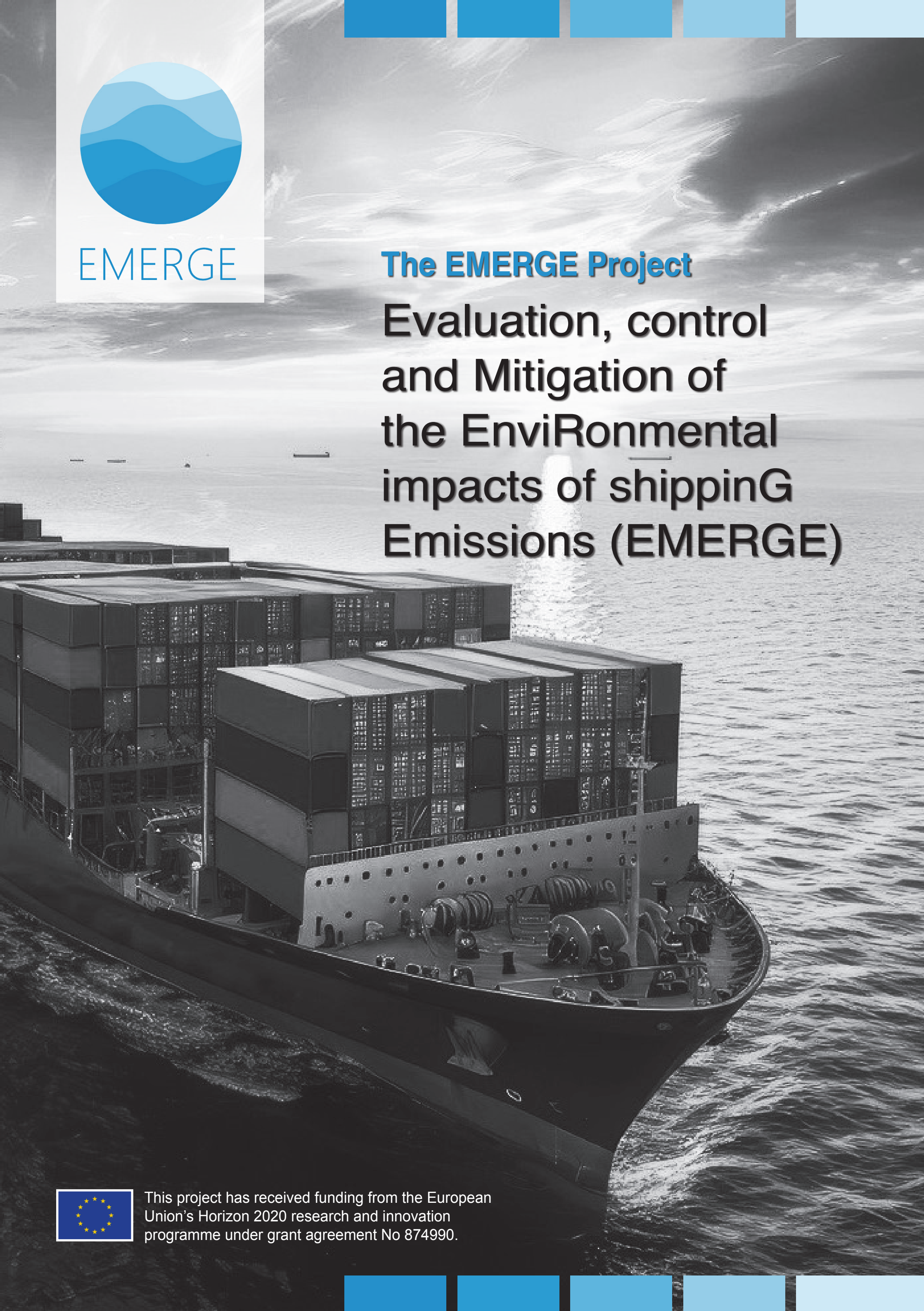

EMERGE

The EMERGE Project

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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 874990.

CONTENTS

1.Background

New global standards were enforced on 1st January 2020 for shipping emissions. This is because of their potentially significant health and environmental effects, especially from sulfur gases and sulfate aerosols. Technologies for controlling pollution from shipping are relatively new. Developing a robust scientific understanding of the environmental impacts of emission reduction technologies within the shipping sector is a major scientific and societal challenge.

The EMERGE project has successfully met its goals by:

- Quantifying and evaluating the effects of potential emission reduction solutions for shipping in Europe for several scenarios; and
- Developing effective strategies and measures to reduce the environmental impacts of shipping.

2. The EMERGE Project

2.1 Consortium

EMERGE was a Horizon 2020 funded European research project with partners from different regions of Europe and different specialisms/fields, including research and policy support institutes, Academia and a shipping company.

EMERGE partners covered the range of organizations required to synthesize scientific and research findings to authoritative evidence-based policies and technical solutions.

Project Coordinator

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Partners

CHALMERS UNIVERSITY OF TECHNOLOGY

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UNIVERSITY OF THE AEGEAN

Maritime Institute of Eastern Mediterranean

ICRA Catalan Institute for Water Research

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2.2 Methods

The EMERGE project has systematically analyzed the complex interactions between technological options, pollutant emissions and dispersion, and the environment (Figure 1). It assessed the effectiveness of Exhaust Gas Cleaning Systems (EFCS) in reducing key pollutants from ship emissions and provided insights into EGCS effluent characteristics, toxicity, and air emissions. Through meticulous collection and synthesis of empirical data on air emissions and waste streams from vessels with specific emission control technologies, the project developed an integrated modelling framework to assess the combined impacts of shipping emission control strategies on the aquatic and atmospheric environments, and on marine ecosystems. The assessment also included evaluations of the benefits and costs of control and mitigation options pertaining to water quality, air pollution exposure, health impacts, climate change, and the bioaccumulation of pollutants. Finally, EMERGE offered recommendations and guidance for stakeholders and decision-makers regarding cost-effective options for the sustainable utilization of shipping in the medium and long term.

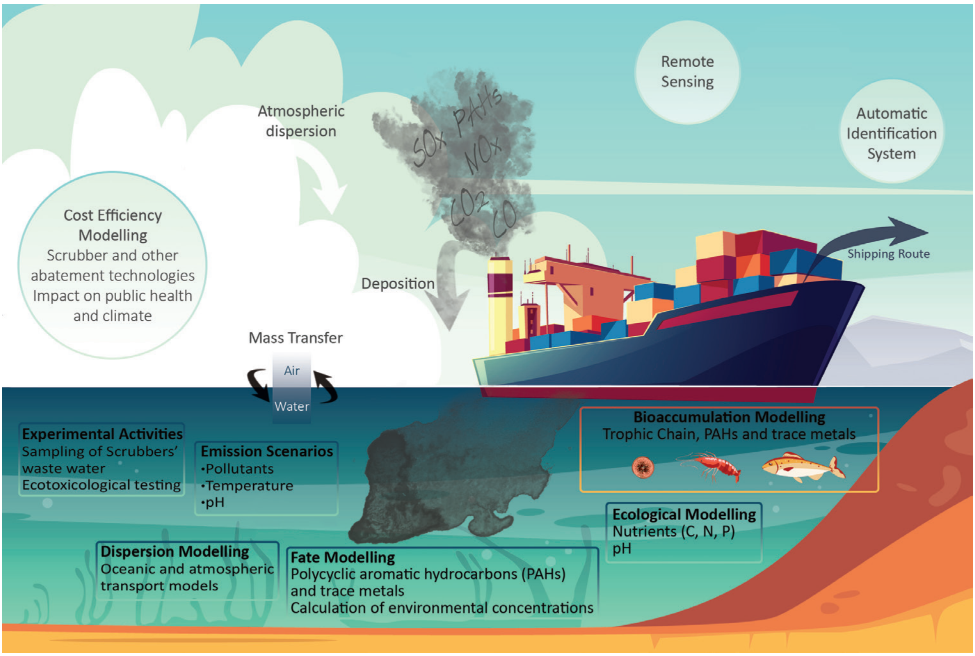


Figure 1: *Schematic illustrating the scope and approach of the EMERGE project.*

3. Main Outputs

3.1 Shipping emission control measures, scenarios and strategies

EMERGE focused on the impact of shipping emissions to air and water using various abatement equipment. We studied open and closed loop scrubbers as abatement technologies for SOx emissions as well as low sulfur fuels, Liquified Natural Gas (LNG) and methanol. The different approaches to reduce NOx emissions from combustion engines either used catalytic reduction of NOx in the exhaust gases or targeted the combustion process. We focused on Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR). Eight scenarios were constructed to estimate the impact of shipping on emissions in 2030 and 2050, exploring the effects of: i) different marine traffic developments, ii) emission control technologies, and iii) alternative fuels (Table 1).

