and human health. Air quality and marine modelling efforts show that for scenario 3, we can expect increased concentrations of metals and PAHs in the marine environment while atmospheric $PM_{2.5}$ and NO_X will decrease in the Baltic and North Sea region. Scenario 8, with no scrubbers in operation, will result in less pressure of metals and PAHs on the marine environment and lower $PM_{2.5}$ and NO_X concentrations. Assessing the impact of single compounds will only provide limited information regarding the actual impact. Therefore, the impact assessment of shipping, and in particular the use of open loop scrubbers, was extended using four different concepts:

i) environmental risk assessment of scrubber discharge water was conducted by comparing Predicted Environmental Concentrations (PECs) of scrubber discharge water, in ship lanes in the Öresund case study area, with Predicted No-Effect Concentrations (PNECs) derived from ecotoxicological studies on open loop scrubber exposure (EMERGE D2.3).

ii) the derivation of marine impact indicators (Critical level exceedance of metals and PAHs) and eutrophication from GAINS model. This impact assessment methodology will however be included in EMERGE D6.3 and not presented here.

iii) air pollution emissions and impacts were assessed on a regional scale through the use of GAINS (Years of Life Loss, exceedance of terrestrial eutrophication)

iv) health impact assessment for the Öresund case study area

3.5.1 Risk assessment of scrubber water discharge

As described in EMERGE D.2.4 and references therein, the ecotoxicological response of whole effluent testing of scrubber water cannot be fully explained by the toxicity of the individual substances identified, or their synergistic effects, in scrubber water. Therefore, as a complement to the conventional monitoring and modelling of individual substances (section State), we present an alternative risk assessment approach where the open loop scrubber water is modelled as one entity and the resulting environmental concentrations, as dilution factors, can be compared to Predicted No Effect Concentrations (as percentage scrubber water) from the ecotoxicological tests (EMERGE D2.3). The relation between the concentration of a chemical substance, expressed as either the Measured Environmental Concentration (MEC) or the Predicted Environmental Concentration (PEC) to the Predicted No Effect Concentrations (PNEC) can be expressed as a Risk Characterization Ratios (RCR).

$$RCR = \frac{PEC}{PNEC} \quad (1)$$

If RCR>1, the risk of adverse effects on the environment is denominated as unacceptable. If the RCR ratio is below 1, the risk of adverse effects on the environment is denominated as acceptable. $PNEC_{TGD}$ for open loop scrubber water was derived from EMERGE ecotoxicological studies (APPENDIX VI.1) in accordance with the European Commission Technical Guidance Document (TGD 27) (EC 2018) by a deterministic approach where an assessment factor is applied to the lowest No Observed Effect Concentration (critical $value_{NOEC}$). The details and dataset are included in APPENDIX 0.1.

To estimate PEC of scrubber water in the Öresund region, the dilution was calculated using the MITgcm model (described in EMERGE D4.3), assuming scrubber water as an entity and assigning a sinking velocity (0-10m/day) to the water parcel (open loop scrubber water). The modelled PECs within the Öresund case study surface water (1.5 m) and full depth profiles of 5 locations from the 2018 baseline data (Figure 3.20 and Figure 3.21) are compared to $PNEC_{TGD}$, critical $value_{NOEC}$ and Lowest Observed Effect Concentration (LOEC) based on the ecotoxicological tests of open loop scrubber water exposures. The surface water concentrations in Figure 3.20 show the results from a simulation running from January to July but, due to the pre-defined sinking velocity, can also be interpreted as the resulting PEC from near-time shipping (<2 days). How long it is possible to consider scrubber water as an entity will be further investigated in EMERGE D6.2 but initial results suggests that after two days from discharge, the scrubber water should not be considered an entity,

because it will be diluted close to background concentrations. The vertical profiles in Figure 3.21 show the daily concentration profiles that will vary depending on the discharge rate and the daily conditions, e.g., wind, currents etc. The dilution approach presented here has also been compared to the regional and local modelling of specific substances (Pb, Cd, Fla and B[a]P) in Table 3.4.

The derived $PNEC_{TGD}$ (=2×10^{-6} %) is 500 times lower than the critical $value_{NOEC}$ and 50 times lower than the lowest LOEC (Table 3.6), which should constitute sufficient protection. From the modelling results, discharge of open loop scrubber water will result in environmental exceedance of the derived $PNEC_{TGD}$ which would correspond to unacceptable environmental risks. When comparing PEC with the lowest detected LOEC (0.0001%) and the critical $value_{NOEC}$ (0.001%), there appears to be a risk of adverse effects in several parts of the Öresund surface water as well as in large parts of the water column for the different locations.

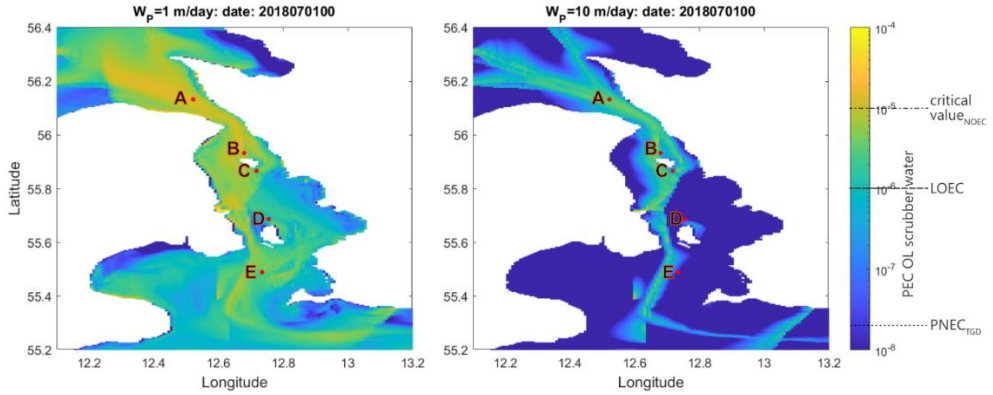


Figure 3.20: Simulations estimating the dilution of scrubber water in the Öresund area at 1.5 meters depth, simulations run from 1st January to 1st of July 2018 with STEAM input of open loop scrubber discharge. Concentrations are expressed as mass scrubber water per mass seawater where the left figure show PEC based on sinking velocity of 1 m/day and the right figure show sinking velocity of 10 m/day. Letters indicate the position of the 5 locations in Figure 3.21. Dotted line shows $PNEC_{TGD}$, dashed line is the lowest LOEC and dotted-dashed line represent the critical $value_{NOEC}$.

The selected locations represent areas of high shipping intensity in potential conflict with marine protected areas (MPAs) and Natura 2000 areas (A, D and E) as well as important fishing grounds (A-C) where discharge of scrubber water may have adverse effects. The results from the modelling of open loop scrubber water distribution represents the ship traffic intensity of 2018 where the number of ships in the Baltic Sea Area were less than 200. The number of vessels equipped with

scrubbers has increased substantially since and therefore the 2018 results should be interpreted as a lower estimate of risk.

Table 3.6: Calculated threshold value, corresponding dilution ratio and whole effluent concentration for $PNEC_{TGD}$, critical $value_{NOEC}$ and LOEC.

	Threshold value (%)	Dilution ratio	Whole effluent concentration
$PNEC_{TGD}$	2×10^{-6}	5×10^{7}	2×10^{-8}
Critical $value_{PNEC}$	1×10^{-3}	1×10^{5}	1×10^{-5}
LOEC	1×10^{-4}	1×10^{6}	1×10^{-6}

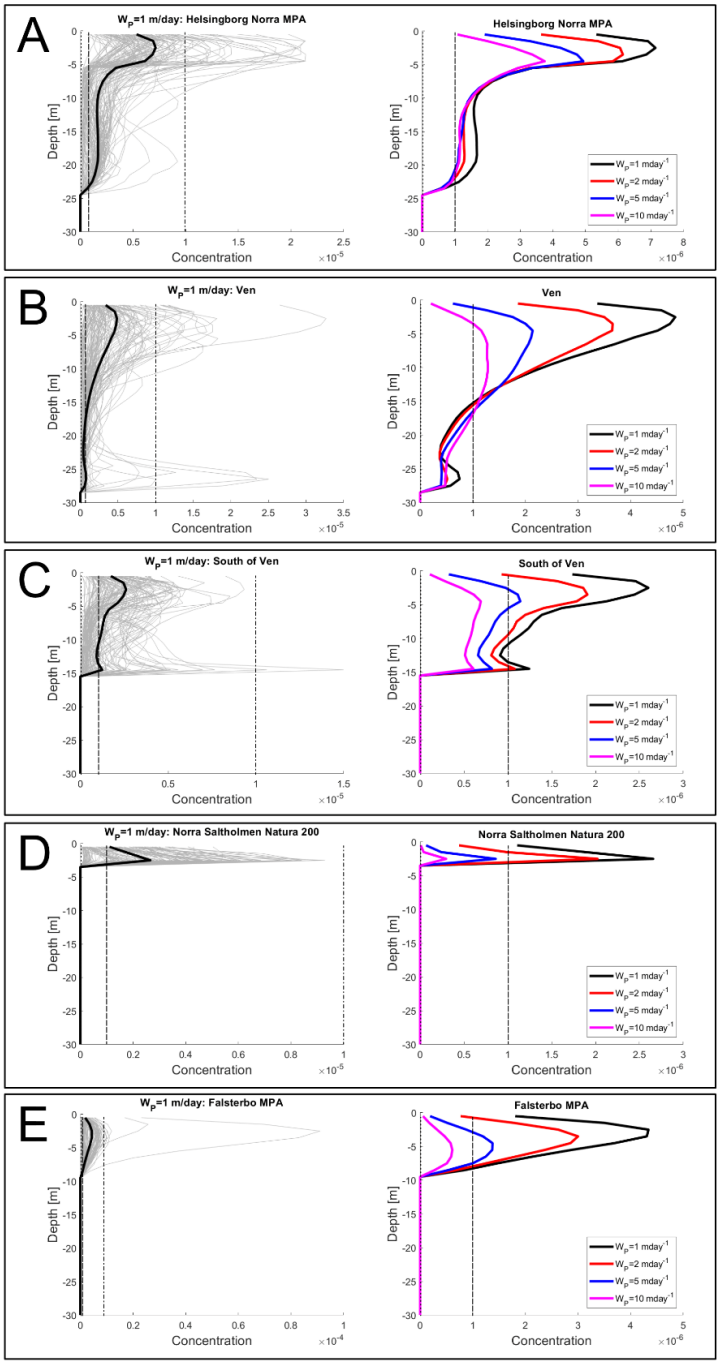


Figure 3.21: Daily snap-shot concentration profiles over depth at 5 selected positions (Figure 3.20) from May to August (average is bold line) at sinking velocity WP=1 m/day (left) and average at different WP (right). Dotted line shows $PNEC_{TGD}$, dashed line is the lowest LOEC and dotted-dashed line represents the critical $value_{NOEC}$.

Based on the low effect concentrations from the ecotoxicological tests (APPENDIX VI – Impact and EMERGE D2.3) we conclude that the toxicity of scrubber water cannot be fully explained by the concentration of the analysed single substances in the scrubber water, indicating potential synergistic effects. In previous work (EMERGE D2.4), a PEC/PNEC summation approach was applied for metals and PAHs (including alkylated PAHs) in the scrubber water to predict the risks for adverse effects from mixture exposure. The results indicated that alkylated PAHs, although rarely included in scrubber water analysis, contribute to >85% of the cumulative risk of open loop scrubber water. Also, scrubbers were shown to have the highest contribution to risk of all waste streams, where open loop scrubbers contributed to more than 99% of the total volume weighted summarised risk (EMERGE D2.4). In a recent paper (Lunde Hermansson et al. 2023), marine environmental risk in ports was assessed with respect to 9 metals and the 16 US-EPA PAHs from different onboard sources (based on 2018 ship activities), both separately and cumulatively. The results showed that three out of four ports were subject to unacceptable risk and that leakage of copper in antifouling paints and discharge of open loop scrubber water were the main contributors to the cumulative risk. Although not fully understood, the results suggest that increased scrubber activity, i.e., increased pressure of scrubber discharge water, will result in adverse effects on marine biota. Both single substances, as well as whole effluents, should be included when assessing the toxicity and potential effects prior to any discharge.

