CSHIPP
Interreg
Baltic Sea Region
EUROPEAN REGIONAL DEVELOPMENT FUND
EUROPEAN UNION

Air pollution from shipping

1) How can emission reduction measures for shipping help us meet the threshold and target requirements in the Air Quality directives?

Ships emit gases and particles into the atmosphere, among them are carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM). Globally, about 100,000 commercial ships are in service. International shipping is responsible for about 2.2% of the global CO_2 emissions, but for 15% of the NO_x and 13% of the SO_x emissions (Fig. 1). CO_2 is an important climate gas, while NO_x and SO_x are important air pollutants, also leading to the formation of particles. In certain regions with dense ship traffic like the Baltic Sea, air pollution may be significantly enhanced due to shipping.

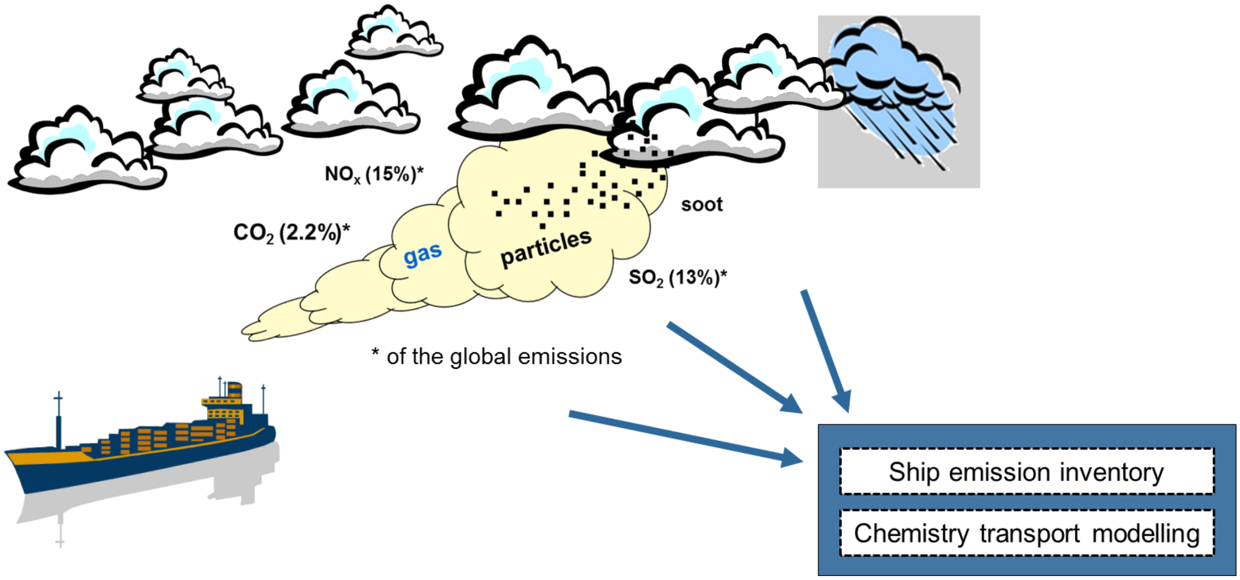

Figure 1: CO_2, NO_x, SO_x, and particles are emitted from shipping. Computer models of the atmosphere take ship emission inventories as input and calculate the dispersion of pollutants in the atmosphere, their chemical conversions, and their deposition on water and land surfaces (chemical transport modelling).

Ship emissions into the air influence climate (through CO_2, CH_4, PM), affect air quality (PM, NO_x, ozone), and lead to acidification of marine and land surfaces (SO_x, NO_x). SO_x and NO_x from ships contribute to the degradation of air quality regionally, especially along the coast where a large portion of the population in the Baltic Sea region lives. These gases are also precursor substances[1] for secondary aerosols and tropospheric ozone. PM, including directly emitted black carbon (BC), sulphate, organic matter, metals and others, has negative health effects. Globally averaged, the net effect of PM from shipping on climate is a cooling (scattering of solar radiation, and changes in cloud albedo). BC, however, has a warming potential due to its light absorption capabilities, both while airborne and when deposited on bright surfaces, such as ice- and snow-covered parts of the Arctic.