Scenario number	DNVGL scenario	Scrubber scenario	SCR	Low sulfur	Type	Alternative fuel
1	High growth	High	NECA	SECA	Fossil	
2	High growth	High	NECA	SECA	Fossil	
3	H High growth	High	Everywhere	Everywhere	Fossil	
4	Low growth	High	NECA	SECA	Fossil	LNG (SSS)
5	Low growth	No HFO	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 HFO	None	SECA	50% reduction	LNG & Methanol

Table 1: *Overview of the scenarios in EMERGE.*

The scenarios for which impact assessments were made represent extreme cases of very high EGCS adoption, both for open and closed loop systems, as well as the situation where EGCSs are unnecessary. The selection of 2018 as the baseline year reflects the situation before the significant adoption of EGCS in the global ship fleet. A strong incentive for scrubber adoption is a large price premium of low-sulfur fuels and large fuel consumption of ships. This is illustrated in Figure 2.

The results highlight that there is a possibility for significant use of scrubbers in the future, leading to the production of large amounts of scrubber water, unless policies are changed.

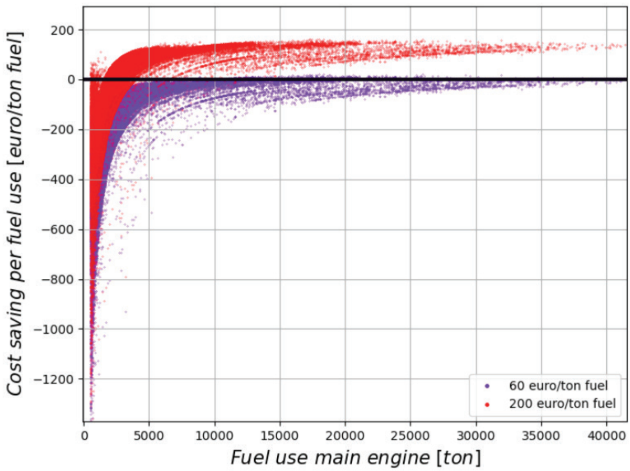


Figure 2: *Cost savings vs fuel use for all ships in Europe when using open-loop EGCSs rather than VLSFO, i.e., the assumed price difference between VLSFO and HFO. 60 and 200 €/ton fuel refer to the high and low-price difference between VLSFO and HFO*

3.2 Ecotoxicological tests

Fifteen different EGCS effluent samples were collected from diverse sources including 2 operating ships equipped with open-loop EGCS systems and a laboratory-scale pilot system at Chalmers University of Technology (Sweden) and analyzed chemically.

Researchers developed an analytical method for detecting pollutants and found significant concentrations of polycyclic aromatic hydrocarbons (PAHs) and metals, with alkylated PAHs emerging as a prominent yet previously underexplored class of contaminants. Low molecular weight PAHs dominated the concentration profile (Figures 3 a) and b)). Naphthalene and phenanthrene were detected at concentrations ranging from 1 to 13 $\mu g\ L^{-1}$. Fluorene and acenaphthene were found at concentrations ranging from 0.3 to 1.6 $\mu g\ L^{-1}$, followed by fluoranthene and pyrene, which are in the range of 0.1 to 0.9 $\mu g\ L^{-1}$.

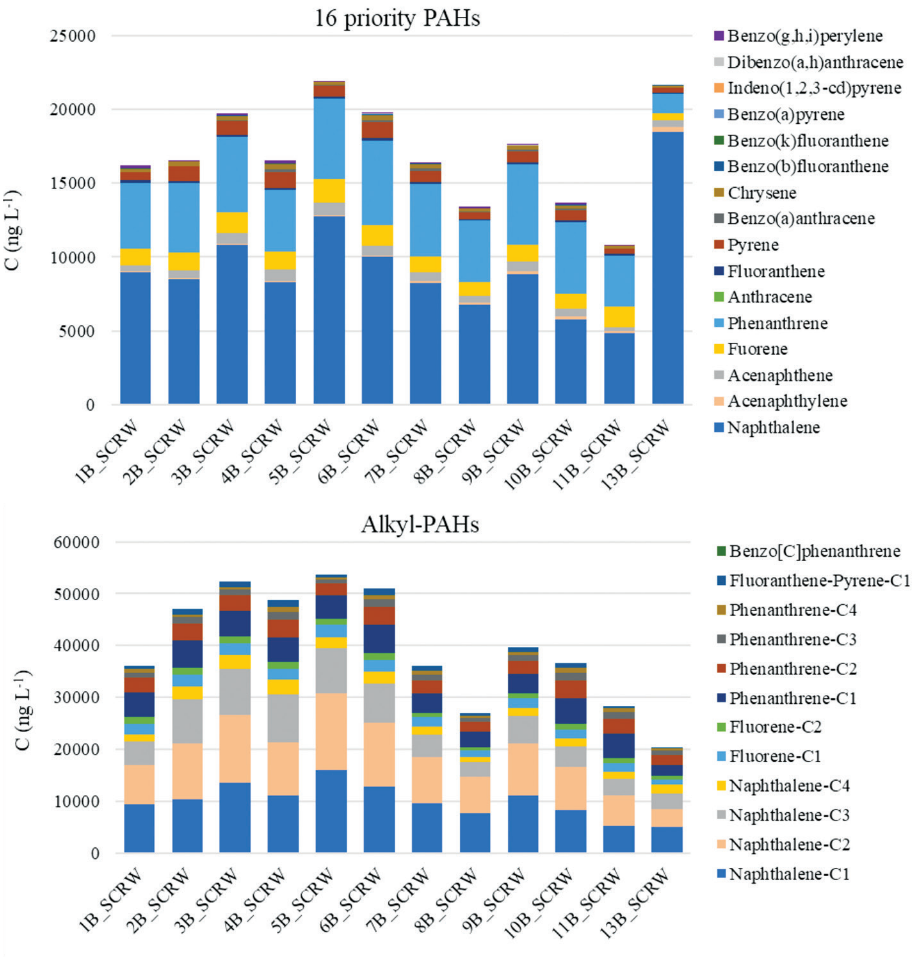
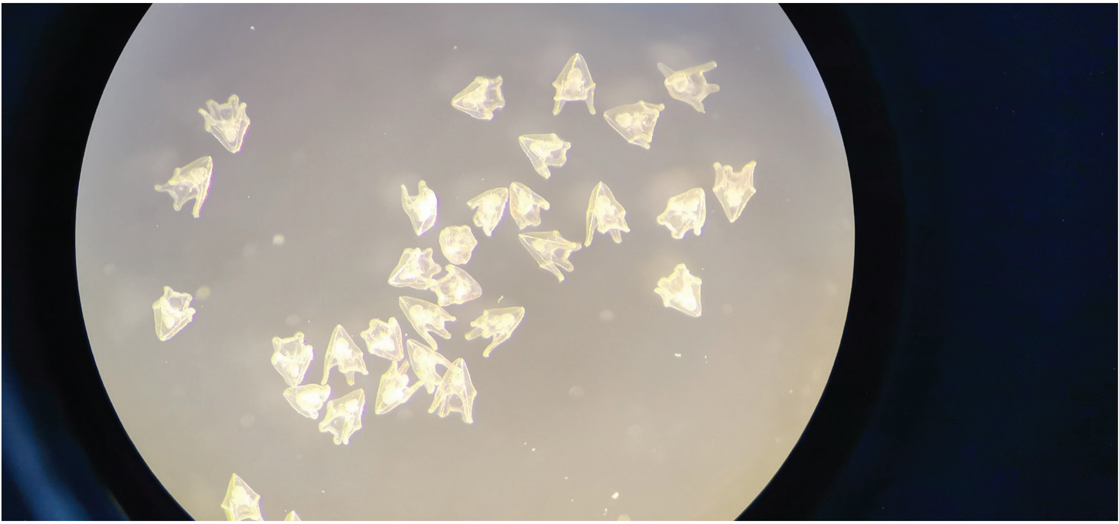


Figure 3: *a) PAHs and b) alkyl PAHs in scrubber water samples collected in the on-board case study.*



Moreover, the investigation uncovered diverse sorption patterns onto particulate matter, especially for high molecular weight PAHs. Significant concentrations of metals like V, Zn, and Fe were confirmed.

Effluents from different ships showed chemical similarities, with the ship Leo C's effluents being 80% similar, while artificial EGCS effluent differed. (Figure 4).