3.5.2 Human health indicators and terrestrial ecosystems indicators

We utilized the GAINS model to assess the impact of shipping activities on the regional scale. We employed three metrics to quantify the impact on human health and ecosystems, outlined as follows:

Years of Life Lost (YOLLs) from $PM_{2.5}$: The YOLL is a key indicator to quantify the impact on human health, measured in months of life lost. In the GAINS-Europe model version, the YOLL metric represents the loss of life expectancy attributable to exposure to outdoor ambient fine particulate matter below 2.5 µm aerodynamic diameter ($PM_{2.5}$) from anthropogenic emission sources. The model processes emissions of all $PM_{2.5}$ precursor emissions in ambient air, including primary $PM_{2.5}$, SO_2, NO_X, NH_3, and volatile organic compounds (VOCs). These emissions are fed into an atmospheric dispersion model to compute annual mean concentrations of $PM_{2.5}$. GAINS employs reduced-form source-receptor relationships and linear transfer coefficients with a native resolution of 0.5° x 0.25° (roughly 28 x 28 km) derived from brute-force perturbation simulations

employing the European Monitoring Evaluation Programme (EMEP) atmospheric Chemistry-Transport Model (CTM) (Simpson et al. 2012). Population exposure is determined by overlaying the calculated ambient $PM_{2.5}$ levels with projected population data on the same grid from the University of Southampton's WorldPop dataset (https://hub.worldpop.org/project/categories?id=3) The cohort- and country-specific mortality data are extracted from life table statistics from the United Nations World Population Prospects (UN 2017). Eventually, the loss of life expectancy due to exposure to ambient $PM_{2.5}$ is estimated using a Cox proportional hazards model (Cox 1972), assuming constant cohort exposure throughout their lifetime.

Exceedance of the terrestrial acidification and eutrophication Critical Loads (CLs) for terrestrial ecosystems: Those two indicators are relevant to quantify the impacts of total sulphur (S) and nitrogen (N) deposition on ecosystems, including forests, catchments, and semi-natural ecosystems. Following the methodology recommended in the Mapping Manual of the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) (Umweltbundesamt 2004), the GAINS model computes exceedances of the acidification and eutrophication CLs for all European countries due to total N and S deposition, and total N deposition, respectively. Total N is calculated as the sum of oxidized (NO_X) and reduced (NH_4) N compounds. The GAINS model notably considers SO_X and NO_X emissions to compute those exceedances. However, NH_3 emissions are not included in the impact assessment, and therefore, the ammonia slip from SCR remains unquantified. Both acidification and eutrophication CLs are mapped at a 0.5° x 0.25° resolution and reported below as a percentage of the total ecosystem area within a grid cell for which the CLs are exceeded. The CLs utilized are those approved by the CLRTAP in 2017 (Hettelingh et al. 2017).

We present impact maps below for the exceedance of eutrophication CLs and YOLLs from $PM_{2.5}$ for the EMERGE scenarios 3 and 8 in 2050. Those maps encompass contributions from both land-based and shipping sources. Due to non-linearities in the computations of GAINS-Europe transfer coefficients concerning emission sources, isolating the shipping contribution from a specific scenario run is not feasible. Instead, we assess the shipping contribution by comparing the differences between two scenarios (here, S3 and S8) for a given year, while maintaining the land-based emission sources identical.

Land-based (i.e., "non-shipping") sources, encompassing power plants, industry, land-based transport, agriculture, and waste, among others, are covered from existing GAINS projections of

the ECLIPSE scenario family. Conversely, shipping sources are directly derived from STEAM model runs and integrated into the existing ECLIPSE scenarios.

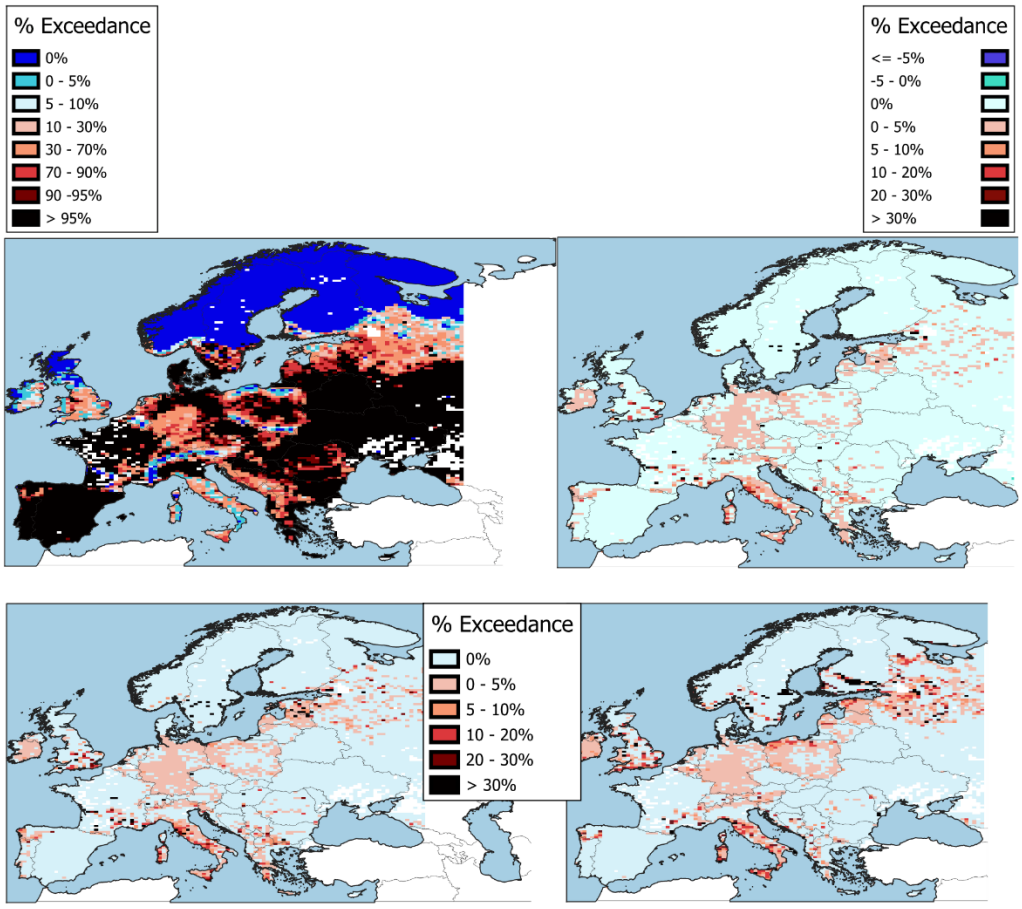


Figure 3.22: Percentage of total terrestrial ecosystem area exceeding eutrophication critical loads for Scenario S8 (top left panel), the difference between Scenarios S8 and S3 (top right panel), the shipping contribution in Scenario S8 (bottom left panel), and the shipping contribution in the baseline Scenario (bottom right panel). Exceedance share in white grid cells was not computed due to data unavailability.

Figure 3.22 above shows, in the top left panel, the proportion of the total ecosystem area within a grid cell for which the eutrophication CLs are exceeded for Scenario S8 in 2050, considering all sources. In the top right panel, the differences of share of exceedances between Scenarios S8 and S3 are shown, representing the shipping contribution corresponding to the scenario switch. Negative values in the right panel indicate that the share of exceedance is higher in S3 compared to S8.

The top left panel of Figure 3.22 indicates that by 2050, most European areas are still severely affected by eutrophication, except for the Scandinavian countries. A change in emissions and subsequent deposition of atmospheric trace constituents may have zero effects on the extent of total ecosystem area exceeding the critical loads, as long as these changes remain below criticality. Some areas, like Eastern and South-Western Europe, have up to 100% of their ecosystem areas exceeding eutrophication CLs. Also here, changes might not appear as long as all areas remain above the critical value. Hence, the top right panel of Figure 3.22 shows that the differences in impact between Scenarios 3 and 8 are mainly observed in Germany and Italy, accounting for up to 20-30% of exceedance of the total ecosystem area within most effected grid cells. Substantial areas show no change at all (depicted in light blue, representing 0%).

The higher eutrophication impact of scenario 8 with respect to scenario3 is attributed to its higher NO_X emissions, particularly in the Mediterranean Sea, Celtic Sea, and the Bay of Biscay. This is mainly due to the lower use of SCR for NO_X abatement in Scenario 8. Although the NH_3-slip arising from the extensive use of SCR in scenario 3 is not quantified in the present analysis, the associated increase of N-NH_3 is more than compensated by the decrease of N-NO_X (NH_3 slip makes up < 5% in weight N of NO_X decrease).

The lower panels of Figure 3.22 represent the shipping contribution to eutrophication impacts for Scenario 8 (bottom left panel) and the baseline scenario (bottom right panel). These contributions are estimated by comparing the differences between a scenario including all emission sources and a scenario without shipping emissions for their respective scenario years. Exceedances are in similar areas to those shown in the top-right panel. Similarly, other substantial areas show no change at all, as they correspond to areas where land-based sources already contribute to 100% of the total ecosystem area exceeding eutrophication CLs. Although both shipping contributions remain relatively similar to each other, with exceedance shares constrained to up to 20-30%, the baseline scenario reveals more highly affected areas by eutrophication compared to Scenario S8, like around the Gulf of Finland and the Gulf of Bothnia. This can be attributed to higher NO_X emissions in the baseline scenario compared to Scenario S8, with areas in the Baltic and North Seas accounting for almost four times higher NO_X emissions.

The results obtained for the metric of exceedances of acidity CLs follow similar trends to those presented above (Figure A.VI- 1 and Figure A.VI- 2).

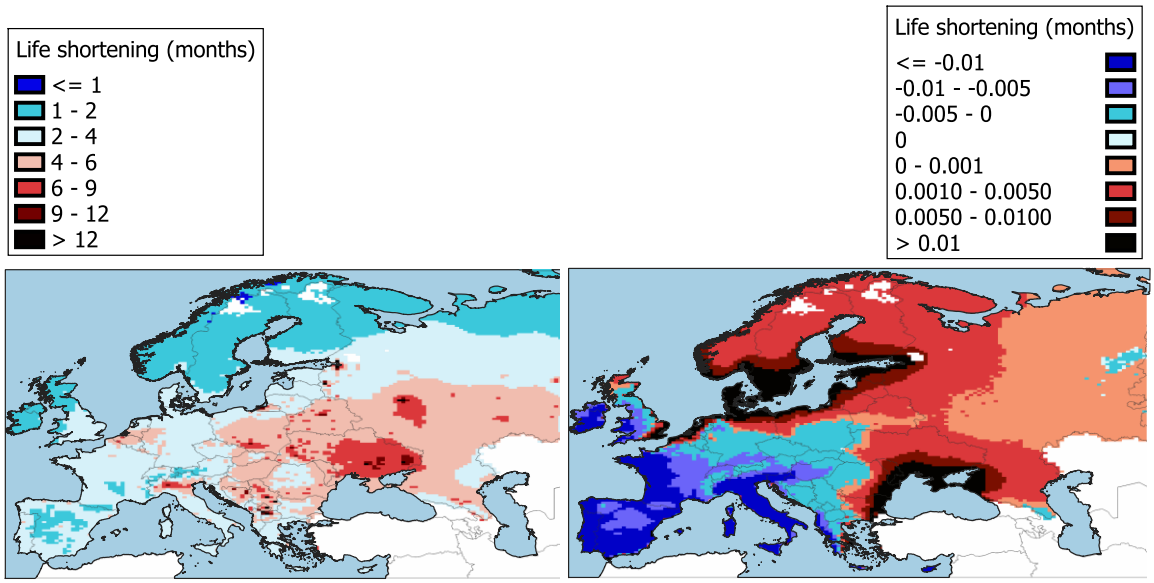


Figure 3.23: Life expectancy loss attributable to $PM_{2.5}$ exposure, expressed in months of life lost, for the Scenario S3 (left panel) and the difference between Scenarios S3 and S8 (right panel).

Figure 3.23 above displays, in the left panel, the loss of life expectancy attributable to $PM_{2.5}$ exposure, expressed in months of life lost, for Scenario 3 in 2050, considering all sources. On the right panel, the differences in life shortening between Scenarios 3 and 8, representing the shipping contribution corresponding to the scenario switch, are shown. Negative values in the right panel indicate that the life shortening is higher in 8 compared to 3.

The left panel of Figure 3.23 indicates that, by 2050, the loss of life expectancy in most areas around the Baltic Sea is limited to two to four months. The most impacted areas are located in Central and Eastern Europe, with the worst grid cells corresponding to a loss of more than a year of life. However, the right panel of Figure 3.23 shows that differences in life shortening between Scenarios 3 and 8 are two to three orders of magnitudes lower than health impacts resulting from all sources displayed in the left panel.

It is noteworthy to mention that human health impacts are higher in scenario 3 compared to 8 in specific sea areas only, like around the Baltic, North, and Black Seas. This difference is likely attributable to variations in $PM_{2.5}$ precursor emissions between the two scenarios. For instance, SO_X and $PM_{2.5}$ emissions are up to eight times larger in scenario 3 than in scenario 8 in the Baltic and Black Seas. However, NO_X emissions in scenario 3 are two to four times lower than in scenario 8 in almost all Sea areas.

3.5.3 Human health indicators – Solent Strait

Triangulation of the GAINS health impact assessment for the Baltic Sea was undertaken for the Solent region using a statistical approach for $PM_{2.5}$. We utilised the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to complete a systematic review and then made use of PRISMA's Synthesis Without-Meta Analysis (SWiM) extension to analyse the collected data (Campbell et al., 2020, Page et al., 2021). Calculations regarding premature deaths attributable to shipping air pollution were undertaken following guidelines for estimating local mortality burdens associated with particulate air pollution published by Public Health England (PHE) (PHE, 2014).

