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Towards a comprehensive evaluation of the environmental and health impacts of shipping emissions

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Abstract

We present a new concept for marine research, applied in the EU-funded project EMERGE, "Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions" (2020 – 2024; https://emerge-h2020.eu/). For the first time, both the various marine and atmospheric impacts of the shipping sector have been and will be comprehensively analyzed, using a concerted modelling and measurements framework. The experimental part of the project focuses on five European geographical case studies in different ecologically vulnerable regions, and a mobile onboard case study. The EMERGE consortium has also developed a harmonised and integrated modelling framework to assess the combined impacts of shipping emissions, both (i) on the marine ecosystems and (ii) the atmospheric environment. The first results include substantial refinements of a range of models to be applied, especially those for the STEAM and OpenDrift models. In particular, the STEAM (Ship Traffic Emission Assessment Model) model has been extended to allow for the effects of atmospheric and oceanographic factors on the fuel consumption and emissions of the ships. The OpenDrift model has been improved to take into account the partitioning, degradation, and volatilization of pollutants in water. The predicted emission and discharge values have been used as input for both regional scale atmospheric dispersion models, such as WRF-CMAQ (Weather Research and Forecasting - Community Multiscale Air Quality Model) and SILAM (System for Integrated modeLling of Atmospheric composition), and water quality and circulation models, such as OpenDrift (Open source model for the drifting of substances in the ocean) and Delft3D (oceanographic model). The case study regions are Eastern Mediterranean, Northern Adriatic Sea, the Lagoon of Aveiro, the Solent Strait and the Öresund Strait. We have also conducted a substantial part of the experimental campaigns scheduled in the project. The final assessment will include the benefits and costs of control and mitigation options affecting water quality, air pollution exposure, health impacts, climate forcing, and ecotoxicological effects and bioaccumulation of pollutants in marine biota.

Keywords: shipping, impacts, environmental impacts, health impacts, EMERGE, STEAM, WRF-CMAQ, SILAM, OpenDrift, Eastern Mediterranean, Adriatic Sea, Aveiro, Solent Strait, Öresund Strait.

1. Introduction

New global standards have been enforced in 2020 for shipping emissions, as a consequence of the potentially significant health and environmental effects, especially from SO_x and sulphate aerosol. In so-called Sulphur Emission Control Areas (SECAs), a stricter regulation of 0.1 % Fuel Sulphur Content has been in place since 2015. In Europe, these comprise the Baltic and North Seas.

In complying with the limit values within SECAs, ships are currently mandated to use fuel oil with fuel sulphur content within the limits. Alternatively, vessels may be equipped with abatement systems - SOx scrubbers - that decrease SO_2 in the exhaust to within the limits. However, the seawater scrubbing process produces large volumes of acidic and contaminated exhaust scrubber effluent. This could potentially result in a substantial deterioration of marine water quality. However, there is limited data on the environmental toxicity of scrubber washwater.

Combustion in ship engines results in a range of primary and secondary airborne pollutants that have important environmental, health, economic and climatic impacts. Particulate matter (PM), SO_x, NO_x and O_3 exposures from shipping have been associated with an increase in morbidity and premature mortality rates of human populations (e.g., Nunes et al., 2021).

The EMERGE project has up to date focused on establishing the overall framework, through the combination of laboratory and field measurements and modelling activities. The overarching objectives of EMERGE are: (i) to comprehensively quantify and evaluate the effects of potential emission reduction solutions for shipping in Europe for several scenarios, and (ii) to develop effective strategies and measures to reduce the environmental impacts of shipping.

2. Methods

We have updated emission factors for shipping, especially regarding the effects of advanced aftertreatment technologies, based on an extensive review of previous literature. These values were collected in a structured database, which contains emission rate values for the most relevant pollutants (SO_x, NO_x, CO, HC, PM), and for various emission abatement options.

The STEAM model (e.g., Johansson et al., 2017, Jalkanen et al., 2021) has been and will be used to provide the detailed emission values to air and discharge values to water, on a high spatial and temporal resolution. The model utilizes automatic identification system (AIS) data from individual ships and evaluates emissions using ship data, modelling of fuel consumption and emission factors. The emission and discharge results have been and will be used in the modelling of dispersion and transport of pollutants in the atmosphere and the seas, and for the impact assessments.