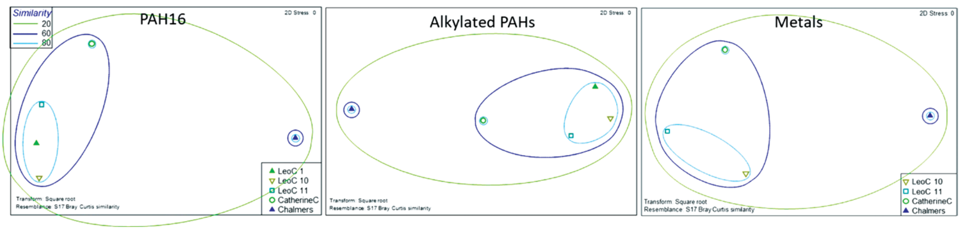


Figure 4: *Non-metric multi-dimensional scaling (nMDS) projections of chemical compositions of analyzed original EGCS effluents used in the ecotoxicological experiments. The Leo C effluents originated from the ship continuously sampled along route from Belgium to Turkey. Chalmers represents artificial EGCS effluent produced at Chalmers Technical University (Sweden) while Catherine C represents EGCS effluent from a different ship. Analyses are based on Bray-Curtis similarity on square root transformed abundance data of individual chemical compounds in unfiltered samples. PAH16: the 16 US EPA PAHs are included, Alkylated PAHs: the measured alkylated PAHs are included, Metals: V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Cd, Hg, Pb, U are included. Degrees of similarity are shown as colored ovals indicating 20, 60 and 80% similarity.*

Ecotoxicological experiments were carried out at five European research laboratories (Figure 5) to assess the impacts of EGCS effluents on a wide range of marine species (bacteria, microalgae, crustaceans, mollusks, echinoderms and polychaetes)

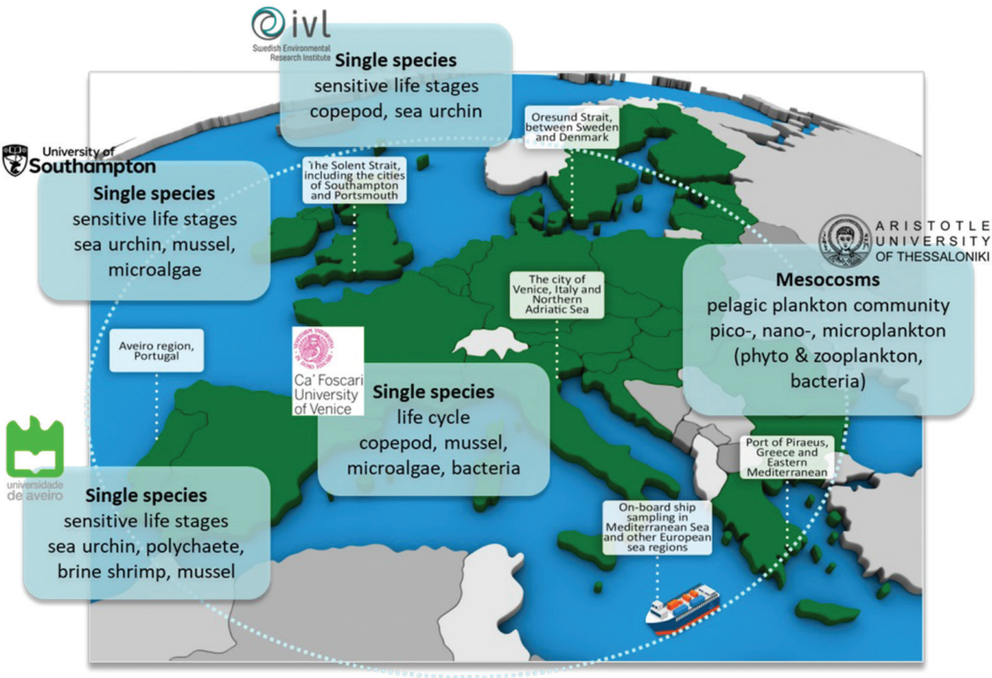


Figure 5: *Research laboratories conducting ecotoxicological experiments and tests of EGCS effluents within the EMERGE project. The type of tests conducted are stated in the blue boxes.*

EGCS effluents were obtained from open loop systems and collected onboard operating ships (DANAOS Shipping co. LTD) and from a pilot system at Chalmers University of Technology, Sweden. Employing a more ecologically relevant methodology than standardized tests, the research revealed surprising sensitivity across multiple species. EGCS effluents exhibited toxicity at much lower concentrations than previously reported, with early life stages of marine invertebrates (egg fertilization and larval development) and microbial communities being particularly susceptible (Figure 6). These findings suggested that EGCS effluent discharge may pose a significant threat to the health of marine ecosystems.

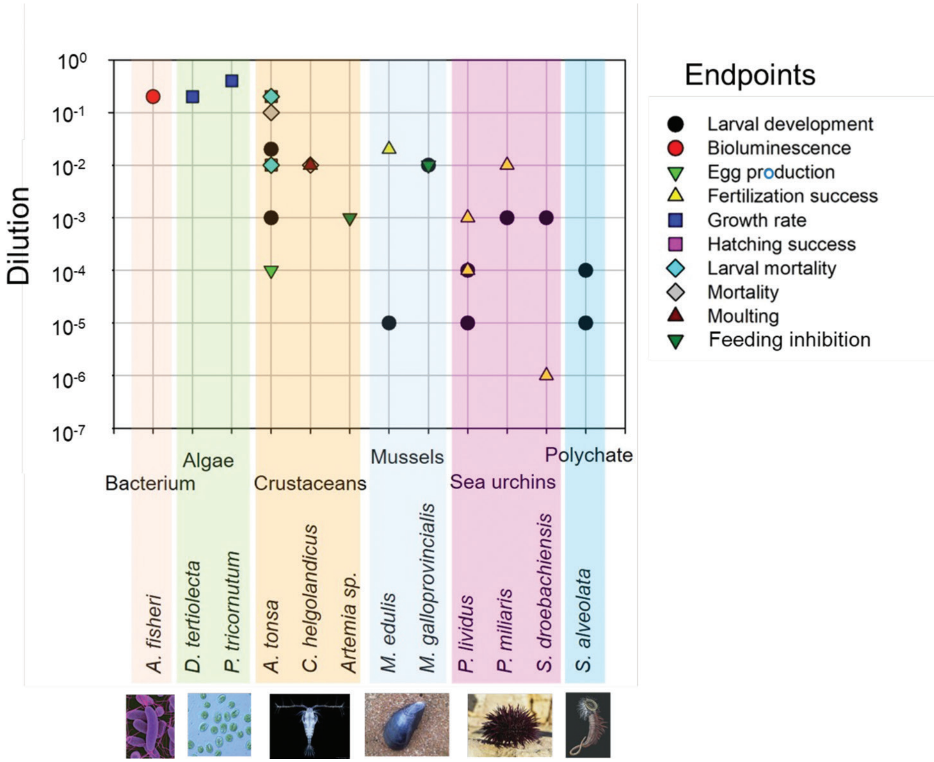


Figure 6. *The lowest observed effect concentration (LOEC) of EGCS effluent on different tested organisms and endpoints from experiments carried out within the EMERGE project. The different organism groups and species tested are shown on the X-axis and the dilution of EGCS effluent is shown on the Y-axis.*

3.3 Shipping emissions to the atmosphere

An extensive onboard measurement campaign from the port of Rotterdam (Netherlands) to the port of Gebze (Turkey) was undertaken using a DANAOS 300-meter container vessel with a large two-stroke slow-speed main engines, equipped with an open-loop scrubber.

Three different fuels were used during the campaign, two batches of high-sulfur Heavy Fuel Oil (HFO) and one batch of Ultra Low Sulphur Fuel Oil (ULSFO). Gaseous and particulate emissions measurements (NOx, SO2, CO, CO2; THC; non-volatile and total size-resolved PM, soot) were performed upstream and downstream of the scrubber and inlet. Discharge water samples were taken at different geographical locations during the trip.

Emission factors (EFs) for NOx, SO2, CO, THC and CO2 were measured for a slow-speed two-stroke engine for several fuels and engine loads. Load dependence of EFs could be observed for CO and NMVOC, weak also for NOx. SO2 has been reduced over the scrubber to the emission factor required by the legislation. Significant reduction of PAHs over the scrubber was measured. Figure 7 shows EFs for PM mass and its composition.