The systematic review resulted in the development of three scenarios for the estimation of mortality burdens:

1) *High $PM_{2.5}$ Contribution Scenario (above 10%),* where the average percentage contribution was found to be 14.6% [highest – 20%, lowest – 11%];
2) *Mid $PM_{2.5}$ Contribution Scenario (5.5-10%),* where the average percentage contribution was found to be 8.6% [highest – 10%, lowest – 6%], and;
3) *Low $PM_{2.5}$ Contribution Scenario (5% and less),* where the average percentage contribution was found to be 2.6% [highest – 5%, lowest – 0%].

Subsequently, local mortality burdens were estimated in Southampton, Portsmouth, Poole, Bournemouth & Christchurch using the three scenarios (Table 3.7).

In the first 'high contribution' scenario, 0.7% of premature deaths were found to be attributed to shipping-related air pollution. In the second, 'mid contribution' scenario', 0.4% of premature deaths were found to be caused by shipping-related air pollution. In the third 'low contribution' scenario, only 0.1% of premature deaths were caused by air pollution arising from shipping (Table 3.1).

Overall, the calculations suggest a decreasing trend in the number of premature deaths attributable to shipping, which is parallel to the overall reductions in $PM_{2.5}$ concentrations. Such relationship can be, for example, seen from 2018 to 2019 where the largest decrease in premature deaths occurred in a span of one year. Despite the reduction in premature deaths in Poole, Bournemouth & Christchurch over the years, the contribution from shipping to $PM_{2.5}$ concentrations seems to change only marginally.

Table 3.7: Overview of the number of premature deaths caused by shipping air pollution in three Solent locations using high, medium, and low scenarios.

Year	Southampton (%)	Portsmouth (%)	Poole, Bournemouth, Christchurch (%)	Total* (%)
		Scenario 1 (Contribution: 14.6%)		
2013	23 (1.2%)	N/A	35 (0.8%)	58 (0.7%)
2014	21 (1.2%)	21 (1.2%)	35 (0.8%)	77 (1%)
2015	15 (0.8%)	14 (0.8%)	37 (0.8%)	66 (0.8%)
2016	18 (0.9%)	17 (1%)	36 (0.8%)	71 (0.9%)
2017	18 (0.9%)	17 (1%)	36 (0.8%)	71 (0.9%)
2018	21 (1.1%)	17 (1%)	30 (0.7%)	68 (0.9%)
2019	15 (0.8%)	12 (0.7%)	29 (0.7%)	56 (0.7%)
2020	14 (0.7%)	N/A	32 (0.7%)	46 (0.5%)
2021	14 (0.7%)	N/A	N/A	14 (0.2%)
				587
		Scenario 2 (Contribution: 8.6%)		
2013	13 (0.7%)	N/A	21 (0.5%)	34 (0.4%)
2014	13 (0.7%)	12 (0.7%)	20 (0.5%)	45 (0.6%)
2015	9 (0.5%)	8 (0.5%)	22 (0.5%)	39 (0.5%)
2016	11 (0.6%)	10 (0.6%)	21 (0.5%)	42 (0.5%)
2017	11 (0.6%)	10 (0.6%)	21 (0.5%)	42 (0.5%)
2018	12 (0.6%)	10 (0.6%)	18 (0.4%)	40 (0.5%)
2019	9 (0.5%)	7 (0.4%)	17 (0.4%)	33 (0.4%)
2020	8 (0.4%)	N/A	19 (0.4%)	27 (0.3%)
2021	8 (0.4%)	N/A	N/A	8 (0.1%)
				310
		Scenario 3 (Contribution: 2.6%)		
2013	4 (0.2%)	N/A	6 (0.1%)	10 (0.1%)
2014	4 (0.2%)	4 (0.2%)	6 (0.1%)	14 (0.2%)
2015	3 (0.1%)	3 (0.1%)	7 (0.1%)	13 (0.2%)
2016	3 (0.2%)	3 (0.2%)	6 (0.1%)	12 (0.1%)
2017	3 (0.2%)	3 (0.2%)	6 (0.1%)	12 (0.1%)
2018	4 (0.2%)	3 (0.2%)	5 (0.1%)	12 (0.2%)
2019	3 (0.1%)	2 (0.1%)	5 (0.1%)	10 (0.1%)
2020	2 (0.1%)	N/A	6 (0.1%)	8 (0.1%)
2021	3 (0.1%)	N/A	N/A	3 (0.03%)
				94
***Total number of premature deaths excludes premature deaths in Portsmouth in 2013, 2020 and 2021, and in Poole, Bournemouth & Christchurch in 2021**				

This statistical approach suggests that a relatively small fraction of all premature deaths in Southampton, Portsmouth, Poole, Christchurch & Bournemouth are attributable to air pollution from shipping.

3.5.4 Human health indicators in Öresund case study area

The health impacts of exposure of the population in the Öresund CS domain to shipping-related air pollutants were assessed with the ALPHA-RiskPoll (ARP) methodology (Holland et al. 2013), which provides basic data necessary for the calculation of a wide range of air-pollutant-specific health effects based on the population weighted concentrations. In particular, these are national population statistics on age distribution of the population, mortality and morbidity data and effect-specific exposure–response relationships. The methodology has been developed and used for the quantification and assessment of the benefits of air pollution controls in Europe for the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP). It is based on work for the Clean Air For Europe (CAFE) program and on the EU project Modelling of Air Pollution and Climate Strategies (EC4MACS), following WHO recommendations (WHO 2013) and the CAFE cost–benefit analysis methodology for the assessment of health impacts of air pollutants. In this study only the most serious impacts (i.e. loss of life) are presented, taking into account the impacts of long-term exposure to PM2.5 and short-term exposure to ozone, i.e. the impacts marked A* in the HRAPIE study (WHO 2013). The health impacts of some pollutants are correlated, and that is why the premature deaths attributed to each pollutant cannot simply be added up.

Table 3.8: The main health impacts from shipping in the Öresund Case Study domain (including the total impacts from air pollution in year 2018): Life years Lost (YOLLs), deaths and life shortening from long-term exposure to $PM_{2.5}$, deaths due to the acute exposure to ozone and loss of working days from exposure to $PM_{2.5}$.

*** Exposure based on EMEP simulations with year-2050 land emissions**

Headline impacts, Öresund case study					
Driver	PM2.5 Life Years Lost	PM2.5 Deaths	Life shortening (months)	Ozone deaths	Loss working days (PM2.5)
Total 2018	9 901	1 005	3	61	263 439
Shippig 2018	1 129	115	0.3	5	30 145
Shipping 2050 S3	427	57	0.1	n.a.	1 164
Shipping 2050 S3*	476	63	0.1	6	13 189
Shipping 2050 S8	331	44	0.1	n.a.	9 180
Shipping 2050 S8*	373	49	0.1	8	10 331

3.6 Response and measures

Until now, most social, and economic analysis of shipping have focused on air pollution assessment and how shipping may impact climate change and human health (Amann et al. 2011, Åström et al. 2018). This risks policies to be biased towards air pollution and climate change, while trading off impacts on the marine environment. One example is the IMO global sulphur cap which requires shipowners to use a compliant fuel with a sulphur content of 0.5% (0.1% in SECA regions) or use compliance options (scrubbers) that are as effective in reducing SO_X emissions to the atmosphere (IMO 2020). While the regulations for sulphur emissions to the atmosphere are mandatory, the discharge water from scrubbers is subject only to guidelines with respect to pH, PAHs, nitrate and turbidity, which in practice implies that the untreated effluent water can be discharged directly to the marine environment. The decision by IMO to allow scrubbers as a compliant method was not based on any risk or impact assessments on how wide-scale use of scrubbers could impact the marine environment (Hassellöv et al. 2020, ICES 2020). Therefore, one objective of EMERGE has been to bridge this knowledge gap by performing various impact and risk assessments on how the use of scrubbers impact the marine environment, health, climate and economy.

EMERGE environmental risk assessment shows unacceptable risks of using open loop scrubbers

In the EMERGE marine environmental risk assessment, modelled predicted environmental concentrations (PECs) of open loop scrubber discharge water in the Öresund region are compared to a tolerable marine threshold value ($PNEC_{TGD}$). Assuming a sinking velocity of scrubber water of 1 m/day, the results showed the concentrations of scrubber water to exceed the $PNEC_{TGD}$ at 1.5 m depth in almost the entire Öresund region. The results also showed the concentrations of open loop scrubber water in Öresund ship lanes to regularly be higher than lowest observed effect concentrations (LOECs), known to cause adverse effects on larvae and embryo development of sea urchins, reef-forming polychaetes and blue mussels (Table 3.6). Notably, the modelling of open loop scrubber discharge water was performed using the ship traffic activity of 2018 where only less than 200 ships used scrubbers in the Baltic Sea (Figure 3.2), which in total released 192 million tonnes discharge water (Figure A.IV- 1). Since 2018, the number of ships equipped with scrubbers operating in the region has increased rapidly to almost 800 in 2022 (Figure 3.2), resulting in a yearly discharge of 312 million tonnes (Figure A.IV- 1). The high scrubber scenario (scenario 3) indicates that the volume of scrubber water discharge in the Baltic Sea may be considerably higher in 2050

(1740 million tonnes), i.e., almost one order of magnitude higher as compared to our baseline scenario in 2018. Hence, if the environmental risk assessment would have been carried out using 2022 or scenario 3 (2050) ship activities, the EMERGE result would have shown an even higher unacceptable environmental risk due to open loop scrubber discharges. Even though the environmental risk assessment is limited to the Öresund region, it should be emphasized that the discharges of scrubber water in the North Sea show a similar increased pressure of discharge water with yearly inputs in 2018, 2022 and scenario 3 (2050) of 170, 490 and 2130 million tonnes, respectively.

EMERGE load compilation shows scrubbers to be a large source of metals and PAHs to the Baltic Sea

Our compilation of loads of metals and PAHs to the Baltic Sea from scrubbers in relation to other natural and anthropogenic sources show the input from scrubbers to be substantial. For example, the load of Ni from scrubbers accounts for 1.7% of the total input in 2018. This share increased to over 10% of the total input in scenario 3 (2050). For V, the contribution from shipping to the Baltic Sea could only be compared with the source of atmospheric deposition. The input from scrubbers in 2018 is higher (41 tonnes) compared to the atmospheric deposition (31 tonnes). This load can also be compared to riverine input from Swedish rivers which is 47 tonnes (Sweden is the only contracting party of HELCOM that monitor and report V input from rivers to HELCOM). The load of V in scenario 3 (2050) from open loop scrubbers is as high as 297 tonnes, while the closed loop mode scenario (scenario 3b) showed lower inputs (80 tonnes). For PAHs, Ytreberg et al. (2022) showed open loop scrubbers to account for almost 9% of the total input of anthracene and phenanthrene to the Baltic Sea in 2018. These are only two out of the 16 PAHs prioritized by the US-EPA normally monitored in European waters, and a small fraction of the many polycyclic aromatic compounds (PACs) shown to be present in scrubber effluents (D2.2) and known to be both toxic and bioaccumulating.

EMERGE Impact assessment, following MEPC guidelines (MEPC 2022a), shows that a ban on discharge water from scrubbers should be considered in the entire Baltic and North Sea region

Regarding the environmental status assessment, as reported by EU member states, all sea basins in the Baltic and North Sea region fail to reach GES as defined by the MSFD, both aggregated and

with respect to D8 (Contaminants). Following the MEPC guidelines on recommended impact assessments that Member States should follow when considering local or regional regulations to protect the sensitive waters/environment from the discharge water from scrubbers, a ban on discharge water from scrubbers should be considered in areas where *environmental objectives in the areas are not met, e.g., good chemical status, good ecological status or GES are not achieved under applicable legislation.* Hence, according to the MEPC guidelines, a ban should be considered in the entire Baltic and North Sea region.

Programmes of measures should be implemented in the Baltic and North Sea region in order to achieve GES

According to the EU MSFD, EU Member States shall develop marine strategies including implementing programmes of measures designed to achieve or maintain GES. None of the Baltic or North Sea basins fulfil GES and EMERGE results have shown scrubbers to be one of the largest anthropogenic sources of some PAHs and metals. However, according to MSFD Article 14 (4), *Member States should not be required to take specific steps where there is no significant risk to the marine environment, or where the costs would be disproportionate taking account of the risks to the marine environment, provided that any decision not to take action is properly justified*. The environmental risk assessment summarized in the beginning of this chapter clearly shows scrubbers to pose an unacceptable risk to the marine environment. However, the costs for the shipping sector that such a measure (ban of discharges from scrubbers, i.e. in practice a ban on scrubbers) would entail, has been questioned within the IMO (MEPC 2022b). In EMERGE, several aspects connected to the potential restriction of scrubber water discharge have been investigated. More specifically to i) estimate to what extent the global scrubber fleet has reached break-even on their scrubber installations and the potential monetary gain of using HFO as compared to the more expensive MGO or VLSFO and ii) to assess external costs of not restricting scrubber water discharge by determining societal damage costs connected to marine ecotoxicity, i.e. deterioration of the marine environment, resulting from discharge of scrubber water. The analyses are based on nine years of real-world simulations of global vessel activity (2014-2022) from STEAM. The results show that 51% of the global scrubber fleet had reached break-even by the end of 2022 and the summarised balance amounts to 4.7 billion €$_{2019}$. Also, the marine ecotoxicity damage cost, by not restricting scrubbers in the Baltic Sea Area, cumulates to >680 million €$_{2019}$ from 2015 to end of 2022, showing the conflict of interest between private monetary gain and external societal costs (Lunde Hermansson et al. in prep.).