Several chemical transport models have been refined and applied for the evaluation of air quality on regional and continental scales. The model predictions will be evaluated against the measured concentrations and deposition of pollutants within the European Monitoring and Evaluation Programme (EMEP), and selected satellite observations. The regional scale models will target a spatial resolution of 5 km at European scale and zoom down to 1 km for the case study areas. In addition, computations on an urban scale will also be done in part of the case studies.

The output of the STEAM model consists of the volumetric fluxes of discharges per area. The fluxes of each pollutant to the sea will subsequently be computed by using the fractions of pollutants in the scrubber discharge effluent; the latter have been evaluated based on the existing literature. The pollutant fluxes per area have then been used as input values in the chemical fate and transport models.

In particular, we have used and will use the Lagrangian OpenDrift model and the Eulerian 3D water quality model Delft3D-WAQ. In addition, we will evaluate the fluxes of pollutants to the sea attributed to atmospheric deposition. The partitioning, degradation, and volatilization of chemicals have been included in a new module (ChemicalDrift) of the OpenDrift model (Dagestad et al., 2018), thus facilitating the modelling of the different environmental behaviour of heavy metals and organic pollutants (e.g., polyaromatic hydrocarbons, PAHs).

Several scenarios have been constructed for estimating the impacts of the application of various emission control technologies in the future. The project will focus on the evaluation of the emission changes resulting from (i) the different developments of marine traffic, (ii) the potential uses of emission control technologies, especially scrubbers, and (iii) the use of various alternative fuels.

We aim to eventually provide for harmonized information on the ecotoxicological effects of scrubber washwater in various European sea regions. The toxicity of scrubber effluents has been tested for a wide range of marine species in different life stages, using different health end points. The consortium has developed a common protocol for one species, the blue mussel larvae, to intercompare the ecotoxicological effects of scrubber water in various European sea regions. The chemical analyses of scrubber water contaminants will be used in water modelling, to estimate whether the seawater concentrations will pose a threat to marine ecosystems.

Several full-scale measurement campaigns have already been conducted.

3. Results

We have compiled the data available in the literature on the content of scrubber effluents, inlet water and sludge. A comprehensive database was compiled, which includes (i) the concentrations of contaminants, nutrients and acidifying substances (e.g., Lunde Hermansson, 2021), and (ii) the available information regarding the mode of operation of a ship. The emission factors for a range of compounds were subsequently evaluated corresponding to various assumptions on the scrubber effluent discharge rates for open and closed loop scrubbers. The corresponding information was also evaluated for other shipping waste streams (e.g., grey water, bilge water and anti-fouling paint).

Untargeted high resolution mass spectrometry analysis was used for a detailed chemical characterization of scrubber water. We found that the substances of major concern were several PAHs, together with their alkylated derivatives, and metals.

Experimental studies have been conducted using both open loop effluents from an operating ship and samples obtained from an open-loop pilot scrubber system operated at a laboratory in Chalmers University of Technology. Repeated experimental studies have found statistically significant effects on marine zooplankton after exposure to concentrations as low as 0.01% scrubber effluent (Thor et al., 2021). However, the data also indicates that the sensitivity to scrubber effluent varies greatly both between species and between different life stages of species (Ytreberg et al., 2019).

The STEAM emission model has been updated to use improved emission factors. In particular, the model has been refined to include the effects of the resistance of sea ice, wind, waves and sea currents on the passage of the ships and on the emissions. These improvements have used the data provided by Copernicus Marine and the meteorological data of ERA5. These updates will substantially improve the capability to accurately evaluate shipping emissions and discharges; the refined model will be used globally in the evaluation of shipping emissions in the future.

The magnitude of these effects has been illustrated in Fig. 1 in case of the Baltic Sea, during one year. The Baltic Sea is commonly covered with ice from December to May. During these months, sea ice cover significantly increases the fuel consumption. Wind and waves are dominant environmental effects in September and October. The effects of sea currents almost totally cancel out in this sea region. The model subsequently evaluates the impacts of such environmental effects on the emissions of various pollutants.