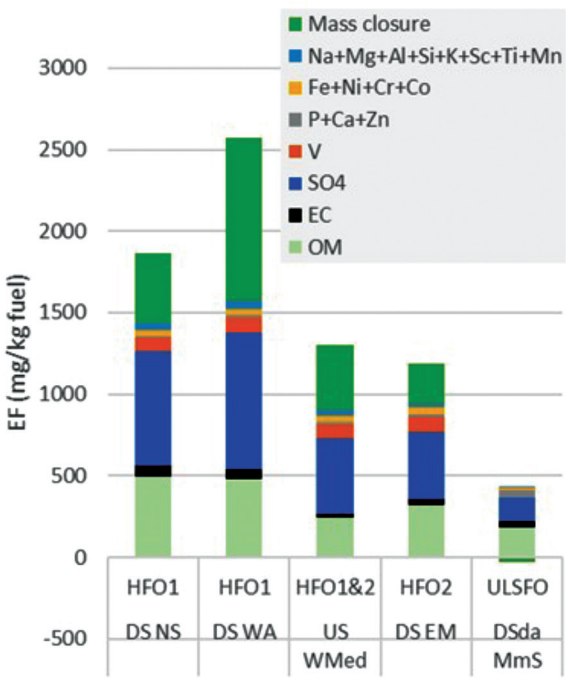


Figure 7: *PM mass closure: Emission factors (in mg/kg fuel) for PM compounds EC, OM (=OC*1.2), SO42- and metals. Mass closure is calculated as PMtot (from gravimetry) – (EC+OC+SO42-+metals).*

A typical EGCS operation for an assumed trip from the North Sea to the Mediterranean Sea is shown in Figure 3.3. The EGCS operation profile is not influenced by the ship type (containers, tankers, bulk carriers, etc.), but by the engine operation and the fuel sulfur regulation that a ship must comply with, according to the area of sailing.

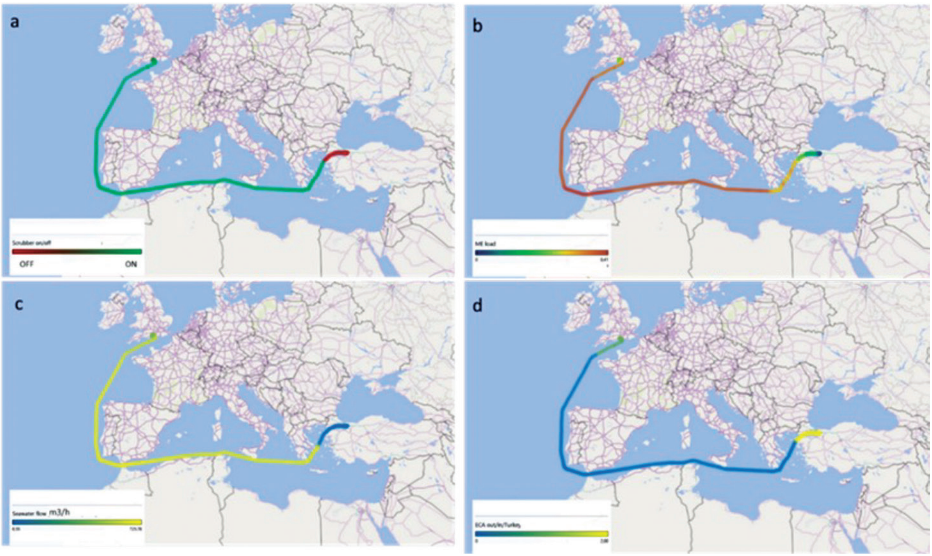


Figure 8: *Typical scrubber operation. a) scrubber operation on/off, b) Main engine load, c) seawater flow spread into scrubber, d) geographical location in respect of legislation*

Load-dependent Emission Factors (EFs) were developed in the framework of the project for marine engines and fuels, focusing on Specific Fuel Oil Consumption (SFOC), to assess emissions reduction potential. EFs were produced for CO_2, SOX, NOX, CO, HC, Particle Number (PN) as well as Particle Mass (PM) and its compounds EC, OC, ash, and SO_4^{-2} and additionally for PAHs and metals.

Analysis highlighted the following:

- Scrubbers achieved a substantial 75% reduction in SO_2 emissions but led to higher Particle Number emissions and a 2% increase in fuel consumption.
- Selective catalytic reduction (SCR) effectively reduced NOx, but increased CO emissions downstream.
- Diesel oxidation catalyst (DOC) reduced CO, HC, and PM emissions, with distillate fuel yielding the lowest PM emissions.
- Diesel particle filter (DPF) increased fuel consumption by 1.5% and raised CO_2 and SO_2 emissions. Positive percentages indicated reduced EFs post-treatment.

The positive percentages shown in Table 2 mean that the EFs are reduced downstream of the aftertreatment, while negative values indicate that the EFs are increased.

Emission control technology	Fuel	SFOC (%)	CO (%)	NOX (%)	SO2 (%)	NMVOC (%)	PM (%)
Wet Scrubber	Bunker Fuel Oil	-2,15	22,7	5,84	98,8	36.3	35,8
	MDO/MGO	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
SCR	Bunker Fuel Oil	-0,335	-59,3	89,0	9,55	68,5	15,1
	MDO/MGO	-0,452	-100	82,0	6,57	78,3	4,71
DOC	Bunker Fuel Oil	1,09	30,7	-0,814	-0,899	69,0	50,0
	MDO/MGO	1,09	30,7	-0,814	-0,899	69,0	50,0
DPF	Bunker Fuel Oil	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
	MDO/MGO	-1,50	0,00	0,00	0,00	0,00	91,70

Table 2: *Overview of emission reduction percentage of different emission control technologies. Negative values indicate an increase, positive values indicate reduction efficiency.*

3.4 Modelling of shipping emissions – produced water

A key achievement has been the development of ChemicalDrift, a new, open-source model for ocean pollution studies (Aghito et al., 2023). The present version includes PAH and metal chemistry. PAH simulations have been verified against field measurements of produced water from oil platforms in the North Sea (Aghito et al., 2024). The chemical processes in ChemicalDrift include the degradation, the volatilization, and the partitioning between the distinct phases that a target chemical can be associated with in the aquatic environment, e.g. dissolved, bound to suspended particles, or deposited to the seabed sediments. The improved ChemicalDrift was applied at European and local scales using STEAM data as input.

In the case of Saronikos Gulf, a comprehensive data base was constructed, including all the coastal sources of pollution and their corresponding contribution to mass-fluxes of water contaminants, to provide realistic estimates of the background concentrations of pollutants in the area. The model Delft3D-FLOW was used to simulate the marine characteristics (temperature, salinity, stratification, currents), based on atmospheric forcing and lateral boundary conditions obtained from other large-scale models. The simulated oceanic fields provided the background for the water-quality simulations for the fate of the most important heavy metals and polyaromatic hydrocarbons in the water column. Due to the alkalinity of the Eastern Mediterranean, the impact of scrubbers on acidification was assessed to be minimal. The above water-quality simulations were forced by the land sources, maritime-shipping scrubber-water effluents and other polluting sources (e.g. grey-water) and atmospheric deposition. Spatiotemporal fields of pollutant concentration were produced to cover the whole reference period (2018) as well as annual scenarios 3 and 8. Comparisons of the scenarios with the baseline year 2018 are shown in Figure 9.

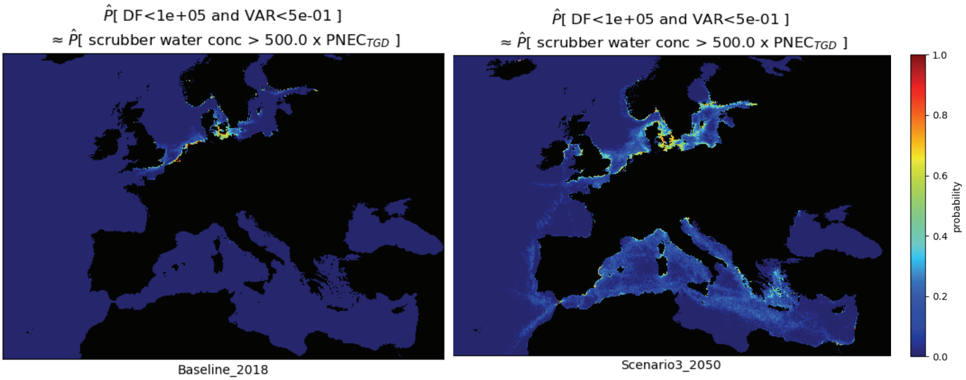


Figure 9: *ChemicalDrift simulations of dilution factor of scrubber water for the baseline year 2018 and scenario 3 (2050) indicating areas with harmful concentrations. For further explanation and details, see D6.2 and D6.3. PNEC (Predicted No Effect Concentration) was derived in D6.1.*

For the Northern Adriatic case-study, ChemicalDrift was applied to simulate water and sediment concentrations of the four common target chemicals (BaP, Flu, Pb, Cd) in the CS domain for the baseline 2018 and for S3 and S8 in 2050. Considered sources of pollutants included riverine loads, all shipping effluents, and atmospheric deposition. Forcing data were obtained from the SHYFEM model, providing ocean currents, temperature, bathymetry, and salinity) and Copernicus Marine Services (CMEMS) (mixed layer depth, suspended particulate matter concentration, and wind). Data on water and sediment quality from Regional Environmental Protection Agencies for 2018 were used to validate the modelling approach. Simulations allowed us to estimate the contribution of shipping discharges to water and sediment quality, and its variation under future scenarios.