Future scenarios decrease the shipping contribution to $PM_{2.5}$ exposure.

When comparing the impacts of the future scenario emissions on exposure in Öresund and Solent regions both scenarios (3 and 8) decrease the shipping contribution to $PM_{2.5}$ exposure. Scenario S8 is somewhat more efficient in decreasing the shipping originated $PM_{2.5}$ than scenario 3. Regarding NO_2, scenario 3 shows a better reduction of NO_2 exposure than scenario S8, mainly due to the lower use of SCR for NO_X abatement in Scenario 8.

GAINS result show minor difference in health impact due to different shipping scenarios

The GAINS human health impact assessment for scenario 3 show the loss of life expectancy in most areas around the Baltic Sea to be limited to two to four months, considering all sources. The differences in life shortening between Scenarios 3 and 8 are, however, two to three orders of magnitudes lower than health impacts resulting from all sources, indicating that scrubbers alone have a minor impact on the human health indicator in the Baltic region. Health impact assessment performed with Alpha Riskpol model for the Öresund Case study shows similar results in terms of loss of life expectancy, with c.a. 3-fold decrease from year 2018 to 2050. Compared to the overall health impacts in the region, contribution from shipping in year 2018 is approximately 10% of the total. The year-2050 simulations show that the future relative contribution of shipping emissions to overall health impacts will be of similar magnitude, i.e., 7-9%. Scenario S8 appears to be 20% more effective than S3 regarding the PM-related health impacts. On the other hand, results from GAINS show a higher percentage of land-based ecosystems to exceed eutrophication critical loads in scenario 8 compared to scenario 3. The higher eutrophication impact of scenario 8 is attributed to its higher NO_X emissions, particularly in the Mediterranean Sea, Celtic Sea, and the Bay of Biscay. This is mainly due to the lower use of SCR for NO_X abatement in Scenario 8 as compared to Scenario 3.

Policy measures

Restrictions or ban on scrubbers have been implemented in 45 countries globally targeting territorial waters and/or ports (ICCT, 2023). However, approximately 75% of the discharge of scrubber water originates from international shipping, that is regulated globally at IMO level. IMO Member States, Regional Seas Conventions, such as HELCOM and OSPAR, and the EU can act individually on a local/regional level, with regional and local regulations, but should also pursue the issue on a global level within IMO. A global decision would contribute to fair regulations and

restrictions, equal to the entire fleet, and would reduce the risk of great resources being spent on ensuring compliance with the different local regulations.

Finally, it is important to consider whether the environmental assessment incorporates a holistic perspective, an ecosystem approach and foremost the precautionary principle on which it should be based. The ERA which has been used in the EMERGE project is designed to strongly condense ecotoxicological information. In order to achieve a holistic, ecosystem-based impact assessment it is therefore important also to report other science based ecotoxicological results and possible ecosystem effects that have been observed. Important information may otherwise be lost, and the assessment will fail to fulfil its task, to protect marine biodiversity and important ecosystem functions. The precautionary principle originates from principle 15 of the Rio declaration on sustainable development (UN 1992) and states that "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation". The expectation on any assessment should therefore be that the calculated outcome will automatically lead to protection of the ecosystem and where scientific information is scarce or lacking this should be evident and clearly flagged. The expectation on UN bodies like the IMO, the EU as responsible for implementing the Integrated Maritime Policy (IMP), and member states of those unions should thus be to react to any indications of environmental deterioration in response to new pollution sources, such as scrubbers, and act according to the precautionary principle.

4 CONCLUSIONS

In Deliverable 6.1, we have successfully developed a holistic framework to evaluate the impacts of shipping emissions, with a focus on scrubbers, on the marine environment, health, climate, and economy. Our assessment followed the DAPSIR framework to analyse environmental pressures arising from the activity shipping (and the use of scrubbers) and to identify and propose measures to reduce and mitigate the pressures and impacts from shipping.

The EMERGE compilation of loads of metals and PAHs to the Baltic Sea from scrubbers in relation to other natural and anthropogenic sources show the environmental **pressure** from scrubbers to be substantial, with up to almost 10% of the total input of different PAHs. Also, the results indicated that alkylated PAHs, although rarely included in scrubber water analysis, contribute to >85% of the cumulative risk of open loop scrubber water.

The **EMERGE marine environmental risk assessment,** conducted in the Öresund region, showed modelled PEC of open loop scrubber water in large areas to be two to three orders of magnitude higher than the derived $PNEC_{TGD}$ (2×10^{-8}), i.e. yielding a PEC/PNEC-ratio of 500-5000. Hence, the results clearly show that the discharges of open loop scrubber water pose an unacceptable environmental risk for adverse effects in the Öresund region. It should also be noted that the risk assessment was conducted based on ship activity (and emissions) in 2018, after which the number of ships equipped with scrubbers in this region has increased rapidly (from 200 in 2018 to 800 in 2022). Triangulation of the impact assessment for the Baltic Sea, undertaken for the Solent region using a statistical technique, corroborated the conclusion that the deployment scrubbers alone has a minor impact on human life shortening.

The **EMERGE impact assessment**, following MEPC guidelines (MEPC, 2022a), shows that a ban on discharge water from scrubbers should be considered in the entire Baltic and North Sea region as the entire sea region fails to achieve good environmental status. Finally, **the EMERGE cost assessment** shows that 51% of the global scrubber fleet had reached break-even, with respect to their scrubber installation costs, by the end of 2022, with an overall surplus of 4.7 billion $€_{2019}$. Based on the results from the **EMERGE assessments of scrubbers,** adopting a ban on discharge of scrubber water is scientifically justified in the Baltic Sea and the North Sea region.

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APPENDICES

APPENDIX I – Synthesis of previous work

Deliverable	Brief description	Connection to other deliverables in D.6.1	Output used in D.6.1	Connection to DAPSIR
1.3 Emission values based on the STEAM model	Refinement of STEAM for emission data to water and air.	Feed into WP3 and 4 on water modelling. Scenarios depending on 1.4	Indirectly to provide input data to modelling of water and air quality	Activity, Pressure
1.4 Description of scenarios to be used in EMERGE	Definition of 2050 scenarios	Determination of future scenarios to be compared and modelled.	Indirectly to provide input data to modelling of water and air quality.	Driver, Response
2.1 Database and analysis on waste stream pollutant concentrations, and emission factors	Concentrations of metals and PAHs in different ship related waste stream	Calculation of PEC/PNEC (2.4). Contaminant addition to feed into ChemicalDrift (4.).	Indirectly to provide input data to modelling of water concentrations. Comparison of loads depending on scenarios.	Activity, Pressure
2.2 Report on measurements of dissolved and particulate contaminants in case study regions	Chemical analysis results of scrubber water	Provide contaminants loads in combination with discharge volumes from 1.2 (STEAM). More input to 2.1 database. Characterisation of scrubber water used in exposure tests (2.3). Mass-balance calculations with WP3. MEC/PNEC calculations (2.4).	Indirectly to provide input data to modelling of water concentrations.	Pressure
2.3 Report on scrubber water whole effluent toxicity testing, at different geographical regions	Ecotoxicological tests scrubber water	Assessment of modelling results (WP4) and dilution of scrubber water. Impact assessment WP7 (decision support tool).	NOEC, LOEC % scrubber water.	Impact
2.4 Original title: Multivariate assessment of eco-toxicological response of waste waters Proposed title: Predicting potential toxicity of scrubber discharge water	Predicting toxicity of scrubber water (MEC/PNEC) and compare to observed toxicity. Identification of other relevant compounds, e.g., alkylated PAHs.	Identification of relevant substances and prioritization of substances by assessing 2.1, 2.2 and 2.3.	Selection of substances to include in full synthesis.	Pressure, State, Impact
3.3 Dataset of emission factors	Emission factors (air) to be used in STEAM model	Input to STEAM output (1.3). Input to atmospheric modelling (WP5) and water modelling (through **deposition**) WP4.	Indirectly to provide input data to modelling of water and air quality	Activity, Pressure

4.2 Baseline concentrations of sea water pollutants	European scale simulations for baseline year 2018.	Connected to water (4.3) and atmospheric (WP5) modelling.	Provide starting conditions for marine environmental concentration comparison (baseline year).	State
4.3 Predicted effects of ship emissions on biogeochemistry and contamination of marine biota			Model output from water modelling to assess State (different scenarios) and Impact (from comparison to ecotoxicological effects).	State, Impact
5.4 Report and datasets on concentration and exposure for health assessments in WP6	Analysis of the changes in air quality and deposition resulting from atmospheric emissions from shipping.		Deposition to be used in water modelling (4.3) and integrated health assessment.	State, Impact
6.4 Decision support tool	Decision support tool to be used on case study levels	Integrate water (WP4) and atmospheric (WP5) modelling to assess environmental impact (WP2) and cost (WP1)	Provide decision support for different scenarios in case study area	Impact, Response
D5.1 Shipping emission dataset for air quality models	Providing baseline modelling (2018) and generate emission scenarios to 2050	Ship emission dataset to be used in 5.3 and 5.4 and deposition to water modelling (4.3).	Indirectly by input to air quality models and deposition to water modelling	
5.3 Report and datasets on shipping contribution to air quality in Europe and case study areas	Global and regional air pollution and the contribution of shipping emissions for scenarios of Task 1.4 and for the EMERGE case study areas.	Provide input to WP7, decision support tool, **Deposition** to WP4.3 (ChemicalDrift)	In description: "…bi-directional air-water exchange…" In appendix: comparison of monthly mean concentration values (ug/m3) in case study areas for NOx, O3, PM2.5 and SO2 with and without shipping from SILAM. To be used in modelling?	Activity, Pressure, State

APPENDIX II - Regulatory landscape

Convention or regulatory framework	Comment in relation to EMERGE
INTERVENTION. International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties, 1969	Mainly concerning ship accidents.
LC or **London Convention**. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (and the 1996 London Protocol)	Compliance assumed.
OPRC. International Convention on Oil Pollution Preparedness, Response and Co-operation, 1990	Mainly concerning preparedness and response in the event of an accident.
HNS convention or **OPRC-HNS**. Protocol on Preparedness, Response and Co-operation to pollution Incidents by Hazardous and Noxious Substances, 2000	Mainly concerning preparedness and response in the event of an accident.
AFS Convention. International Convention on the Control of Harmful Anti-fouling Systems on Ships, 2001	Only addresses TBT and Cybutryne.
BWMC. International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004	Spreading of non-indigenous species is not included in the analysis.
Hong Kong Convention. The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, 2009	Focus beyond normal ship operations, and thereby outside the scope.
SOLAS. International Convention for the Safety of Life at Sea (1974, as amended)	E.g., safety measure for ships operating in polar waters reduce the risk for accidents in these areas.
STCW. International Convention on Standards of Training, Certification and Watchkeeping for	Not addressed in the analyses, but in reality very important that crew members know how

Seafarers (as amended, including the 1995 and 2010 Manila Amendments)	to run the ship according to least possible negative environmental impact.

APPENDIX III – Activity

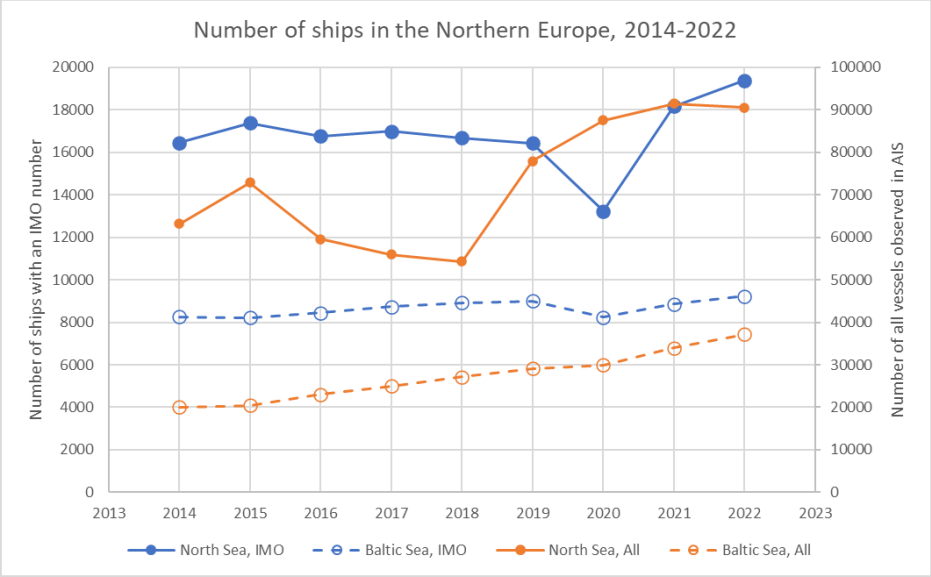

Figure A.III- 1: Number of observed ships in North Sea and Baltic Sea areas. Blue symbols illustrate the large vessels with an IMO registry number, whereas the orange symbols depict all observed AIS targets regardless of registration. Note: different scale on Y-axis.