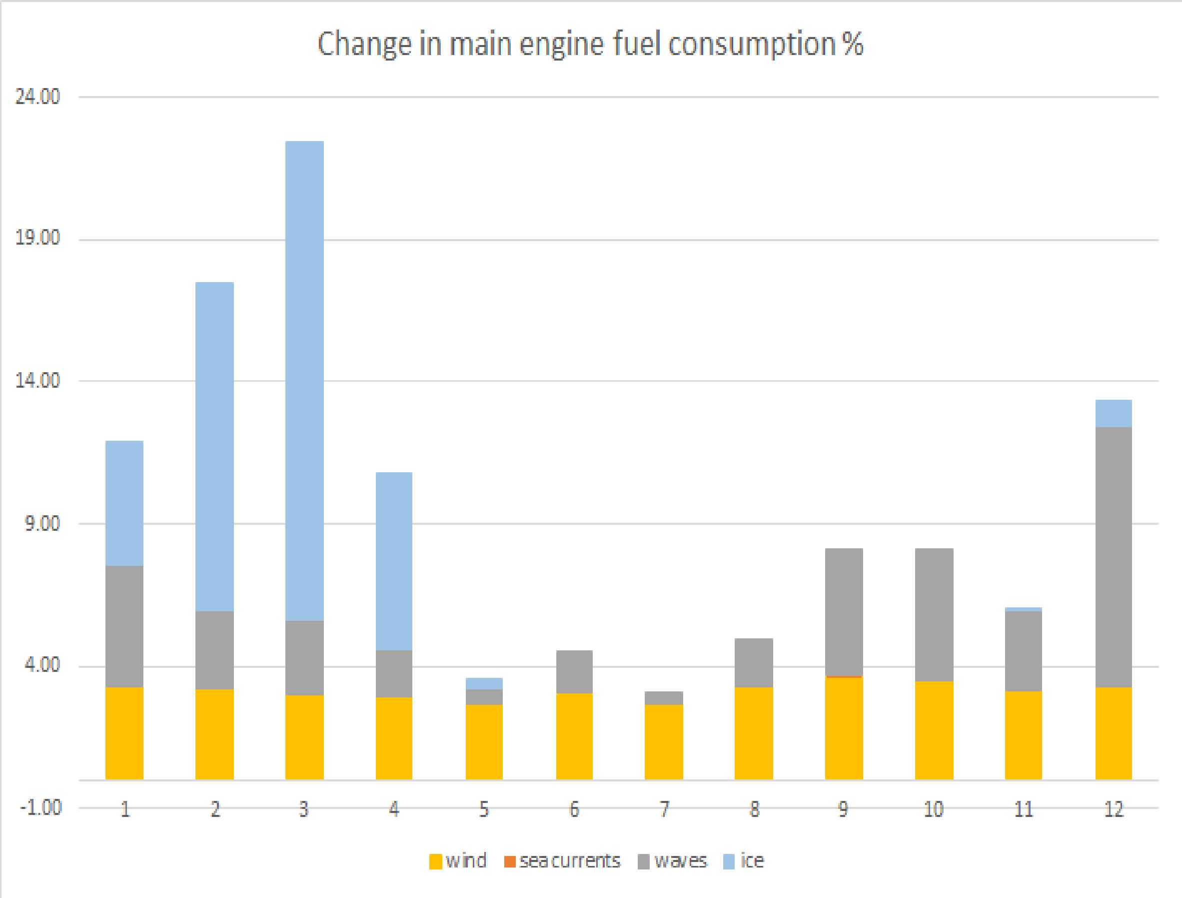
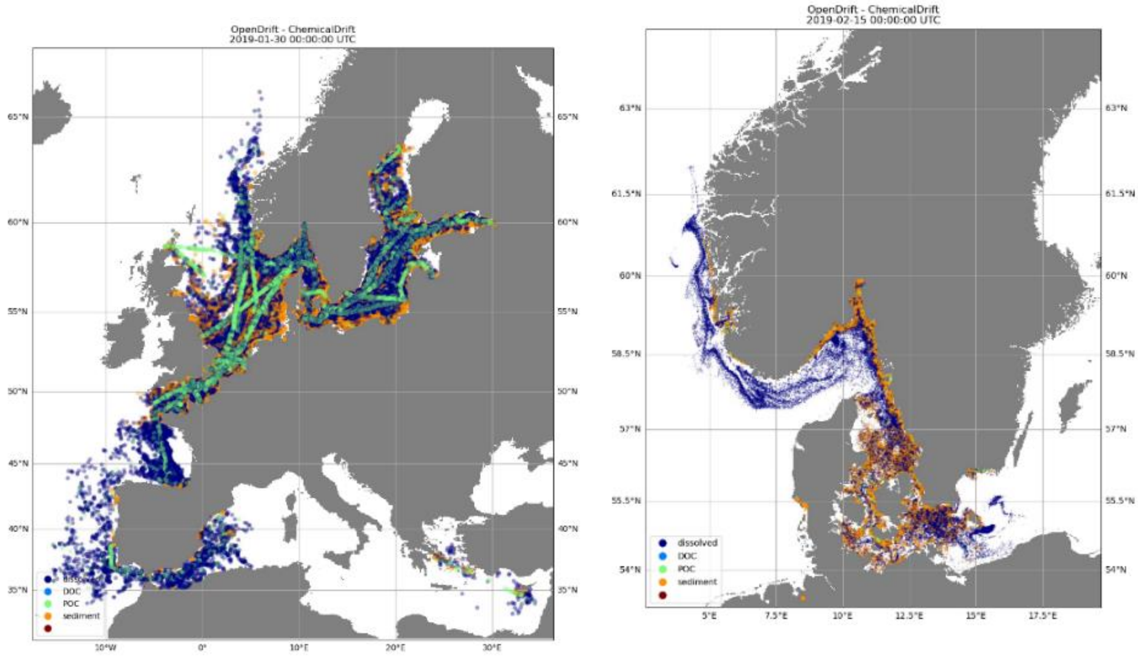