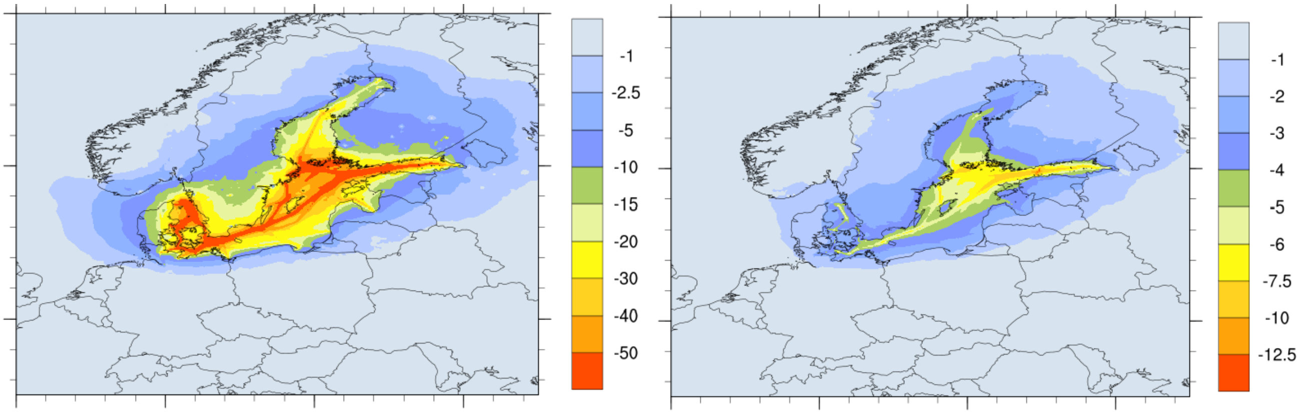

Figure 2: Percentage change in annual-mean concentrations of SO_2 (left panel) and $PM_{2.5}$ (right panel) due to the 2015 IMO regulations on sulphur content in fuel for shipping in the Baltic Sea. The maps are based on model calculations on 10 km x 10 km resolution for the Baltic Sea region (Jonson et al., 2019).

The Air Quality directives set limits for NO_x (NO_2), SO_x (SO_2), particulate matter and CO. The Baltic Sea (and the North Sea) are SECAs (Sulphur Emissions Control Areas), where the regulations have been strengthened in several steps, with the latest 2015 IMO regulation having led to a significant reduction in SO_2 concentrations (Fig. 2). Figure 3 shows comparisons between model results and measurements from 2016, illustrating that SO_2 concentrations would have been much higher than observed, if the new IMO regulations had not been in place or complied with (blue line in Figure 3, right panel).

Levels of sulphate (either emitted directly or formed from emitted SO_2) have also decreased. As sulphate is a major contributor to $PM_{2.5}$ (particles suspended in the air with diameters less than 2.5 microns), $PM_{2.5}$ levels are also reduced (Fig. 2, right panel). The percentage reduction in $PM_{2.5}$ is smaller than for SO_2 since $PM_{2.5}$ also has many sources other than shipping.

In the case of SO_2, air quality standards were largely met already before 2014 so that the 2015 SECA rules had no significant effect on the number of exceedances. However, in the case of PM, exceedances are more likely to be avoided through reductions of ship emissions. In absolute terms, the annual mean $PM_{2.5}$ load has decreased by up to 0.5 µg/m^3 according to regional and local model simulations. Locally, and especially in coastal cities, the effect can be larger, up to a few µg/m^3.

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[1] A *precursor* is a compound that participates in chemical reactions producing another compound, e.g. aerosols.