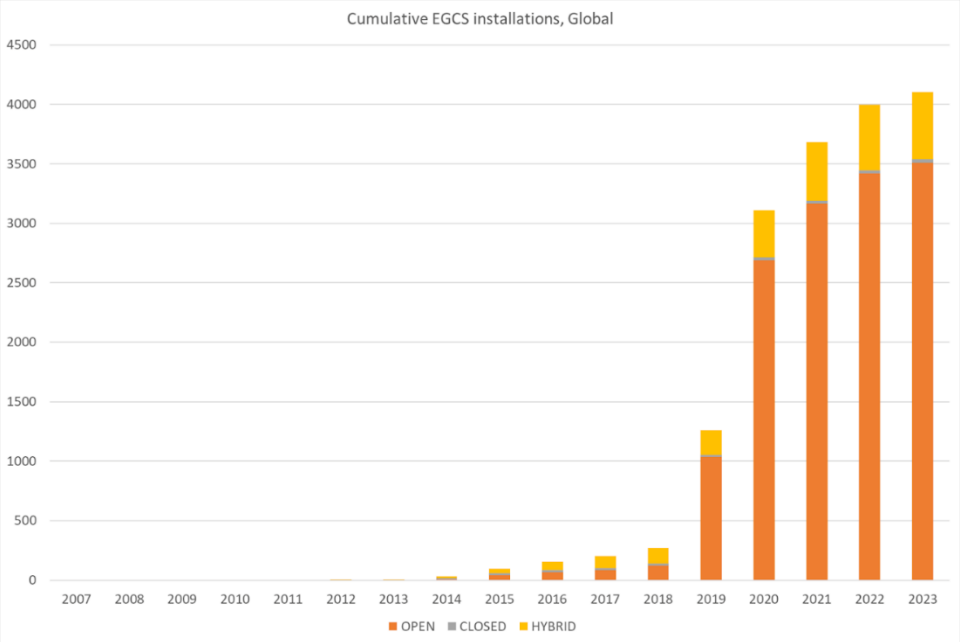

Figure A.III- 2: Global scrubber (EGCS) fleet and equipment type. These numbers are based on global emission calculations for vessels which were sending AIS position reports during each of the studied years.

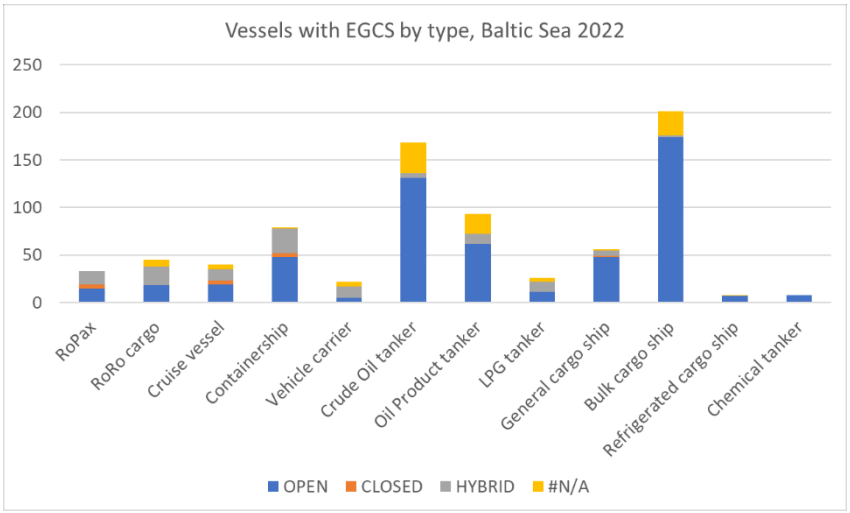

Figure A.III- 3: Scrubber (EGCS) installations by ship type, Baltic Sea, 2022.

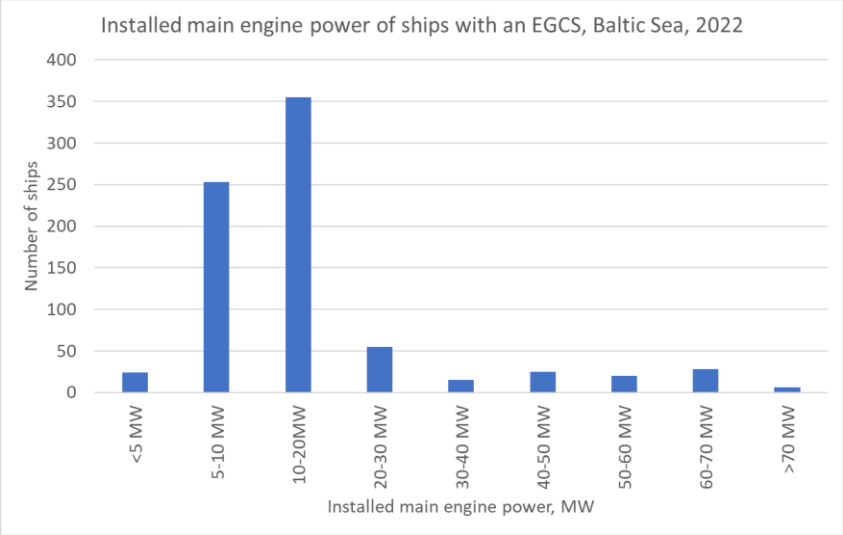

Figure A.III- 4: Ships with a scrubber (EGCS) and main engine size (MW) in the Baltic Sea area during 2022.

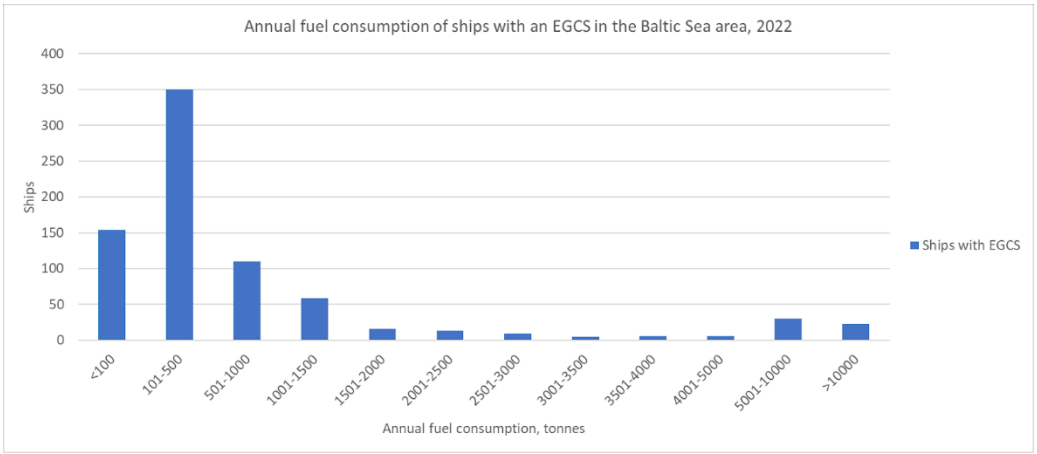

Figure A.III- 5: Ship with a scrubber (EGCS) grouped according to the predicted annual fuel consumption in the Baltic Sea area, 2022. This figure includes only the fuel consumed in the Baltic Sea area.

APPENDIX IV – Pressure

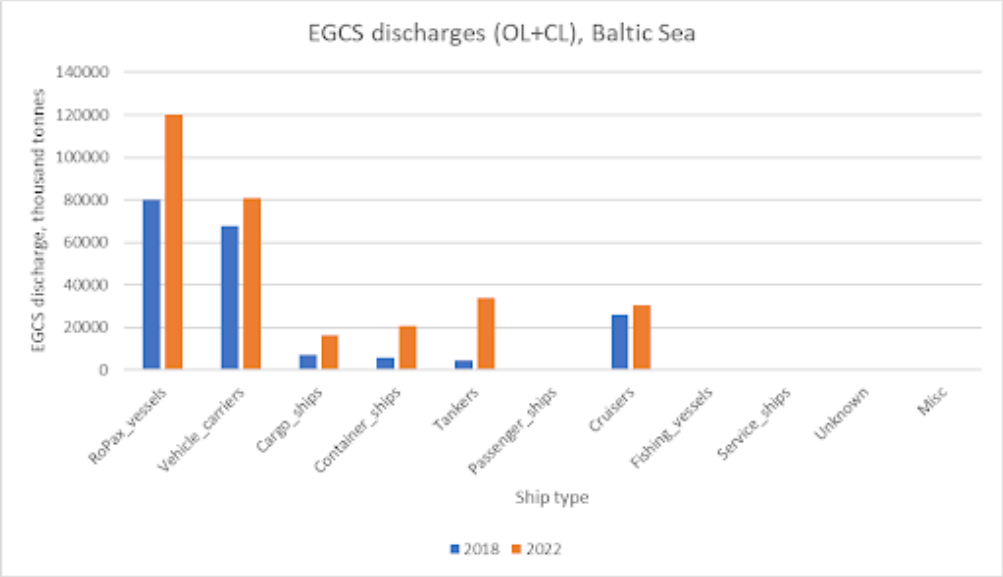

Figure A.IV- 1: Comparison of scrubber (EGCS) discharge in the Baltic Sea area during 2018 (192 million tonnes) and 2022 (312 million tonnes). Category Vehicle_Carriers includes the RoRo ships.

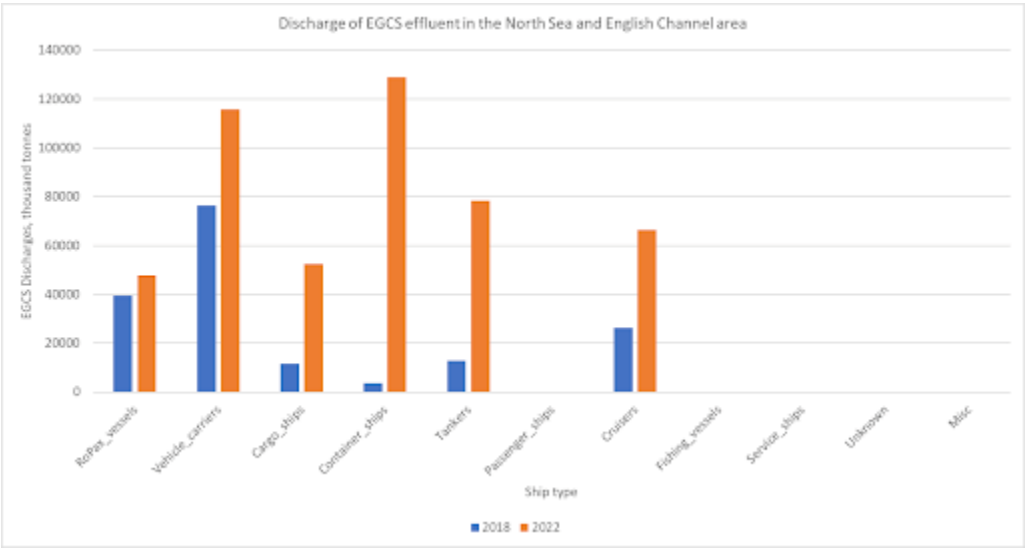

Figure A.IV- 2: Discharges of scrubber (EGCS) effluent in the North Sea area in 2018 (170 million tonnes) and 2022 (490 million tonnes). Category Vehicle_Carriers includes the RoRo ships.