Fig. 1. The impact of ambient conditions, including wind, sea currents, waves and ice cover, to monthly totals of fuel used in the Baltic Sea in 2018. The results were computed using a refined version of the STEAM model. The colours refer to the influence of sea ice (blue), waves (grey), sea currents (red) and wind (yellow).

Grönholm et al. (2021) presented for the first time a quantitative assessment of the climatic impacts of various liquid natural gas (LNG) -fuelled ships in real-life marine conditions. They found out that the unintentional release of methane (called also as the methane slip) was substantial for part of the LNG-fuelled ships. They evaluated that these releases will actually cause larger impacts on the climate, compared with the corresponding releases originating from ships that use conventional marine fuels.

The predicted discharges to the sea were used as input values in the computations on water quality, using the ChemicalDrift module of the OpenDrift model (Dagestad et al., 2018). Preliminary results have been presented in Fig. 2.



dissolved chemical **sorbed to DOC (dissolved organic carbon)**
sorbed to POC (particulate organic carbon) **sorbed to sediment**

Fig. 2. Preliminary model results on the transport and fate of phenantrene emissions from shipping activity in the European sea regions (panel on the left) and in the Öresund area and its surroundings (panel on the right), computed using the OpenDrift-ChemicalDrift model. The legend (colours) indicates the chemical species. The shipping emission data was provided by the STEAM model (data from January-February 2019). The forcing data was extracted from the global models HYCOM (HYbrid Coordinate Ocean model) and CMEMS (Copernicus Marine Environment Monitoring Service).

Meteorological datasets have been computed using the Weather Research and Forecasting (WRF) model. These datasets have been evaluated against experimental meteorological data on a European scale. The results will be used in the atmospheric dispersion computations by the partners in their regional and partly also in urban scale computations.

Conclusions

Finally, we will analyze the impacts of ship emissions and effluents on both the atmospheric and marine environments. The cost-efficiency will also be analyzed for various abatement methods, fuels and technological solutions. The project adopts a holistic approach: for the first time, both the various marine and atmospheric impacts of the shipping sector will be comprehensively analyzed, using a concerted modelling and measurements framework.

The project is expected to provide new harmonised knowledge on water and air pollution and their impacts, both on a European scale, and within the vulnerable case study regions. The assessment of scenarios for the future will highlight the optimal procedures towards the mitigation of the environmental and health impacts. The scenarios address various emission abatement technologies, fuel switch and different operation of the ships. The project will provide for recommendations on policy actions for decision-makers and ship owners in the EU and globally.

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QUESTIONER: Lafafi Borge

QUESTION: The increase of shipping emissions due to the explicit consideration of wind and surface ice has an impact on consumption, and therefore CO2 / SO2 emissions. Is that taken into account to estimate emission of other pollutants, such as NOx ?

ANSWER: Yes. The ambient effects will change the power need and engine load of vessels and therefore these will also affect fuel consumption and the emissions of all atmospheric pollutants. In addition, the ambient effects will influence also the discharges to water (such as, e.g., the scrubber discharges), as these have been modeled as a function of the instantaneous engine power.