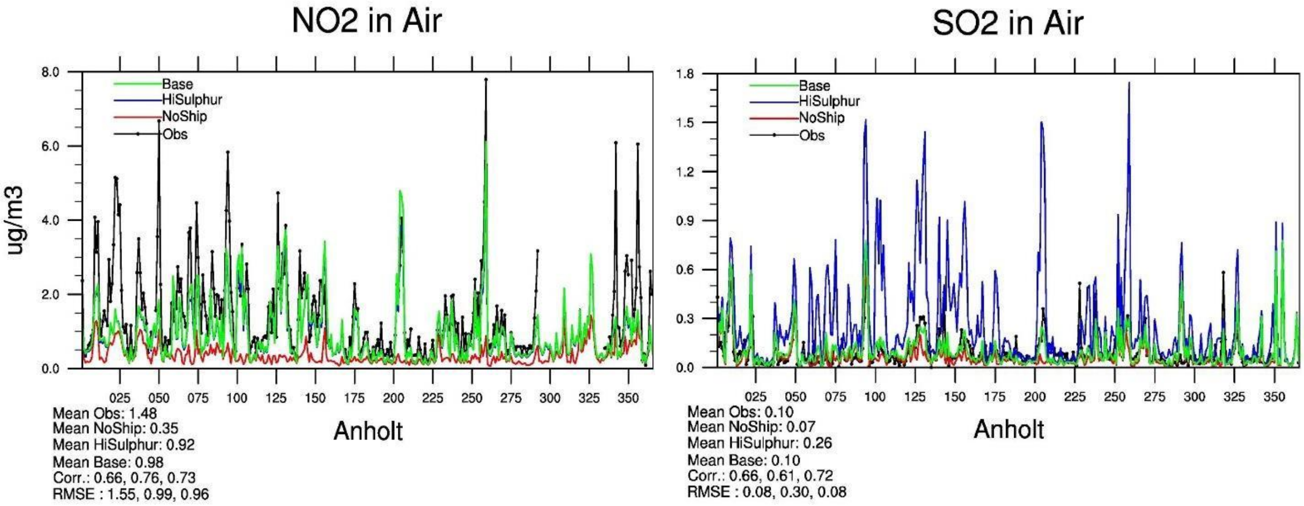

Figure 3: Calculated and measured concentrations of NO_2 (left) and SO_2 (right) at Anholt in Denmark. 'Base': Results with ship emissions according to 2015 IMO regulations, 'HiSulphur': with ship emissions before the 2015 IMO regulation, 'NoShips': without any ship emissions, and 'Obs': concentrations measured in 2016.

2) Remarks on the health impact

Based on model results, health impact calculations have been performed. Figure 4 shows the additional population exposure to $PM_{2.5}$ caused by Baltic Sea ship emissions for selected countries. It is proportional to concentrations but decreases with distance to the Baltic Sea.

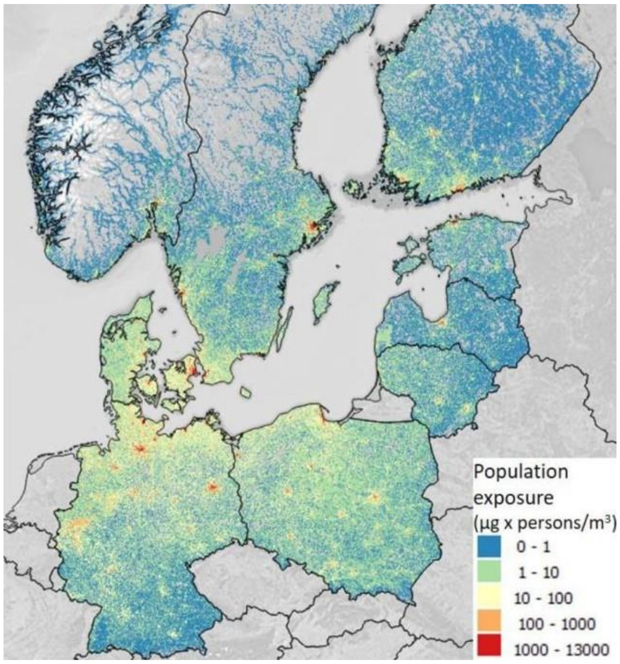

Figure 4: Estimated contribution of shipping emissions in the Baltic Sea to population exposure of $PM_{2.5}$ in 2016 (after the SECA regulations of marine fuel sulphur) in each 0.1° x 0.1° grid cell (about 11 km x 6 km wide). The unit is $\mu g/m^3$ $PM_{2.5}$ x number of persons.

The figure is taken from the publication of Barregård et al. (2019), where also numbers on premature deaths were presented. According to these calculations, $PM_{2.5}$ air pollution due to emissions from Baltic Sea shipping caused about 1500 premature deaths in 2015 and about 1000 in 2016, a decrease due to the 2015 IMO regulation.

3) Remarks on compliance

Figure 5 shows airborne sulphur fuel compliance measurements of individual ships in the Baltic Sea in the summer of 2017. The results show that 6% of the ships were operating with non-compliant fuel. The general results, based on numerous measurements, show compliance rates of 95% on the open sea (airborne, Great Belt bridge) and 97-98% in the ports. Here typically one third of the non-compliant ships were in gross non-compliance (fuel sulphur content around 1.5%) while two thirds were operating on fuel closer to SECA sulphur limit (fuel sulphur content around 0.3%).