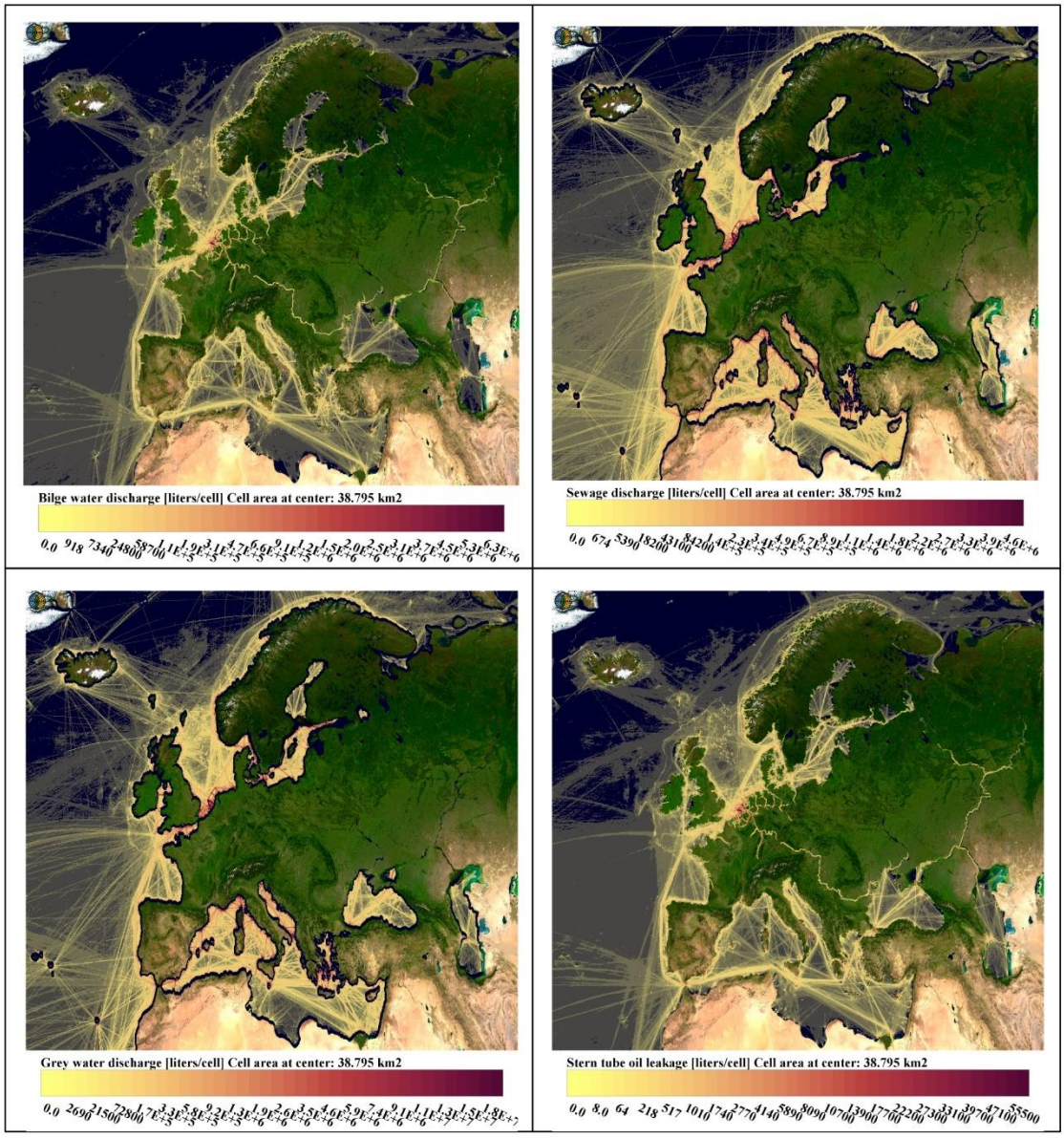

Figure A.IV- 3: Annual discharge volumes from bilge water (top left), sewage (top right), grey water (bottom left), and stern tube oil (bottom right) to European seas in 2018.

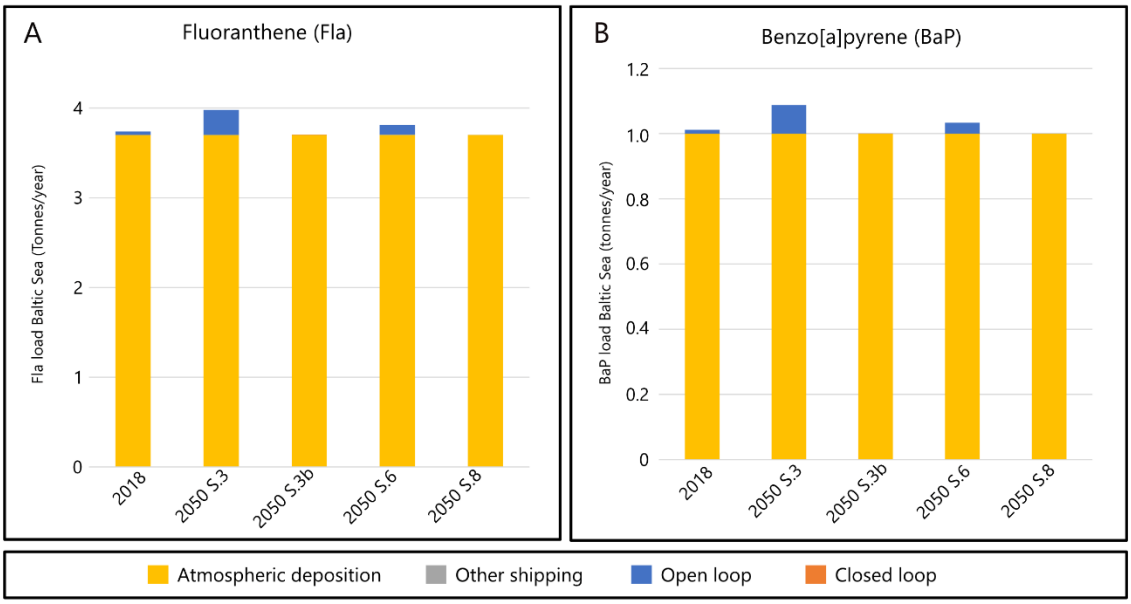

Figure A.IV- 4: Environmental load of fluoranthene (A) and benzo[a]pyrene (B) in Baltic Sea region for 2018. No data of riverine input or point sources exist and are not included.

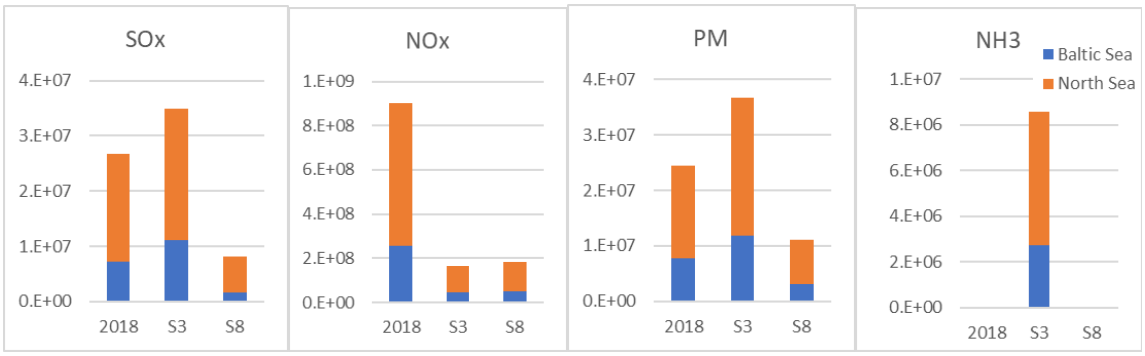

Figure A.IV- 5: Total emissions (in kg/year) of SOx, NOx, $PM_{2.5}$ and NH_3 from shipping in the Baltic Sea and the North Sea in year 2018 and in scenarios S3 and S8 in year 2050.

APPENDIX V – State

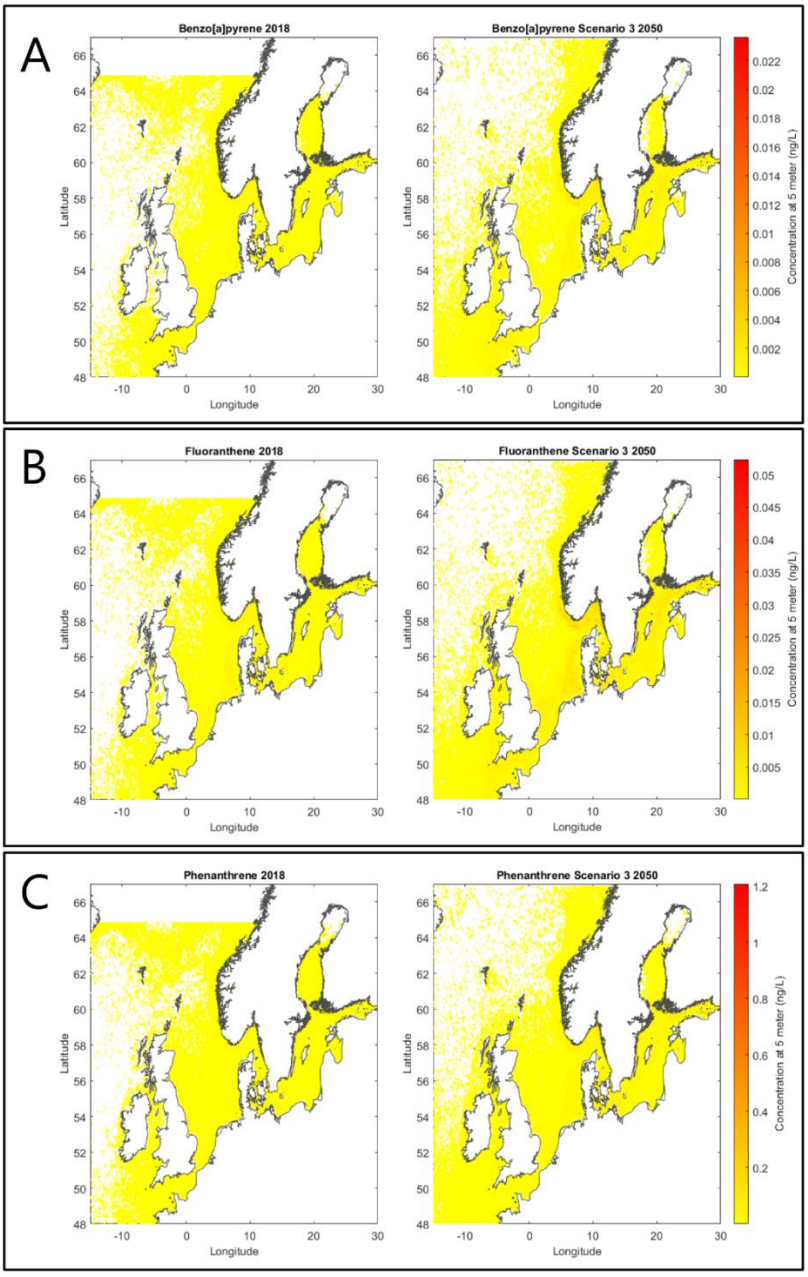

Figure A.V- 1: Example from ChemicalDrift output comparing 2018 with scenario 3 2050 (concentrations from OL scrubber water discharge in upper 5 meter).

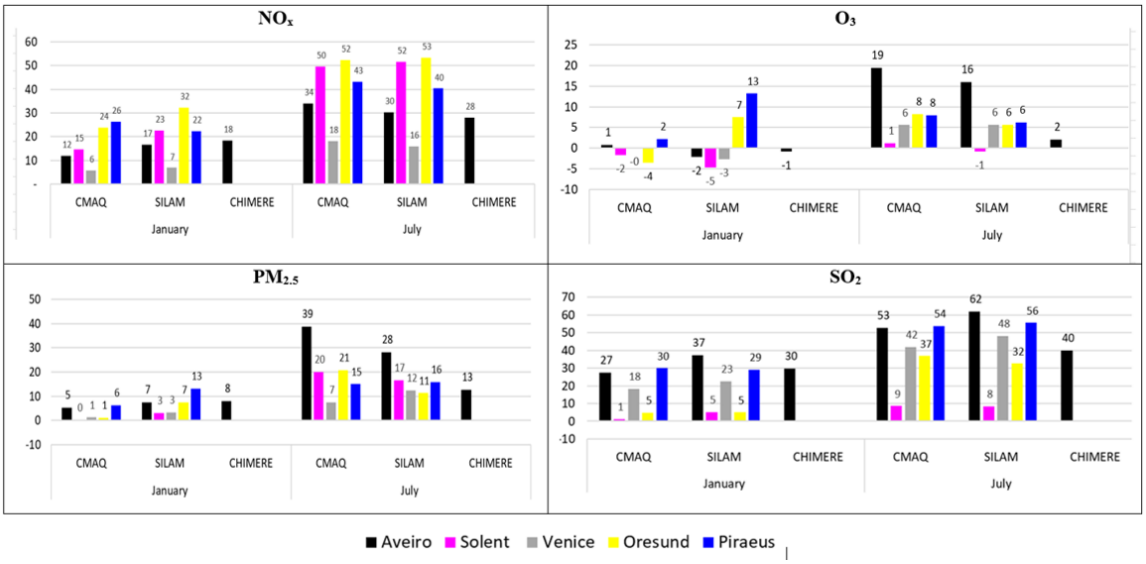

Figure A.V- 2: Comparison of the percentage changes of NOx, O_3, $PM_{2.5}$ and SO_2 due to shipping, predicted by CMAQ, SILAM and CHIMERE in µg/m^3 for five case study regions (Aveiro, Solent, Venice, Oresund and Piraeus) for January and July 2018.

Description of the model system used for simulations of air quality in Öresund Case Study

The investigation of effects of the shipping emissions on air quality and deposition of air pollutants in Öresund Case Study in the current (year 2018) situation and the year-2050 scenarios is based on model simulations with emission models, meteorological models and chemistry transport models (CTMs). For high-resolution simulations the CTM setup has been prepared on 3 nested domains on 15 km x 15 km, 5 km x 5 km and 1 km x 1 km (Figure A1), the coarser domains are providing boundary conditions for the high-resolution simulation. The model used was EMEP MSC-W model, version rv4.45 with chemical mechanism EmChem 19a (Simpson et al., 2012; Simpson et al., 2020). The meteorological fields were calculated by CACP with the Weather Research and Forecasting (WRF) model for year 2018. These meteorological fields were used for all scenario simulations, more details are presented in deliverable report D5.2 and D5.3.