A series of week-long simulations were conducted focusing on the two main shipping lanes towards Venice and Trieste ports, considering the week in spring, summer, and autumn when nitrogen discharges were the highest within each area. Spatial distributions of zoo- and phyto-plankton, chlorophyll-a and DIN suggested that the pulsed DIN ship emissions could locally lead to short-term non-negligible increases of the second and primary productions. In turn, this extra biomass could be transferred to higher trophic levels.

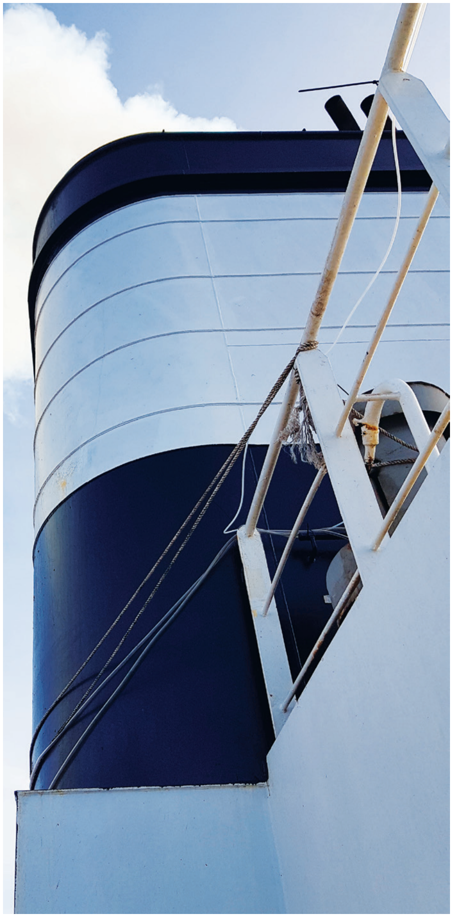
3.5 Modelling of air pollutant concentrations

EMERGE developed an optimised approach using the Weather Research and Forecasting (WRF) model for modelling atmospheric deposition of pollutants across Europe, and in five specific case study areas.

Deposition fluxes of the shipping-related air pollutants (metals, N and S) to the sea were calculated on the European domain with air quality models SILAM (FMI), CMAQ (CACP) and EMEP (IVL). Fate of atmospheric emissions of metals from shipping were calculated as part of ash particles resulting from the combustion of HFO. All models simulated shipping emissions for 2018 and for 2050 scenarios (scenario 3 -high use of scrubbers and Mediterranean NECA implemented- and scenario 8 -no scrubbers, no Mediterranean NECA-) in combination with land-based emissions for 2018. A sensitivity study was also included.

Deposition maps and annual atmospheric deposition fluxes to European sea regions (Mediterranean Sea, Black Sea, Bay of Biscay, Irish and British Seas, English Channel, North Sea, Baltic Sea) were calculated for S, total N and ten metals. Results showed varying shipping contributions to deposition, with significant decreases projected in future scenarios. Notably, atmospheric deposition played a dominant role in N input to the sea. Deposition of S showed a notable decrease in future scenarios, particularly outside SECA regions. The contribution of shipping emissions to metals deposition varied, with some metals negligible compared to other sources.

The reduction of S content in fuels was hypothesized to influence ocean surface warming, although simulations did not definitely confirm this hypothesis. Thus, further global studies are required to comprehensively assess the climate impacts of fuel-related changes alongside other contributing factors.



3.6 Environmental impacts of Exhaust Gas Cleaning Systems

The EMERGE project investigated the environmental impacts of Exhaust Gas Cleaning Systems in the Baltic and North Sea, the Mediterranean Sea report and other areas using the established DAPSIR (Driver-Activity-Pressure-State-Impact-Response) framework.

The assessments were performed using a baseline year of 2018, and future scenarios for the year 2050, based on different projections of transport volumes scenarios and considerations for fuel efficiency requirements and ship size developments. Two extreme scenarios were selected for impact studies which illustrate the differences between extensive EGCS utilization and a future without the need for EGCS yet compliant to IMO initial GHG strategy. Projections for the high EGCS adoption scenario in 2050 indicated that about a third of the fleet sailing the studied sea areas would use EGCS and effluent discharge volumes would be increased tenfold for the Baltic Sea and hundredfold for the Mediterranean Sea in comparison to 2018 baseline levels.

Experimental analysis of EGCS effluents stressed that the composition's complexity demands further scrutiny. However, the significant contribution of alkylated PAHs to cumulative risks, comprising more than 85% (Figure 10), remains unaccounted for in discharge criteria. To enhance the accuracy of monitoring and ensure a more comprehensive assessment of EGCS effluent impact on marine ecosystems, the inclusion of alkyl-PAHs needs to considered alongside the existing EPA list of sixteen priority PAHs.

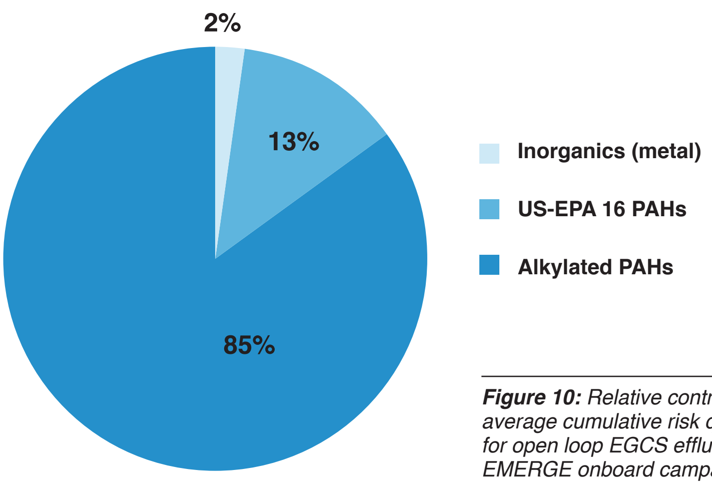


Figure 10: *Relative contribution to the average cumulative risk quotient, calculated for open loop EGCS effluent from the EMERGE onboard campaign.*

Economic analyses of EGCS revealed that that 51% of the global fleet reached break-even by the end of 2022, resulting in a profit of 4.7 billion €2019. Moreover, within five years of installation, over 95% of ships with open loop EGCS achieved break-even.

Moreover, a web-based decision support tool was developed in EMERGE to assess shipping's environmental impacts across various future scenarios and case studies within the European domain and selected case studies. It integrates seven Sustainable Development Goals-aligned impact endpoints for spatial and temporal assessments and quantifies diverse risk categories, encompassing impacts on human health, land-based ecosystems, and marine ecosystems and provides a score for geographically explicit areas (see Figure 11). The tool is publicly accessible at https://gains.iiasa.ac.at/dashboard/eiindex/index.menu, and it stands as a project legacy, designed for broad applicability and transferability.

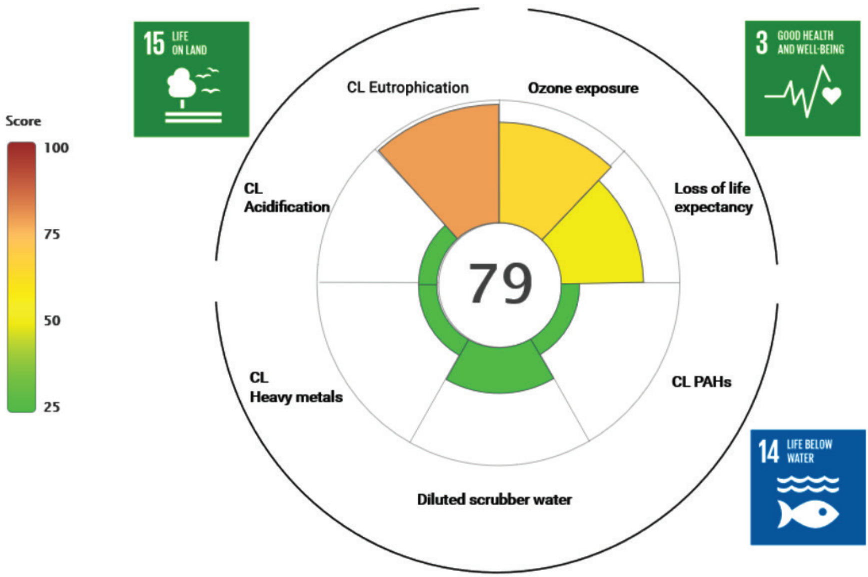


Figure 11: *Visualization of multiple environmental impacts using the Decision Support Tool.*

3.7 Cost-efficient methods for mitigating and reducing the emissions and impacts

EMERGE WP7 aimed to rank emission control technologies by cost-effectiveness and determine the least-cost set of controls for ensuring good environmental quality across sea regions. This was achieved by integrating outcomes from other EMERGE activities, particularly the Decision Support Tool, to establish a logical chain linking causes of pollution to their impacts. The approach integrated shipping into the GAINS model framework, considering emission streams comprehensively. Findings indicated that reducing SO2 and NOx emissions from shipping is cost-efficient (Figure 12), while PM and CO2 are more effectively mitigated from land-based sources. The analysis also underscored the necessity of holistic approaches to emission control, highlighting the environmental impacts associated with the combustion of residual fuels typical in shipping. Specifically, investigation into diluted scrubber water revealed adverse impacts on marine biota, emphasizing the need for regulatory measures to ensure sustainable development within the shipping industry.