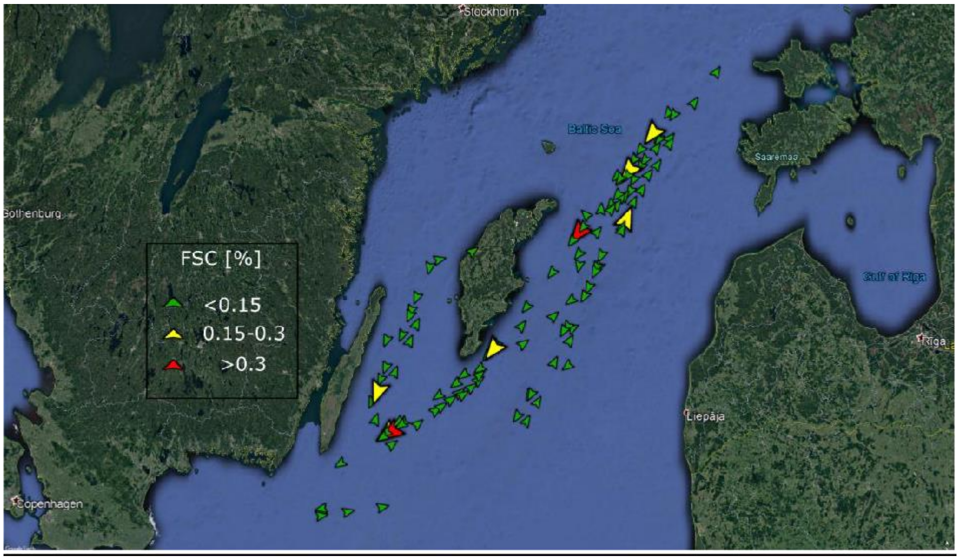

Figure 5: Airborne sulphur fuel compliance measurements in the Baltic Sea in 2017. Out of 114 ships, 6% of the ships ran with non-compliant fuel above 0.15% in fuel sulphur content.

Similar measurements were successfully carried out for NO_x content (in g NO_x per kg fuel). However, it is not straightforward to compare a spot check of NO_x emissions with the IMO NO_x rules, which apply to the *average NO_x emissions* of a ship (in g NO_x per kWh axial power) at several different load factors of the engine.

Figure 6 illustrates how non-compliance may affect total emissions from Baltic Sea shipping. Assuming 6% of the ships are non-compliant, with 1/3 of the non-compliant ships using 1.5%S fuel and 2/3 using 0.3% S fuel (as indicated by the compliance measurements), SO_2 emissions in the Baltic Sea would be about 36% higher, according to a simple calculation based on total ship fuel consumption. In a scenario were all non-compliant ships used 1.5%S fuel the increase would be as large as 84%, while it would be

12% if all non-compliant ships used 0.3%S fuel. The figure also shows results from a more detailed calculation, performed by the Ship Traffic Emission Assessment Model (STEAM, Jalkanen et al., 2009; 2016), taking into account that sulphur in fuel also leads to emission of other pollutants, such as fine particulate matter and sulphate and distributing the non-compliance randomly over ship types.