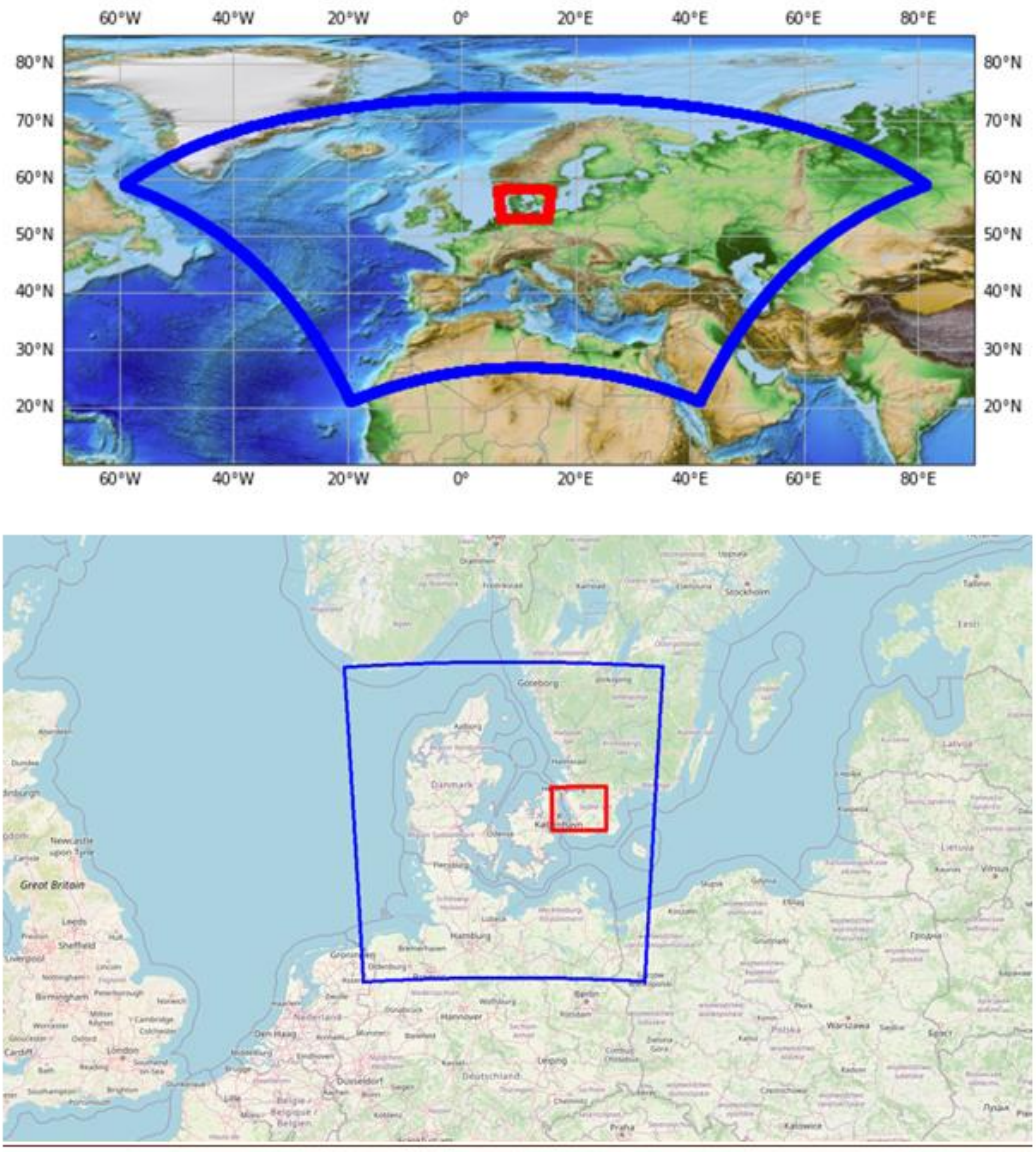

Figure A.V- 3: The 3 nested domains used for EMEP simulations. Upper panel: 15 km x 15 km resolution domain (blue) with the 5 km x 5 km domain (red). Lowe panel: the 5 km x 5 km domain (blue) and the high-resolution 1 km x 1 km domain (the Öresund Case Study domain).

The EMEP model simulations down to 5 km x 5 km resolution used emissions of NOx, SOx, NH_3, NMVOC, CO and PM from CAMS REG datadrt for year 2018 (version 4.2), the shipping emissions were calculated by the STEAM model, version 3.5 (Emerge report D5.3). For the high-resolution simulations for year 2018, emissions for Swedish part of the Öresund model domain were retrieved from the Swedish National Emission Database for year 2018 while the Danish emissions were retrieved from the WelfAir project emission inventory for year 2014 which were scaled to the year-

2018 emissions with help of total emissions in Denmark reported for year 2014 and 2018 to EMEP. Hourly emissions from ships on 250 m × 250 m grid resolution used by the EMEP model were calculated with the STEAM model.

The chemical mechanism builds on surrogate VOC species (Simpson et al. 2012 extended with benzene and toluene) and has 171 gas-phase and heterogeneous reactions. The model always assumes equilibrium between the gas and aerosol phase, using the MARS equilibrium module (Model for an Aerosol Reacting System) of (Binkowski and Shankar, 1995). For secondary organic aerosol (SOA) a so-called volatility basis set (VBS) approach (Robinson et al., 2007; Donahue et al., 2009; Bergström et al., 2012) is used. All primary organic aerosol (POA) emissions are treated as non-volatile, to keep emission totals of both particulate matter (PM) and VOC components the same as in the official emission inventories, while the semi-volatile ASOA and BSOA species are assumed to oxidize (age) in the atmosphere by OH-reactions (Simpson et al., 2012).

The aerosol module of the EMEP model distinguishes five classes of fine and coarse particles (fine-mode nitrate and ammonium, other fine-mode particles, coarse nitrate, coarse sea-salt, coarse dust), which for dry-deposition purposes are assigned mass-median diameters (Dp), geometric standard deviations (σg), and densities (ρp). The characteristics of these aerosol classes are given in Table A.V-1.

Table A.V- 1: Characteristics of the aerosol classes used in the EMEP scheme. Table gives mass median diameter (Dp), geometric standard deviations (σg), and densities (ρp).

Dp	σ_g	ρ_p	Species
μm		kg m-3	
0.33	1.8	1600	fine-mode nitrate, ammonium
0.33	1.8	1600	other fine-mode particles, eg sulphates, EC, OA
3	2	2200	coarse nitrate
4	2	2200	coarse sea-salt
4.5	2.2	2600	coarse dust, sand

The following natural emissions are calculated in the model: Biogenic emissions of isoprene and monoterpenes based on near-surface air temperature and photosynthetically active radiation. Soil NO emissions from soils of seminatural ecosystems are specified as a function of the N-deposition

and temperature. Generation of sea salt aerosol over the oceans is driven by the surface wind, as described by (Monahan et al., 1986) and (Mårtensson et al., 2003).

Dust emissions consider windblown dust from deserts, semi-arid areas, agricultural and boreal lands within the model domain. African dust is accounted for through boundary conditions. The key parameter driving dust emissions is wind friction velocity, the dust mobilisation by wind occurs when the wind friction velocity exceeds a threshold value. The model employs a partitioning scheme of wind shear stress between the erodible and non-erodible surface elements to calculate the threshold friction velocity (Marticorena and Bergametti, 1995).

Additionally, daily emissions from forest and vegetation fires are taken from the “Fire INventory from NCAR version 1.0” (FINNv1, (Wiedinmyer et al., 2011).

For this study standard initial and boundary conditions provided with the Open-source model distribution for the year 2018 were used.

APPENDIX VI – Impact

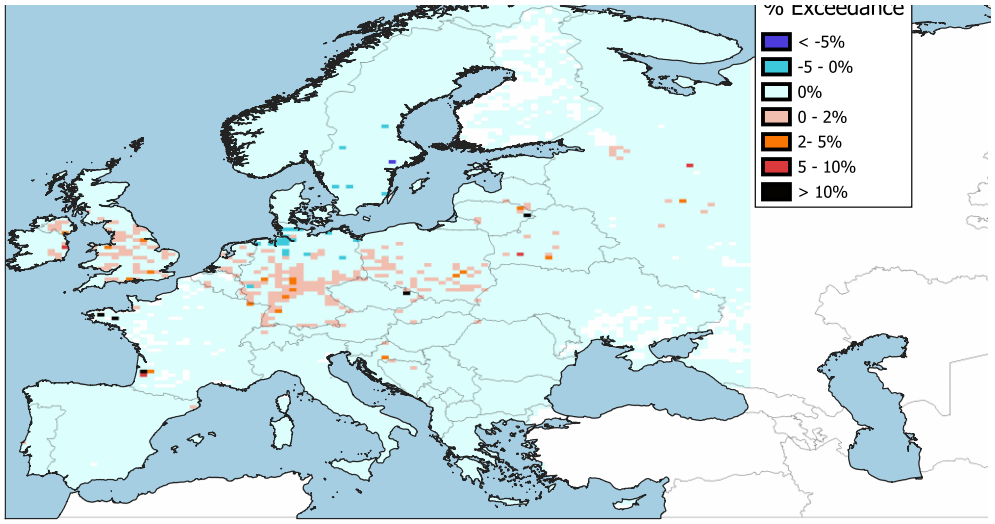

Figure A.VI- 1: Percentage of total ecosystem area exceeding acidification critical loads for the difference between Scenarios S8 and S3 in 2050. Exceedance share in white grid cells are not computed due to data unavailability.

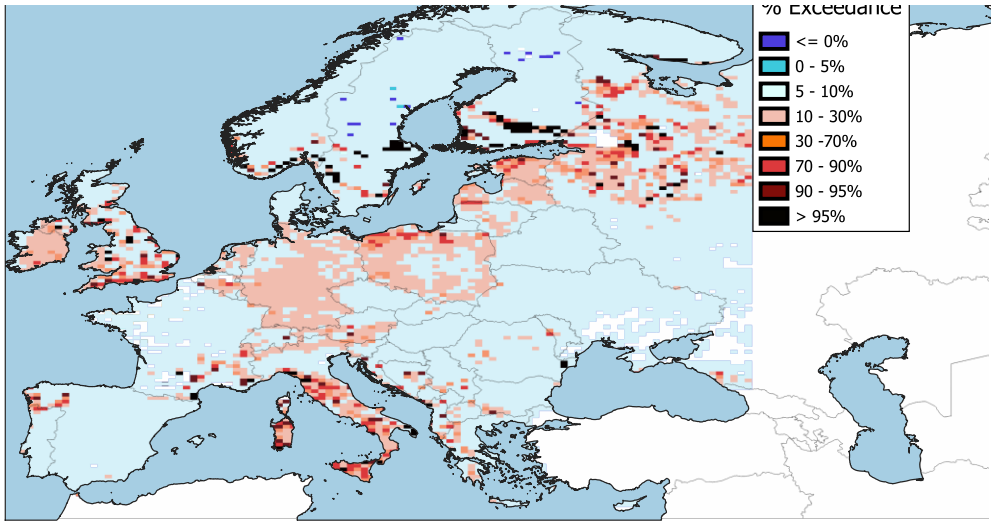

Figure A.VI- 2: Percentage of total ecosystem area exceeding acidification critical loads for Scenario S8 in 2050 including all sources. Exceedance share in white grid cells are not computed due to data unavailability.

Derivation of open loop PNEC from ecotoxicological studies

Environmental Quality Standards (EQSs) are tools used under the Water Framework Directive (WFD) for assessing the chemical and ecological status of waterbodies. Under EU REACH regulation and the EU Biocidal Product Regulation (BPR), the term Predicted No Effect Concentration (PNEC) is used instead of EQS. Despite different terminology, PNECs are derived according to the same methods and principles outlined in the Technical Guidance Document (TGD 27) on how to derive EQS values which has been published by the European Commission (EC 2018). The first version of TGD 27 was published in 2011 and an updated version was issued in 2018. Briefly, TGD 27 addresses the steps involved for deriving an EQS, e.g., types and quality of ecotoxicity data required, extrapolation and choice of assessment factors and how to account for background concentrations and bioavailability.

Two methods are presented to derive an EQS, the deterministic and the probabilistic approach. For the deterministic approach, the lowest credible toxicity value is combined with an assessment factor (typically 10 – 1000 depending on the available data) to obtain an EQS value (EC 2018). The probabilistic approach requires more data since it adopts a statistical species sensitivity distribution (SSD) methodology, in which all available ecotoxicity data (usually chronic NOEC and/or EC10 data) are ranked and fitted into a cumulative probability distribution model. In the TGD 27, an EQS derived from an SSD-curve is considered reliable if the database contains preferably more than 15, but at least 10 NOECs/EC10s values, from different species covering at least 8 taxonomic groups. Based on the SSD-curve, the hazardous concentration where 5% of the test species included in the SSD-curve are affected (HC5) can be estimated. The HC5 is typically divided by a smaller assessment factor of 1-5 to derive an EQS value. In EQS derivation, field and mesocosm data have an important role as lines of evidence in helping define the assessment factor.