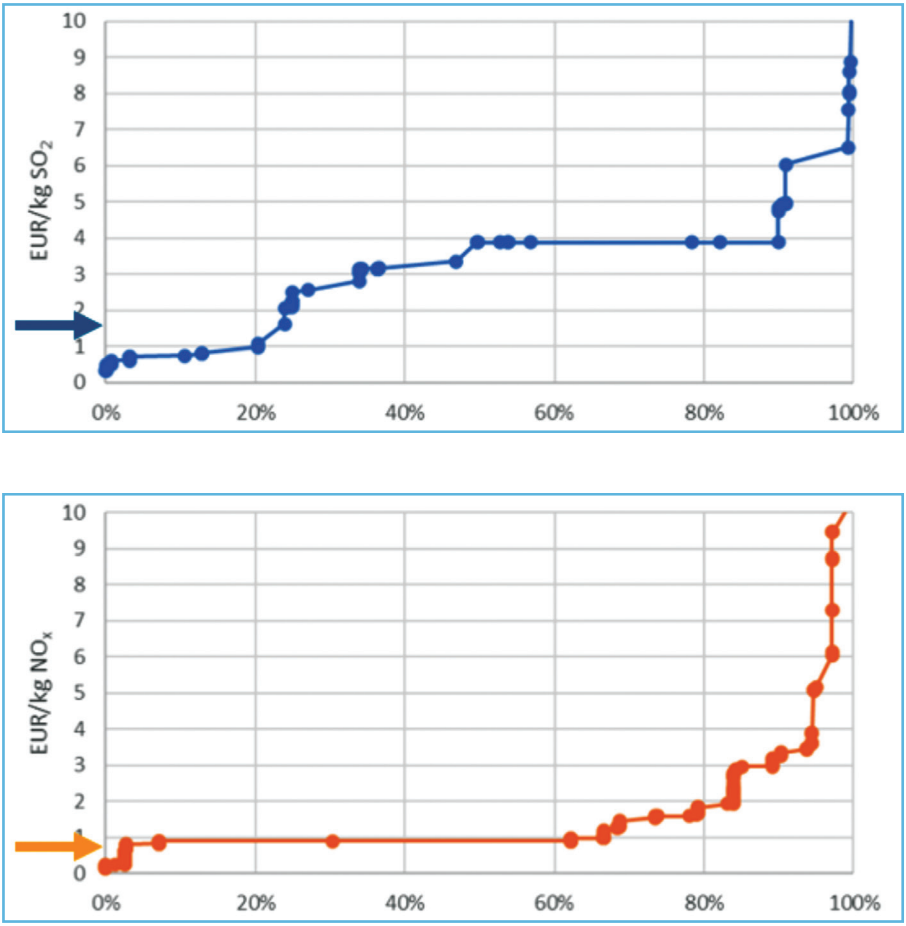


Figure 12: *Cost curves of emission abatement of land-based sources for the pollutants SO2 and NOx (from GAINS). Arrows indicate costs for emission abatement in shipping.*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4. Case Studies

The EMERGE project conducted five case studies in vulnerable environments like estuaries and straits, along with a mobile study on ships in European sea regions (Figure 13). Significant progress was achieved, meeting all set objectives. Most sampling and ecotoxicology experiments were completed from 01/08/2021 to 31/01/2023, followed by analysis and synthesis from 1/2/2023 onwards. Table 3 summarizes the case study status and experimental work from 1/2/2023 to 31/5/2024.

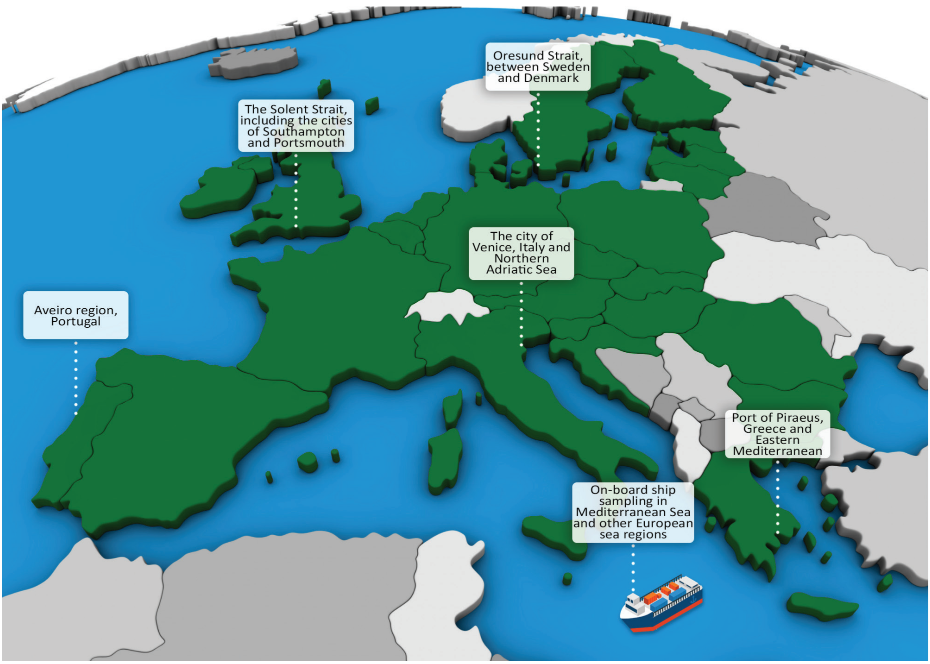


Figure 13: *The project included five selected geographical case studies in vulnerable environments, which represent sensitive areas, such as estuaries, straits and enclosed waters. In addition, one mobile case study was conducted onboard ships, operating in various European sea regions.*

Responsible partner institute	Short name of the case study	Main environmental issues	Original period planned	Status of experimental work
UAV	Aveiro region case study	Impact on water and air quality, eutrophication, bioaccumulation, marine and water ecosystems	Q1/2021	Three scrubber water samplings were conducted and tested during 2021/2022: one artificially produced and two produced on-board of Containership 1 and Containership 2. Ecotoxicological tests were conducted during 2021/2022 on fertilisation success and larval development of two distinct species. An additional water quality measurement campaign was completed in October 2022, with heavy metal and PAHs concentrations below detection limit of the equipment.
AUTH, DANAOS	On-board case study	Performance of emission characterisation on board the vessel, scrubber washwater composition and volume	Q4/2021	Campaign was held during 14-24 November 2021 onboard Containership 1 between Antwerp, Rotterdam and Gebze, Turkey. Samples of exhaust gases and particles were collected upstream/ downstream of scrubber and analysed for organics, PAHs and metals. Scrubber water was used for ecotoxicological experiments, incubation tests were also performed onboard.
AUTH; UAegean;	Eastern Mediterranean case study	Impact of scrubber effluents on water and air quality, water ecosystems, eutrophication, bioaccumulation, health impacts of air pollution	Q4/2022	Two field campaigns were completed on the Saronikos Gulf, along and across the traffic-lane of approach to Piraeus Port. Experiments were also made in ships' wakes. Ecotoxicological testing of scrubber effluent started in January 2022. Collection and analysis of results were completed in October 2022. The main work during 01/02/2023-31/05/2024 was focused on analysis of the results and preparation of relevant publications.

Responsible partner institute	Short name of the case study	Main environmental issues	Original period planned	Status of experimental work
UGOT; CTH IVL	Öresund case study	Impact on water and air quality, marine ecosystems, eutrophication, bioaccumulation, health impacts of air pollution, importance of ship induced mixing for dispersion of scrubber water.	Q3/2021	Collection of sea water samples and measurement of ship induced mixing was done in Q3/2020. Ecotoxicology experiments were performed in 2021 and 2022.
US	Solent case study	Impact on water and air quality, marine ecosystems, health impacts of air pollution	Q1/2021	Ecotoxicology experiments were conducted between July 2021 - November 2022. Algae experiments were conducted by end November 2023.
UV	Northern Adriatic Sea case study	Chemical pollution of water, eutrophication, bioaccumulation, effects on fishing and aquaculture, marine ecosystems, health impacts	Q3/2021	Sampling of scrubber water from Containership 1 was conducted in November 2021 during the on-board campaign. The ecotoxicological testing planned with scrubber water from CHALMERS and Containership 1 on bacteria, mussels and copepods have been successfully concluded. During the past reporting period (i.e. from 01/02/2023-31/05/2024), efforts were focused on modelling activities (WP4-WP5) and impact assessment (WP6).