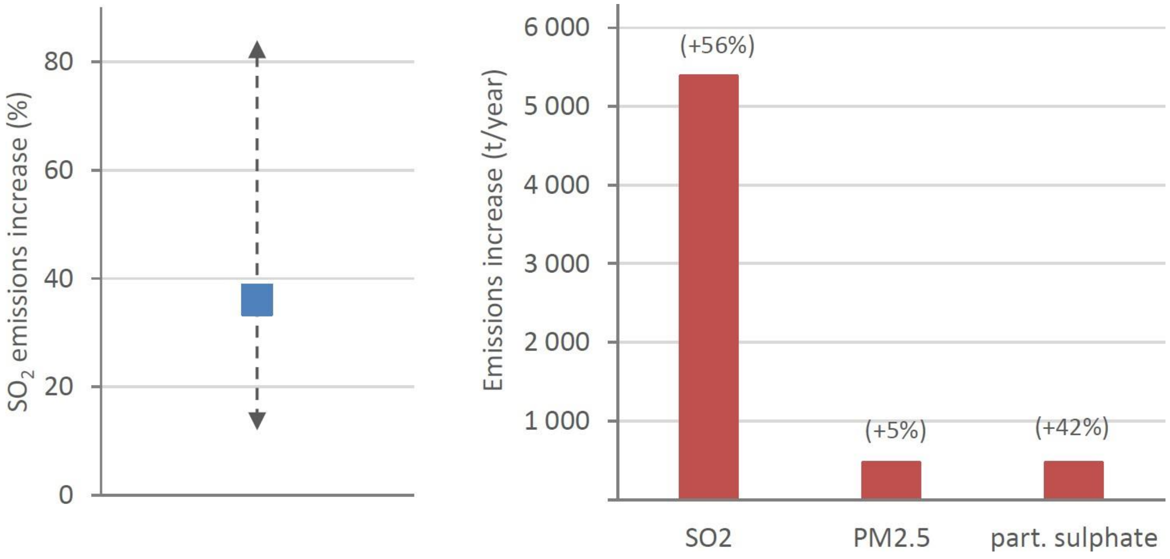

Figure 6: Increase in total emissions from Baltic Sea shipping in a scenario where about 6% of the ships are non-compliant. The range indicated in the left panel indicates the uncertainty in the amount by which the sulphur limit is exceeded. If all non-compliant ships used 1.5%S fuel the total emission from Baltic Sea shipping would be 84% higher than in a full-compliance scenario. The blue square (36%) is for a scenario were 1/3 of the non-compliant ships use fuel with 1.5%S and 2/3 use fuel with 0.3%S. The right panel is based on more detailed calculations with the STEAM model, assuming that all non-compliant ships use 1.5%S fuel, but taking into account the emission of other pollutants as well, such as $PM_{2.5}$ and SO_4 ('part. sulphate').

4) Looking forward

Although significantly reduced since 2015, shipping continues to be an important source of $PM_{2.5}$ in the Baltic Sea region, mainly related to emissions of NO_x. From January 2021 the Baltic Sea and the North Sea are designated as NECAs (NOx Emission Control Areas). The NECA regulation only applies to new ships, or in case of a major modification of existing ships. Ships built after 2021 must comply with 80% NO_x reduction with respect to the Tier I regulation of 2000. Thus the expected emissions reduction will take effect only gradually over several years as the fleet is renewed. Nevertheless, by 2030 roughly one third of the fleet will emit 80% less NO_x than Tier I ships, whereas another third built in the period 2010 to 2021 will emit 20% less NO_x (Tier II). Ships built before 2010 will still follow Tier I NO_x emissions.

The results for nitrogen dioxide near the surface (Fig. 7) demonstrate that shipping is a large contributor to the NO_2 concentrations in the Baltic Sea area. NO_2 concentrations in shipping lanes are comparable or higher than those in big cities along the Baltic Sea coastline. By year 2040, however, substantial reductions in NO_2 levels are expected. For comparison, Figure 7 also shows what the situation in 2040 *would be* without the NECA regulations in place.

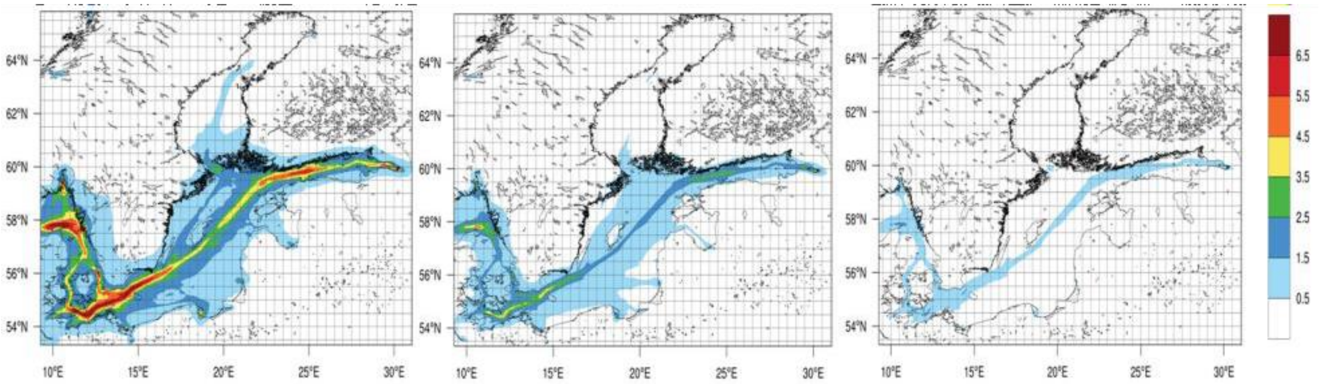

Figure 7: Modelled NO_2 concentrations in 2012 (left), in 2040 ***without*** *NECA implementation (middle) and* ***with*** *NECA implementation (right). Unit: ppbv (parts per billion by volume), based on Karl et al. (2019a,b).*