We applied the methodology outlined in TGD 27 to derive EQS values for open loop scrubber discharge water. Hence, chronic studies and the most sensitive endpoint were used. A chronic toxicity study is defined for the purpose of EQS derivation as a study in which: (i) the species is exposed to the toxicant for at least one complete life cycle, or (ii) the species is exposed to the toxicant during one or more sensitive life stages (EC 2018).

The derivation of an PNEC of open loop scrubber water is based on the ecotoxicological test results within the EMERGE project, described in D.2.3 (some results also published in Picone et al. (2023)).

Within the EMERGE project, ecotoxicological tests and experiments were carried out on various life stages of single species belonging to different organism groups i.e., bacteria, microalgae, echinoderms, polychaetes, molluscs, and crustaceans, spending all or some part of their life cycle in the open water as plankton (EMERGE D2.3). The aim was to target sensitive life stages and species and to provide the No Observed Effect Concentrations (NOECs), the Lowest Observed Effect Concentrations (LOECs) and EC10 values for the risk assessment, as well as to understand the ecotoxicological impact exerted by the complex mixture of metals, PAHs, nutrients and acidic effluent that scrubber water constitutes. Effects of scrubber water were also tested on microplankton communities (organisms <200 µm), including both plants and animals. Since scrubber water is released directly into the seawater, it will affect all marine pelagic life.

From EMERGE ecotoxicological studies, the number of species (n=9) do not amount to the requirements to perform a probabilistic approach, defined by TGD 27, and a deterministic approach was applied. The studies included in the determination of a critical value are based on chronic tests where all organisms are pelagic or have pelagic larvae, that is, they spend their entire life, or part of their life cycle, in the water column. The most sensitive periods of the life cycle for any marine organism are the early life stages, i.e., the fertilized eggs and the development of the larvae (often including many stages) (Hutchinson et al. 1998). In addition, mesocosm studies on natural plankton communities were exposed to open loop scrubber water (Genitsaris et al. 2023).

Moreover, test results from three external studies (Koski et al. 2017, Magnusson et al. 2018, Ytreberg et al. 2019) were assessed for comparison. In all the external studies, the effect concentrations were substantially higher than the NOECs presented in deliverable 2.3. In Ytreberg et al (2019) Ytreberg et al. (2019), the filamentous cyanobacteria *Nodularia spumigena* showed negative responses in photosynthetic activity and EC10=8.6%. Koski et al. (2017) investigated the threshold concentrations of scrubber discharge water for survival, feeding and reproduction of the copepod *Acartia tonsa*. In all concentrations >10% scrubber discharge water, the adult copepod mortality increased. Koski et al. (2017) also observed a dose-response relationship with reduced feeding with increasing scrubber water concentrations, but no effect on reproduction and little effect on egg survival. Magnusson et al. (2018) exposed *Mytilus edulis* to open and closed loop scrubber water. *Mytilus edulis* byssus strength was the only endpoint measured that showed a significant effect of the scrubber treatments, while this effect was detected at 1.25% and upward but only in closed loop exposures.

Biological effects of the scrubber water were observed at extremely low concentrations, LOECs being: 0.0001-0.001% of scrubber water in the exposure water (Table VI-1 and EMERGE D2.3), and the most sensitive parameters were fertilisation of sea urchin eggs (Chen et al, in prep) and larval development across organism groups (Picone et al. 2023). In many cases a NOEC could not be established since an effect was already apparent at the lowest test concentration. This implies that effects from scrubber water are likely to occur at even lower concentrations than those tested here. Both lethal and sublethal effects were observed. While mortality has a direct influence on population growth, sublethal effects may have many different implications. If an organism is affected so that it is unable to move from one life stage to the next e.g., if the process of moulting is impaired, it will still live for a certain amount of time and interact with the ecosystem whereafter it will die prematurely as larva and thus not contribute to the adult population (Figure A.VI- 3) (Thor et al. 2021). Sublethal effects may also offset the timing of larval development in such a way that a grazer may miss annual phytoplankton blooms or seasonal chemical cues e.g., determining settling. Slowed or abnormal larval development may thus lead to temporal or spatial offsets that will affect not only the individual species or population but may induce cascading effects along food webs.

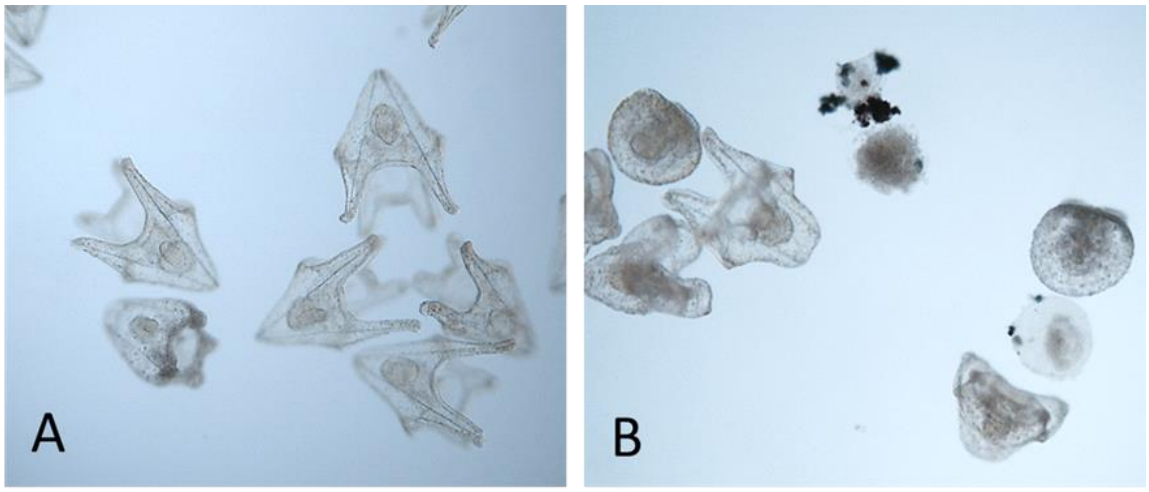

Figure A.VI- 3: Sea urchin larvae exposed to A. clean seawater and B. scrubber water 5%. The larvae are ca. one week old and show normal development in clean seawater (A) while the scrubber water exposed larvae show abnormal development with no appendages (B). Carcasses also grow a biofilm of bacteria to which combustion particles from the scrubber water adsorb (B top).

To summarize, the uncertainties raised above in combination with the ecotoxicological test results of nine different species representing the larval stages of two trophic levels (including taxa of mollusc, crustacean and algae) that are included in the PNEC derivation calls for an assessment factor of 500 according to Table 4 in TGD 27. The assessment factor is applied to the critical value to ensure protection of the entire ecosystem.

The critical value$_{NOEC}$ = 0.001% was given from three tests of *Sabellaria alveolate* (polychaete), larval development and *Artemia sp*. (crustacean), post-exposure feeding inhibition. Applying the assessment factor, the resulting PNEC=2×10-6 %, equivalent to a dilution ratio of 1:50000000.

The lowest critical value, i.e., critical value$_{NOEC}$=0.001%, equivalent to a dilution factor of 1:1000000 and the lowest LOEC=0.0001, equivalent to a dilution factor of 1:1000000.

The proposed EQS values appear to be protective to microplankton communities, as Genitsaris et al. (2023) found microplankton communities not to be affected in terms of abundance and population density when exposed to scrubber discharge water concentrations below 1%.

Data included in PNEC$_{TGD}$ derivation							
Lab	**Taxa**	**Species**	**Life stage**	**End-point**	**NOEC (%)**	**LOEC (%)**	**Comment**
Venice	Bacteria	*Aliivibrio fisheri*	bacteria	bioluminescence	10	20	
Venice	Copepod	*Acartia tonsa*	adult	mortality	5	10	
Venice	Microalga	*Phaeodactylum tricornutum*	-	growth rate	20	40	
Venice	Microalga	*Dunaliella tertiolecta*	-	growth rate	10	20	
Venice	Mussel	*Mytilus galloprovincialis*	embryos	larval development	0.1	1	
Venice	Copepod	*Acartia tonsa*	from egg to copepodite	hatching success	10	20	
Venice	Copepod	*Acartia tonsa*	from egg to copepodite	larval survival	10	20	
Venice	Copepod	*Acartia tonsa*	from egg to copepodite	larval development	1	2	
Southampton	Blue mussel	*Mytilus edulis*	embryo	fertilization success (%)	1	2	
Southampton	Sea urchin	*Psammechinus miliaris*	embryo	fertilization success (%)	0.1	1	
Southampton	Sea urchin	*Psammechinus miliaris*	larvae	abnormal larval development	0.01	0.1	

IVL	Sea urchin	*Strongylocentrotus droebachiensis*	Larvae	abnormal larval count (%)	0.01	0.1	
Aveiro	Sea urchin	*Paracentrotus lividus*	embryo	fertilization success (%)	0.01	1	
Aveiro	Sea urchin	*Paracentrotus lividus*	larvae	abnormal larval development	0.001	0.01	Critical $value_{NOEC}$
Aveiro	Polychaeta	*Sabellaria alveolata*	Larvae	abnormal larval development	0.001	0.01	Critical $value_{NOEC}$
Aveiro	Sea urchin	*Paracentrotus lividus*	embryo	fertilization success (%)	1.56	3.125	Pre-study
Aveiro	Crustacean	*Artemia sp.*	nauplii II	Post-exposure feeding inhibition	0.001	0.1	Critical $value_{NOEC}$
Aveiro	Mussel	*Mytilus galloprovincialis*	Adult	Post-exposure feeding inhibition	0.1	1	
Aveiro	Crustacean	*Artemia sp.*	nauplii II	Post-exposure feeding inhibition	0.001	0.1	Critical $value_{NOEC}$
Not included in $PNEC_{TGD}$ derivation							
Lab	**Taxa**	**Species**	**Life stage**	**End-point**	**NOEC (%)**	**LOEC (%)**	**Comment**
Venice	Copepod	*Acartia tonsa*	adult (F0)	egg production	n.c.	n.c.	See note-u shaped data
Venice	Copepod	*Acartia tonsa*	eggs (F1)	hatching success	>1	>1	
Venice	Copepod	*Acartia tonsa*	larvae (F1)	larval survival	>1	>1	
Venice	Copepod	*Acartia tonsa*	larvae (F1)	larval development	n.c.	n.c.	See note-u shaped data
Southampton	Blue mussel	*Mytilus edulis*	Larvae	abnormal larval development	<0.001	0.001	
IVL	Copepod	*Calanus helgolandicus*	copepodite CIII	moulting	<1	1	Thor et al.
IVL	Copepod	*Calanus helgolandicus*	copepodite CIII	mortality	<1	1	Thor et al.
IVL	Sea urchin	*Strongylocentrotus droebachiensis*	embryo	fertilization success (%)	<0.0001	0.0001	
Averio	Sea urchin	*Paracentrotus lividus*	embryo	fertilization success (%)	<0.01	0.01	
Aveiro	Sea urchin	*Paracentrotus lividus*	larvae	abnormal larval development	<0.001	0.001	
Aveiro	Polychaeta	*Sabellaria alveolata*	Larvae	abnormal larval development	<0.001	0.001	
Aveiro	Sea urchin	*Paracentrotus lividus*	larvae	abnormal larval development	<1.56	1.56	Pre-study

Aveiro	Mussel	*Mytilus galloprovincialis*	Adult	Post-exposure feeding inhibition	<0.001	0.001	Response not clear
Mesocosm results							
Lab	**Taxa**	**Species**	**Life stage**	**End-point**	**NOEC (%)**	**LOEC (%)**	**Comment**
AUTH	Microalga	*Pseudonitzschia cf. pungens*		population density	<10, >1	10	
AUTH	Microalga	*Heterocapsa rotundata*		population density	<10, >1	10	
AUTH	Microalga	*Chrysochromulina sp.*		population density	<10, >1	10	
AUTH	Microalga	*Teleaulax sp.*		population density	<10, >1	10	
AUTH	Microalga	*Gymnodinium sp.*		population density	<10, >1	10	
AUTH	Microalga	*Chrysochromulina sp.*		population density	<10, >1	10	
AUTH	Microalga	*Teleaulax sp.*		population density	<10, >1	10	
AUTH	Microalga	*Skeletonema sp.*		population density	<5, >2	5	
AUTH	Microalga	*Gymnodinium sp.*		population density	<5, >2	5	
AUTH	Microalga	*Chrysochromulina sp.*		population density	<5, >2	5	
AUTH	Microalga	*Teleaulax sp.*		population density	<2, >1	2	
AUTH	Microalga	*Gymnodinium sp.*		population density	<5, >2	5	
AUTH	Microalga	*Chrysochromulina sp.*		population density	<5, >2	5	
AUTH	Microalga	*Teleaulax sp.*		population density	<5, >2	5	