Impact of shipping emissions on the air and water quality of selected European port and harbour cities

Air emissions and discharges to marine waters from shipping were estimated for the baseline year 2018 and for two selected scenarios (S3-S8) in 2050. Findings showed a limited contribution of shipping to coastal pollution in the Northern Adriatic (Figure 14), but a more relevant role in the open sea both for the baseline and the two scenarios, with S3 highlighting a clear increase in ship-borne pollutants concentration.The outcomes of **bioaccumulation modelling**, targeting current offshore shellfish farms, showed that for the four target chemicals concentrations in mussels simulated for the “high-scrubber scenario” S3 in 2050 are expected not to exceed the maximum levels acceptable in seafood (bivalve molluscs) set by the EU Regulation 915/2023. Shipping emissions of nitrogen account for only 6% of the riverine input and therefore have limited impact on the long-term overall Northern Adriatic biogeochemical cycles under current and future scenarios.

Shipping’s contribution to air quality was investigated. The current contribution from shipping to surface concentration is limited to shipping lines and to the vicinity of the harbours for SO2 and NOx, while changes in O3 and PM2.5 extend much further. Future scenarios were explored through regional air modelling. A significant reduction in monthly mean concentrations of SO2 is expected in both S3 (SECA introduced for the Mediterranean) and S8 (transition to LNG and methanol). PM2.5 from ships is simulated to decrease by ~7-8% in both scenarios.

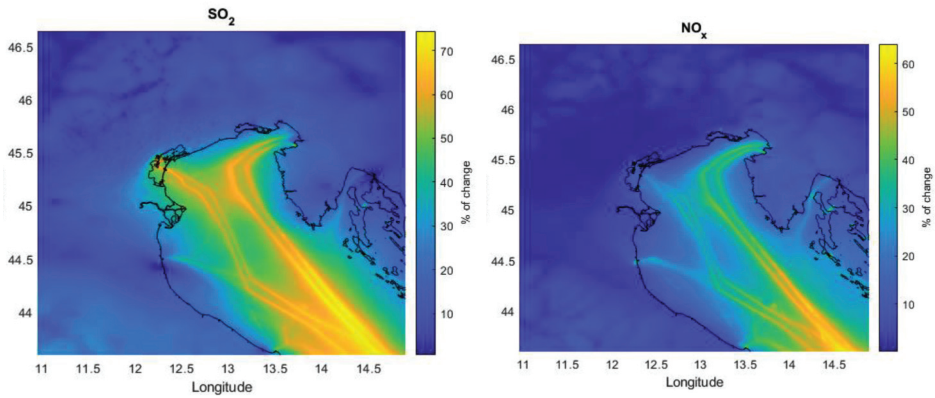


Figure 14: *Annual average difference of pollutant concentrations from SILAM for the Northern Adriatic case-study. The change for SO2 and NOx is defined as the difference of contaminants concentrations between simulations with shipping emissions and without shipping emissions. Results are presented in percentage change.*

Ecotoxicological testing of scrubber water samples on a suite of planktonic bioindicators representative of Northern Adriatic nearshore environments proved that toxic effects are possible at very low scrubber water concentrations (<0.1% dilution for copepods and bivalve larvae) (Picone et al., 2023). The modelling of scrubber water dilution for the Northern Adriatic CS area revealed that a continued release of scrubber water over several days could lead to concentrations comparable to those detected in the ecotoxicological studies to cause adverse effects on the tested species. The PNEC derived from bioassays (equal to $2*10^{-6}$ %) can be exceeded by the estimated exposure to scrubber water under current conditions up to 30% over the year, and this exposure is estimated to increase significantly under S3 future scenario (Figure 15).

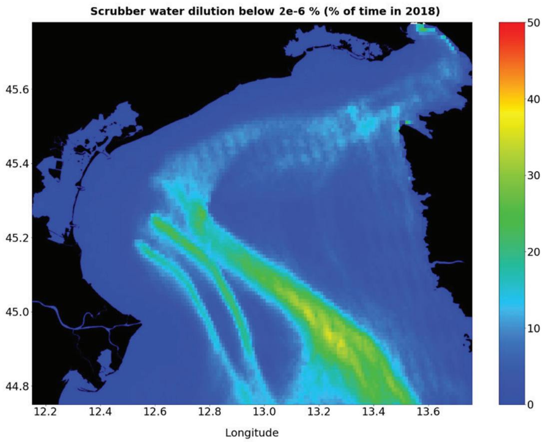


Figure 15: % of frequency of exceedance of scrubber water exposure over the derived PNEC in one year under current conditions.

Atmospheric modelling results for the Solent case study region reveal an average annual increase in concentrations attributed to shipping activities: approximately 10% for PM2.5 (Figure 16). There is an annual increase of 35% for NOx and 4% for SO2, as averaged across all models. In the absence of shipping emissions, O3 concentrations would experience a 4% increase. This rise can primarily be attributed to the decrease in NOx emissions and subsequent changes in relevant photochemistry.

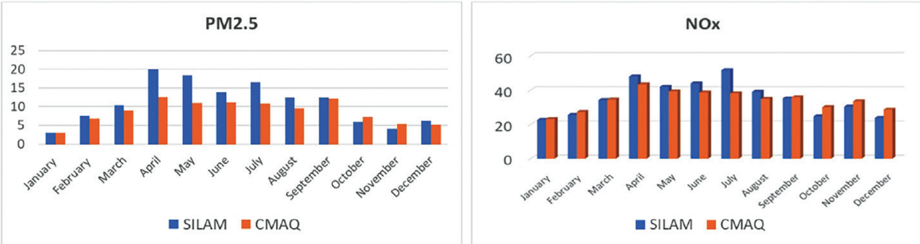


Figure 16: *The percent contribution of shipping to NOx and PM2.5 concentrations in Solent case study region predicted by SILAM and CMAQ models.*

The annual average of total NOx deposition in the Solent region is 29% (Figure 17). The modelling outputs highlighted that the Solent case study region exhibited the highest levels of PM2.5 deposition within all case study regions, showing an approximate 12% increment attributed to shipping. There is an annual average of 11% increase in SO2 deposition and shipping emissions contribute a decrease of 2.5% O3 deposition.

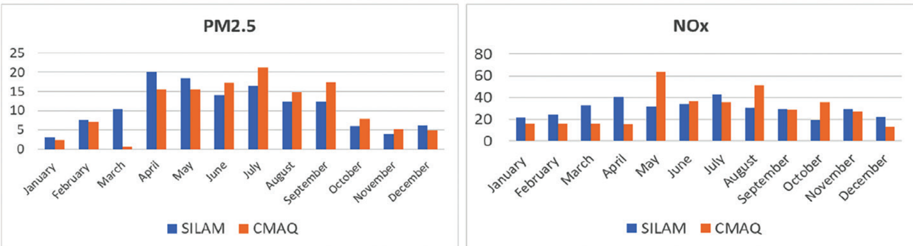


Figure 17: *The percent contribution of shipping to NOx and PM2.5 depositions in Solent case study region predicted by SILAM and CMAQ models.*

Figure 18 illustrates the predicted percentage contribution of shipping emissions to PM2.5 and NOx concentrations in the cities/ports of the Solent case study region. Shipping activity increases in the summer months, and this is reflected in the results.