Ships are expected to be more energy efficient in the future to reduce their emissions of greenhouse gases (GHG). An IMO resolution from 2018 (initial IMO Strategy on reduction of GHG emissions from ships) states the objective to reduce the total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008. Technical measures including the Energy Efficiency Design Index (EEDI) with requirements on minimum mandatory energy efficiency performance levels that increase over time, have, together with slow steaming and other operational measures, the potential to decrease fuel consumption of ships by almost 50%. Biofuels, wind power and electrification could play a large part in closing the gap between this potential and the 50% target for the entire sector, which is expected to continue its growth in volume in the coming decades. One of the co-benefits of the energy efficiency increase is a reduction of emissions of air pollutants. The difference between the left and middle panels of Figure 7 reflects this co-benefit in regard to NO_2 concentrations[2].

Finally, the global sulphur cap has been in force since 1 January 2020, limiting sulphur content in ship fuel globally to 0.5%. As the sulphur regulations in the Baltic Sea (and the North Sea) are already stricter than this, the global sulphur cap will not affect air quality in the Baltic Sea region significantly, with reductions in long-range transport from other sea areas being minor. However, for countries facing the North Atlantic and in Southern Europe the effects of the global sulphur cap will be significant as shown in Figure 8, illustrating the effect of the reduction in fuel sulphur content from about 2.6% (pre-2020 global average value) to 0.5%. This will likely lead to avoidance of threshold exceedances and thousands of premature deaths related to particulate matter pollution. A designation of the Mediterranean as SECA area would reduce health impacts even further. However, this policy step is still being discussed (REMPEC, 2019).

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[2] Between 2012 and 2040, CO_2 emissions are expected to decrease by about 20% due to the energy efficiency increase.

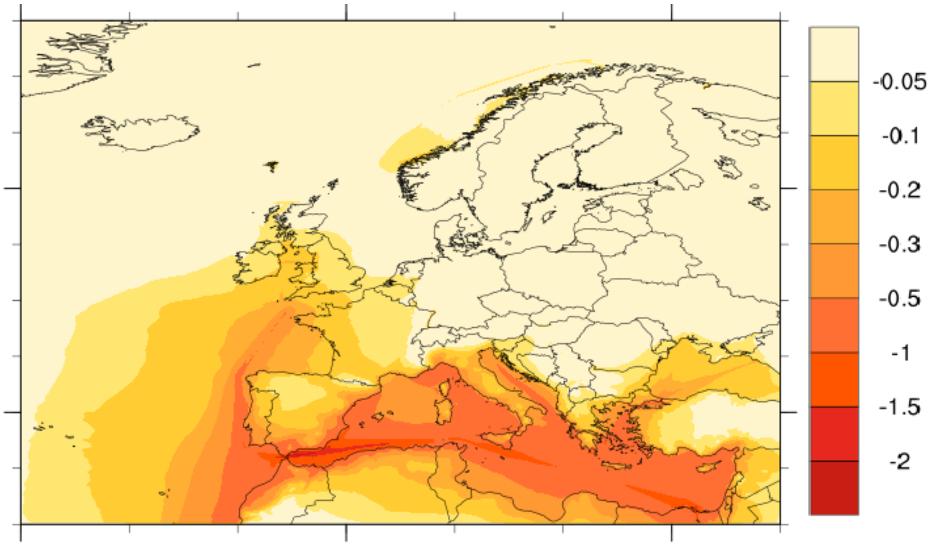

Figure 8: Estimated absolute reductions in annual mean $PM_{2.5}$ due to the introduction of the global sulphur cap in 2020 (unit: µg/m^3). The map is based on chemistry transport model calculations where emissions of SO_2 from shipping were reduced corresponding to the reduction of sulphur content in ship fuel to 0.5%.

4) References

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REMPEC (Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea), 2019. REMPEC/WG.45/INF.9 / Technical and feasibility study to examine the possibility of designating the Mediterranean Sea, or parts thereof, as SOx ECA(s) under MARPOL annex VI.

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It has been prepared by Michael Gauss (Norwegian Meteorological Institute), Jan Eiof Jonson (Norwegian Meteorological Institute), Jana Moldanova (IVL Swedish Environmental Research Institute), Johan Mellqvist (Chalmers University of Technology), Jukka-Pekka Jalkanen (Finnish Meteorological Institute), Volker Matthias (Helmholtz-Zentrum Geesthacht), and Matthias Karl (Helmholtz-Zentrum Geesthacht). Version date: 16.03.2020