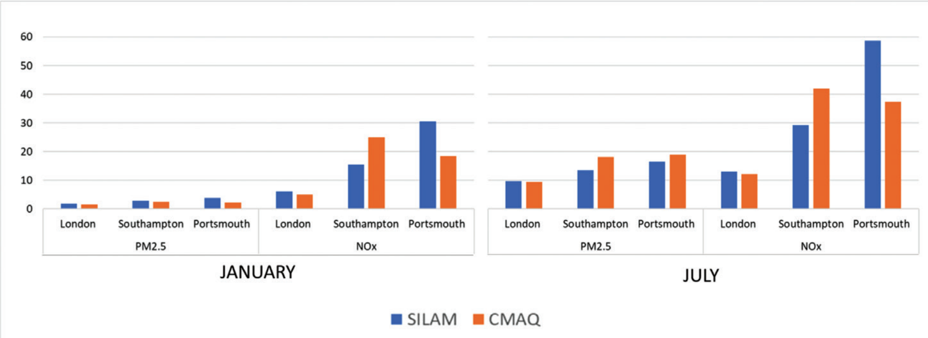


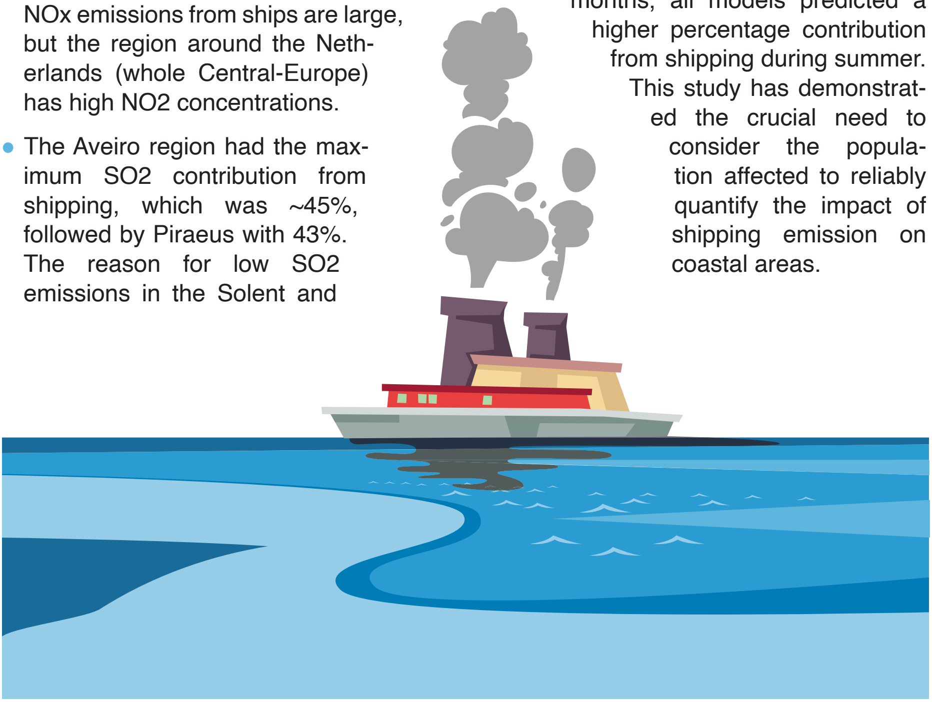
Figure 18: *The percent contribution of shipping to NOx and PM2.5 concentrations in selected cities predicted by SILAM and CMAQ models for January 2018 (left) and July 2018 (right).*

The average contribution of shipping emissions in 2018 for the five case study regions was estimated to be 28% for SO2, 19% for NOx and 6% for PM2.5. Similar relative changes in the monthly mean concentration of NOx of 20% and 30% during the months of January and July were predicted by all models. Key findings include:

- Shipping has a large impact in port areas and coastal communities in a country. Focusing on the Aveiro Lagoon area, the differences between the simulations with and without shipping showed an average contribution of shipping of 28% for SO2, 19% for NOx and 6% for PM2.5.

- At a local- and city-scale air quality around the port of Piraeus, Greece, shipping contributions of atmospheric pollutants concentrations were found to be localised near the entrance-exit routes of the passenger and freight ship docking areas as well as in areas of manoeuvring traffic. Shipping had a considerable contribution in total NO2 concentrations ranging from ~12% to ~21%, whereas its impact was diminished in terms of the relative contribution of SO2 (<5.5%) and PM2.5 (3.7% - 5.5%), due to the presence of strong nearby land sources. The scenario including designation of the Mediterranean Sea as a NECA was found to have the highest influence in the reduction of shipping contribution regarding NO2 in all examined locations, whereas the introduction of alternative fuels as projected in the alternative scenario played a more important role in controlling PM2.5 and SO2 levels. At a Mediterranean scale, the findings highlighted the effective mitigation of shipping related SO2 and PM2.5 contributions in both scenarios, while emphasizing the superior performance of S3 (introduction of Mediterranean NECA) in controlling NO2 contributions, similarly to the local case study results.

- Ozone is a solely secondary air pollutant. The largest contribution from shipping is found to be around Denmark, in the North Sea, English Channel, Mediterranean Sea, and around the Sea of Marmara. Around the coast of the Netherlands, the shipping contribution to NOx is the most important one. The largest increase in ozone is in the Eastern part of the Mediterranean Sea. The emissions from shipping that appear in sea regions also affect the air quality at inland locations far from the coast. The maximum contribution of NOx concentrations due to shipping was found in the Oresund region with 42%. The Solent case study region is close to the peak NOx emissions regions. Not only the NOx emissions from ships are large, but the region around the Netherlands (whole Central-Europe) has high NO_2 concentrations.
- The Aveiro region had the maximum SO_2 contribution from shipping, which was ~45%, followed by Piraeus with 43%. The reason for low SO_2 emissions in the Solent and Oresund regions is regulations that prevent the usage of high S fuel in the English Channel and the North Sea. A high correlation was found between surface concentrations and the deposition of various air contaminants.
- These developments have sharply improved modelling capabilities and allow for a robust application of the updated models. The impact of shipping emissions on air quality for the case study regions were prominent near coast regions and shipping routes, especially in the regions where shipping fuels are not controlled by the regulations. Because shipping activity increases in the summer months compared to the winter months, all models predicted a higher percentage contribution from shipping during summer. This study has demonstrated the crucial need to consider the population affected to reliably quantify the impact of shipping emission on coastal areas.



5. Policy Recommendations

The EMERGE project team has synthesized its outputs to provide policy recommendations. The three key urgent policy recommendations are to:

- Adopt policies that quickly discourage the use of Exhaust Gas Cleaning Systems (EGCS) with high-sulfur fuels and adopt cleaner and sustainable energy sources within the maritime industry.
- Consider both atmospheric deposition and direct discharges of pollutants into marine environments during the regulatory process.
- Swiftly implement a policy to restrict scrubber water discharge in regional sea areas.

Other important policy recommendations include:

- Traditional assessments of PAHs in environmental and marine samples focus only on the U.S. Environmental Protection Agency (EPA) list of 16 priority PAHs, which includes only parent PAHs. Considering the complex PAHs assemblages and the importance of other related compounds, it is important to extend the EPA list to include alkyl-PAHs to obtain a representative monitoring of EGCS effluent and to assess the impact of its discharges into the marine environment.
- EGCS effluents pose a risk of having serious impact on populations of key species of marine food webs. It is therefore not advisable to release EGCS effluents to the sea.
- Shallow coastal areas that are nurseries and feeding grounds for most marine organisms including commercial fish species will be particularly exposed to EGCS effluent release and should be protected.
- EGCS effluents may harm populations of many species either directly through toxicological effects, or indirectly through the marine food web thus affecting feeding of species. There is an apparent conflict between shipping and sustainability goals, which must be considered in concert.
- Considering the current poor chemical status of the European seas, the release of EGCS effluents will violate the objectives of the EU's Water Framework Directive.

- As a UN body, the IMO should, according to its directives established by all member States, apply the precautionary principle as stated in principle 15 of the Rio declaration (UN 1992). The expectation on IMO should thus be to ban the option of installing EGCS as alternative means to comply with the new S regulations since there is sufficient scientific evidence to suspect that irreversible damage to marine ecosystems may be caused by their use.
- The economic advantage of EGCS fleet may lead to an acceleration of negative consequences for the marine environment. It is recommended to make alternatives to scrubbers more economically attractive.
- Relative shipping contribution to exposure to NOx and PM2.5 in Öresund region is substantial. For emissions of NOx, only slow decrease is expected from NECA implementation and regulatory loopholes can lead to a failure in enforcement of the NOx emission limits. To facilitate enforcement of NOx emission limits, these should be connected to fuel use (g/kg of fuel), not engine power (g/kWh).
- Reduction of the use and carriage of residual fuels is crucial to mitigating the environmental risks associated with accidental oil releases into the sea.
- Prioritization of the use of low- or no carbon fuels will reduce the overall pollutant loads associated with shipping activities and will make scrubbers obsolete.
- The small difference between the scenarios for the Aveiro region highlights the importance of additive measures to reduce the impact of shipping emissions. A combination of measures is needed to improve the state of the environment in this area. Since the Aveiro coastal region is in the Atlantic, measures such as emission control areas could be extended to parts of the Atlantic to include the Portuguese coastline.
- Future emission scenarios considering different abatement measures may have different efficiency depending on the targeted pollutant and location of interest. This emphasizes the necessity of conducting a comprehensive analysis of impacts, to provide scientifically justified policy recommendations for the abatement of shipping impacts.
- We recommend international collaboration to promote cleaner shipping.

Call:	H2020-MG-2019-SingleStage-INEA
Section:	
Topic:	MG-BG-02-2019 Ship emission control scenarios, marine environmental impact and mitigation
Duration:	52 (End May 2024)
Budget:	Euro 7,493,885
Coordinator:	Finnish Meteorological Institute
Total Beneficiaries:	18
Website:	https://emerge-h2020.eu/

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EMERGE consortium

This booklet reflects the authors' views.

ISBN: 978-1-912431-28-1.
Published by the University of Southampton.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 874990.